Supported by: Hosted by: Endorsed by:
ISSN 2986-1268
Volume 7, 2024

THE 9th INDONESIA INTERNATIONAL
GEOTHERMAL CONVENTION & EXHIBITION
20 - 22 SEPTEMBER 2023
JAKARTA CONVENTION CENTER

SOUTHEAST ASIA'S LARGEST GEOTHERMAL CONVENTION & EXHIBITION

A CALL FOR GEOTHERMAL RESOURCES OPTIMIZATION

PROCEEDING BOOK

www.iigce.com

Proceeding Book
9th Indonesia International Geothermal Convention & Exhibition
IIGCE 2023: A Call for Geothermal Resources Optimization

ISSN 2986-1268
Volume 7, 2024

The 9th Indonesia International Geothermal Convention & Exhibition (IIGCE) 2023

September 20-22, 2023

A Call for Geothermal Resources Optimization

Editors:

Abadi Poernomo
Doddy Astra
Suryantini
Ali Ashat

Reviewers:

Ali Ashat (ITB)
Aquardi Suminar (SEGSD)
Christovik S (Baker Hughes)
Doddy Astra (INAGA)
Fernando Pasaribu (PGE)
Hari Widianto (Mannvit)
Hill Gendoet (ITNY)
Khasani (UGM)
Marino C. Baroek (INAGA)
Mulyanto (PGE)
Rizal Abiyudo (MCG)
Suryantini (ITB)
Yudi Indra Kusumah (SEGS)
Yunus Daud (UI)

Indonesian Geothermal Association

2024

ISSN 2986-1268
Volume 7, 2024

Published by:

Asosiasi Panasbumi Indonesia (API)

ISSN 2986-1268
Volume 7, 2024

Sanksi Pelanggaran Pasal 72 Undang-Undang Nomor 19 Tahun 2002 Tentang HAK CIPTA

1. Barangsiapa dengan sengaja dan tanpa hak melakukan perbuatan sebagaimana dimaksud dalam Pasal 2 ayat (1) atau Pasal 49 ayat (1) dan ayat (2) dipidana dengan pidana penjara masing-masing paling singkat 1 (satu) bulan dan/atau denda paling sedikit Rp. 1.000.000,00 (satu juta rupiah), atau pidana penjara paling lama 7 (tujuh) tahun dan/atau denda paling banyak Rp. 5.000.000.000,00 (lima miliar rupiah).
2. Barangsiapa dengan sengaja menyiarkan, memamerkan, mengedarkan, atau menjual kepada umum suatu Ciptaan atau barang hasil pelanggaran Hak Cipta atau Hak Terkait sebagaimana dimaksud pada ayat (1) dipidana dengan pidana penjara paling lama 5 (lima) tahun dan/atau denda paling banyak Rp. 500.000.000,00 (lima ratus juta rupiah).

ISSN 2986-1268
Volume 7, 2024

The 9th Indonesia International Geothermal Convention & Exhibition (IIGCE) 2023

September 20-22, 2023

COMMITTEE

ADVISOR
Director General of New, Renewable Energy and Energy Conservation (MEMR)

STEERING COMMITTEE
Director of Geothermal (MEMR)
Prijandaru Effendi (INAGA)
Abadi Poernomo (INAGA)
Sanusi Satar (INAGA)
Ahmad Yuniarto (INAGA)
Paul Mustakim (INAGA)
Tafif Azimudin (INAGA)
Heribertus Dwiyudha (INAGA)
Yudistian Yunis (INAGA)
Usman (INAGA)
Iwan Azof (INAGA)
Rangga W (INAGA)
Ismoyo Argo (INAGA)
Sisca Tan (ORMAT)

CHAIRMAN IIGCE 2023
Dion Murdiono (ORMAT)

SECRETARIAT
Andry Susanto (INAGA)
Aldi (INAGA)

FIELD TRIP
Erwin Patrisa Floris (Supreme Energy)
Sherlie (Supreme Energy)

TECHNICAL PAPER
Ali Ashat (ITB)
Arias Sugandhi (SEGSD)
Asrizal Masri (SEG
Aquardi Suminar (SEGSD)
Budi Kristianto (Geo Dipa)
Christovik Simatupang (Baker Hughes)
Doddy Astra (INAGA)
Fernando Pasaribu (PGE)
Ginanjar (Star Energy)
Hari Widianto (Mannvit)
Hill Gendoet (ITNY)
Ilham Kurniawan (Star Energy)
Jooned Hendrarsakti (ITB)
Khasani (UGM)
Marino C. Baroek (INAGA)
Mulyadi (SEGSD)
Mulyanto (PGE)
Muhammad Irfan (ORMAT)
Peter (SEGSD)
Riki Irfan (ITS)
Riostantieka Mayandari (ITB)
Rizal Abiyudo (Medco Energi)
Suryantini (ITB)
T.A Fauzi Soelaiman (ITB)
Tommy Souvanir (ORMAT)
Tony Abimanyu (ORMAT)
Yudi Indra Kusumah (SEGS)
Yayan Sofyan (WJEC)
Yunus Daud (UI)
Yunia Syafittri (SEGSD)
Wambra Aswo (PT NewQuest Geotechnology)

ISSN 2986-1268
Volume 7, 2024

This page is intentionally left blank

ISSN 2986-1268
Volume 7, 2024

SPEAKERS

H. E. K. H. Ma'aruf Amin, Vice President of the Republic of Indonesia

H. E. Mr. Stefan Haukur J, Ambassador Iceland to Indonesia

Arifin Tasrif, Minister of Energy and Mineral Resources of the Republic of Indonesia (*Represented by **Yudo Dwinanda Priaadi**, Director General of New, Renewable Energy, and Energy Conservation*)

Yudo Dwinanda Priaadi, Director General of New, Renewable Energy, and Energy Conservation

Dr. Ir. Herman Darnel Ibrahim, M.Sc. IPU., Member National Energy Council Republic of Indonesia

Sri Mulyani Indrawati, Minister of Finance of the Republic of Indonesia (*Represented by **Febrio Nathan Kacaribu**, Head of Fiscal Policy Agency, Ministry of Finance Republic of Indonesia*)

Siti Nurbaya Bakar, Minister of Environment and Foresty of the Republic of Indonesia (*Represented by **Prof. Dr. Haruni Krisnawati**, Ministerial Expert Staff for Energy at the Ministry of Environment and Forestry*)

Alin Halimatussadiah, Head of Environmental Economic Research Group, LPEM FEB UI

Edo Mahendra, Head of Just Energy Transition Partnership (JETP) Secretariat (*Represented by **Paul Butarbutar**, Head of Deputy Secretariat of JETP Secretariat*)

Ann Robertson-Tait, President of GeothermEx, Inc (a Schlumberger company)

Wiluyo Kusdwiharto, Director of Project Management and New Renewable Energy of PT PLN (Persero) (*Represented by **Christyono**, EVP Geothermal PT PLN (Persero)*)

Julfi Hadi, President Director of PT Pertamina Geothermal Energy Tbk

Hendra Soetjipto Tan, Director-Chairman of Star Energy Geothermal

Ran Reshef, Vice President International Sales of Ormat Technologies, Inc

Ahmad Yani, Director Operation of PT Pertamina Geothermal Energy Tbk

Riza Pasikki, Chief Operating Officer of Sarulla Operations Ltd

Novianto, General Manager of PT Medco Cahaya Geothermal PLTP Blawan Ijen

Marit Brommer, Executive Director of International Geothermal Association (IGA)

Nisriyanto, President & CEO of Supreme Energy

Yudistian Yunis, President Director of PT Geo Dipa Energi (Persero)

Tri Harso Widirahmanto, Regent of Banjarnegara

Dr. Yan Tang, President Director KS Orka Renewables Pte Ltd

Tomy Suryatama, Marketing Director of Nalco Water, an Ecolab Company

Ajit Menon, Vice President Geothermal Global of Baker Hughes

ISSN 2986-1268
Volume 7, 2024

This page is intentionally left blank

ISSN 2986-1268
Volume 7, 2024

FOREWORD PRESIDENT OF INAGA

To advance knowledge and capacity of its geothermal community, Indonesian Geothermal Association (INAGA) conducted the 23th Annual Scientific Meeting in conjunction with the Annual Indonesia International Geothermal Convention & Exhibition (IIGCE) 2023.

The 9th IIGCE 2023 was held successfully on September 20 - 22, 2023 at Assembly Hall the Jakarta Convention Center and attended by more than 1000 people around the globe. The 9th IIGCE 2023 is a continuous success of the annual events that have been held since 2013.

This year, the Committee of PIT as part of The 9th IIGCE event, has received 121 abstracts and 87 papers with various topics focusing on Earth Science, Engineering, General, Resources Management and Special Topics. Papers were presented in the Technical Papers Session during the 2 (two) days convention.

By this opportunity, I would like to express my gratitude and appreciation to the Technical Paper Committee, the Chairperson of Technical Paper Presentation, Authors, Presenters and all parties who have made the 2023 Technical Papers Session successful.

I believe that the content and the quality of all papers, with various interesting topics, were great and excellent. Therefore, on behalf of INAGA, I have the pleasure to share these papers for our geothermal community.

Yours Truly,

Prijandaru Effendi
President of INAGA
Period 2017-2023

ISSN 2986-1268
Volume 7, 2024

This page is intentionally left blank

ISSN 2986-1268
Volume 7, 2024

Proceeding Book

The 9th Indonesia International Geothermal Convention & Exhibition (IIGCE) 2023

September 20-23, 2023

Published by

Asosiasi Panasbumi Indonesia
Apartemen Menteng Square, BR-9 Tower B
Jl. Matraman No. 30E, Jakarta Pusat – 10320, Indonesia

Topics

Earth Sciences (19 articles)
Engineering (35 articles)
Resource and Management (7 articles)
Social, Politics, Economics, and Community (8 articles)
General (18 articles)
TOTAL = 87 articles, 925 pages

CONTENTS

Committee ..... **i**
Speakers ..... **iii**
Foreword President of INAGA ..... **v**

Paper Categories	Page
Part 1: Earth Sciences	1
Part 2: Engineering	205
Part 3: Resource Management	547
Part 4: Social, Politics, Economics, and Community	605
Part 5: General	719

ISSN 2986-1268
Volume 7, 2024

EARTH SCIENCES

Identification of Permeable Zones Using Magnetotelluric Data and Gravity Data on the "ALPHA" Geothermal Area **3**
Denny Simbolon, Yunus Daud, and Tony Rahadinta

Assessment of Hot Sedimentary Aquifer (HSA) Resources Potential in Central Sumatra Basin, Indonesia **13**
Rismawan Nurhuda, Muhammad Kurniawan Agung Aristo, Miftahul Jannah Nurul Azizah, and Suryantini

Preliminary assessment of the Pentadio geothermal prospect, Gorontalo, Indonesia **30**
M. Ghassan Jazmi Shalihin, Ferdino R. Fadhillah, and Astri Indra Mustika

Fluid Chemistry Evolution after one year production at Sokoria Geothermal Field **35**
Radhitya E Pradipta and Ryan Hidayat

Identification of Geothermal Potential in the Sangkar Oil and Gas Working Area Using Landsat-9 with a Gravity and Geomagnetic Approach **41**
Dwandari Ralanarko, Fadhlur Rahman, Nanda Ridki Permana, Dhika Faiz Fadrian, Fardhan Rafshan Zani, Dennya Angeline, Muhammad Sulhan, and Hafid Rizki Nur Rohman

Identification of Geothermal System Based on 3D Inversion Gravity, Land Surface Temperature, and Landsat 9 at Cubadak - Panti, Pasaman, West Sumatera **54**
Muhammad Wildi Nurul 'ilmi, Fadhlur Rahman, Fardhan Rafshan Zani, Ferdian Budi ar-rouf, Dhika Faiz Fadrian, and Baiq Yola Wahyu Febryanty

Identification of low to moderate fault-controlled geothermal system using satellite gravity method – A comparative study **69**
Fadhila Friany Putri, Yunus Daud, Surya Aji Pratama, Wambra Aswo Nuqramadha, and Fikri Fahmi

Identification of New Geothermal Manifestation Using Remote Sensing Method at Solok, West Sumatera **76**
Ghaly Yana Putra, Maulana Mafazan Budiyanto, Safira Auriska Qurotta Aini, Kamila Azzahra Meinareza, Dani Mardiati, and Sutarto

Waesano Geothermal Prospect Assessment **85**
Luthfi Rahmawati, Airlangga Sani Cahya Margaliu, and Ambrosius Hernawan Wibisono

LUSI FANDANGO - From A Natural Disaster to A Natural Geothermal Opportunity **98**
Adriano Mazzini, Matteo Lupi, Anindita Samsu, and Soffian Hadi

Magnetotelluric Signature over the Low to Moderate Temperature Geothermal System **101**
Wambra Aswo Nuqramadha, Fikri Fahmi, Donny Isa MSP, Surya Aji Pratama, and Yunus Daud

Potential of Hot Sedimentary Aquifer Calculation with Heat in Place Equation and Determination of Prospect Area Using Ordinary Kriging Method in South Sumatra Basin, Indonesia **107**
Chotimah. N, Kenny. L, Solomon. M, Fauzan. M, and Suryantini

ISSN 2986-1268
Volume 7, 2024

Review of Lithium Extraction Suitable for Indonesia Geothermal Brine **116**
Esty Mustika Suud, Suryantini, and Herbert Lubis

Surface Thermal Manifestation Characteristics and Hydrology Conceptual Model of Hu'u Daha Geothermal Prospect Area, East Sumbawa **131**
Joshua Satriana Benyamin, Juni Sianipar, Marina Sari, Muhammad Asri, Rachmat Pratiwinda, and Petto Mawajaya

Understanding Technical Document Requirements in Geothermal Exploration Funding in Indonesia **141**
Dorman Purba, Andreas Suseno, Desak Nyoman Inten Apriani, Agung Hardinugroho, Eviyanti, Afandi, Aryani Amir, and Ery Surandaru

Looking back into Galunggung Geothermal Field through geoscience study **163**
Triwening Larasati, Jessica Ivana, Alya Dhiya Oktaviani, Ferdino R Fadhillah, Dyah Nindita Sahdarani, and Tri Rani Pujiastuti

Geothermal Manifestation Identification using Multispectral UAV **173**
Firmansyah Maulana Azhali, Mauliate Agustinus Sihotang, Indra Agoes Nugroho, Herwin Azis, and Agung Budi Cahyono

Evaluation of Cisolok-Cisukarame Geothermal System using Gravity Inversion **184**
Fanzly Togap Zisochi Lase, Dandi Baskoro Soebakir, Tony Rahadinata, and Ahmad Zarkasyi

The Study of Supercritical Geothermal Potential in Indonesia from Geoscience Perspective **192**
Astri Indra Mustika, Triwening Larasati, Aulia Rizky Pratama, M. Ghassan Jazmi, Ferdino R.F, and Serina A.P

ENGINEERING

Geothermal Power Plants and Energy Transition Mechanism, Unleashed a challenge Under Just Energy Transition Partnership (JETP) **207**
Sugeng Triyono, F. Xaverius Guwowijoyo, and Tarwaji Warsokusumo

Using High-Pulsed Power for Successful Scale Removal in Geothermal **225**
Chris Graham, Charles Fensky, and Mike Perri

Brine Drum Design Comparison **230**
Wijaya Jatmiko Putro and Budi Permana Hadi

Steam Trap Maintenance Using Ultrasound for Energy Efficiency and Reduce Emission **238**
Raka Anugrah Pratama, Andisyah Purdanto, and Yana Handriana

Success Story of Implementation and Stabilization during Performance Test of Lumut Balai Geothermal Power Plant's Governor Free in Compliance with Indonesia's Grid Code Regulation 2020 **250**
Surya H. Silitonga, Erwandi Yanto, Azhari S. Adiputro, Dzuriat Khasani, Priatna Budiman, and Hadi Suranto

ISSN 2986-1268
Volume 7, 2024

The GreenLoop Closed-Loop Geothermal (CLG) System: Optimizing Power Generation and Evaluating Its Impact on the Reservoir **261**
Joseph Scherer, Glenn Golla, Harish Chandrasekar, Alvaro Amaya, Hollis Chin, Steven Brown, Eric Sonnenthal, Jonny Rutqvist, and Curt Oldenburg

3rd Generation Silica Inhibitor Technology: Breakthrough Solution for Higher Energy Extraction **271**
Nugraha Y. Arifpin, Muhamad Andhika, Mona N. Siahaan, and Tomy Suryatama

An Approach to Using PDC Refurbished Bits Delivers Effective Bit Utilization in Geothermal Drilling Sorik Marapi **278**
Triadi H. Aribowo, Juliana Phan, Ari Budiman, Kiki Yustendi, Ashadi, and Kurnia D. Huway

Case Study: Field Evaluation of Anti Scalant in The Geothermal Fluid **286**
Arsyan Sasoni, Logan Muller, Megan Low, Michael Bluemle, Michael Todd, Muhammad Thasril, Fajar Mustofa, and Efrata Meliala

Challenges and Modelling Practices for Low and Medium Temperature Geothermal Resources **295**
Theo Renaud, Joris Popineau, Michael Gravatt, Rony Nugraha, Jeremy Riffault, John O'Sullivan, Ryan Tonkin, Ken Dekkers, and Michael O'Sullivan

Closed Loop Geothermal Power Generation: Case Study of High Temperature Low Permeability Well **305**
Azaria Haykal Ahmad, Daniel Adityatama, M. Rizqi Al Asy'ari, Firman Bagja Juangsa, and Prihadi Setyo Darmanto

Collapse Challenges in High-Temperature Geothermal Wells **315**
François Penven, Khaled Hamdani, Beatriz Yabarra, and Jean-Guillaume Besse

Comprehensive Analysis and Mitigation Strategies for Slim Hole Drilling Challenges in Geothermal Exploration: A Case Study in Cisolok, Indonesia **321**
Geofri W. O. Sairdola, Huda Nahrudi Ilham, Redha Bhawika Putra, Sentanu W. Reksalegora, Rizki Davidtri, Lano Aditya, Dikdik Risdianto, and Dudi Hermawan

Development of A Coupled Wellbore-Reservoir Simulator **332**
Ryan Tonkin, Michael Gravatt, Theo Renaud, Rony Nugraha, John O'Sullivan, and Michael O'Sullivan

Drilling Rig Selection for Geothermal Exploration: Evaluating Factors and Decision-making Criteria **341**
Dorman P. Purba, Daniel W. Adityatama, M. Rizqi Al Asyari, Brian Christiantoro, Vincentius A. Brilian, and Nadya Erichatama

The Effort to Achieve The Best Performance Geothermal Drilling **359**
Redha Bhawika Putra, Idam Rafif Maulana, Irfan Rasyid, Sentanu W. Reksalegora, Huda Nahrudi Ilham, and Charlotte T Mandagi

Reducing Stuck Pipe Risk in Geothermal Drilling Operations Through Anomaly Prediction with Artificial Neural Network Algorithm **367**
Fandika Galih Pradana, Redha Bhawika Putra, Darnisa Azzahra Nasution, Charlotte T. Mandagi, Ridha Nugraha, and Edyson Purba

ISSN 2986-1268
Volume 7, 2024

Exploring Geothermal Energy Development Strategies: Insights from Indonesian Practice, Regulation, and Case Studies **377**
Daniel Adityatama, M. Rizqi Al Asy'ari, Ferdino R. Fadhillah, Dorman Purba, and Nadya Erichatama

Geothermal Captive Use to Support Industrial Activities: Applicable Industry Sectors, Worldwide Experience, and Its Potential and Challenges in Indonesia **391**
Vincentius A. Brilian, Daniel W. Adityatama, Agung W. Mukti, M. Rizqi Al Asy'ari, Dorman Purba, Ferdino R. Fadhillah, and Nadya Erichatama

Enhancing Geothermal Well Workover Planning Through Data-Driven Performance Evaluation **400**
Nadya Erichatama, Daniel Adityatama, M. Rizqi Al Asy'ari, Agung W. Mukti, and Dorman Purba

High Consumption of pH Adjuster in Geothermal Powerplant **409**
A.H. Fauzi, A.T. Putra, A.K. Prabowo, B. Ilmi, and D. Cahyadi

Inconel 625 Laser Metal Deposition on Geothermal Steam Turbine Rotor **414**
Andrianto Hapsoro, Rasyid Aziz, and Hepy Hanipa

Inhibiting Co-deposition of Smectite and Calcite to Prevent Production Well Output Decline **422**
Fritz Earwin Monterozo, Dinesh Mantri, and Tuğçe Şencan

Mechanical, Operation and Chemistry Approach in Monitoring and Controlling Deposition Control Program in Binary Power Plant **427**
Muhamad Andhika, Nugraha Y. Arifpin, Tomy Suryatama, and Mona N. Siahaan

Metal Sulfides and Silicates Inhibition and Impact on Amorphous Silica Scaling **434**
Fritz Earwin Monterozo and Aarthi Narayanan

ORC Online Cleaning to Improve Electricity Generation at Binary Geothermal System **452**
Nur Choiri Amin, Arsyan Sasoni, Logan Muller, and Ebta Pasaribu

Safe and Effective Online Cleaning Program, an Insurance for Reinjection Operation **459**
Mona Natalia Siahaan, Rachmad Darmawan, Harita Cahyo Baskoro, Yohanes Arifpin Nugraha, Muhamad Andhika, and Tomy Suryatama

Silica Kinetics Test to Prevent Scaling in Hululais Geothermal Field **465**
Ferdinan Rianto Sipayung, Edy Sudarmadi, and Jodhi Pramuji Giriarso

Slim Hole Drilling Performance Evaluation for Geothermal Exploration in Nage Field, Eastern Indonesia **474**
Charlotte T. Mandagi, Darnisa Azzahra Nasution, Huda Nahrudi Ilham, Redha Bhawika Putra, Rizki Davidtri, Arif Munandar, and Robertus S. L. Simarmata

Penta Helix Approach for Geothermal Technology Research and Development in Indonesia: The Adoption from the United States **482**
Vincentius A. Brilian, Dorman P. Purba, Daniel W. Adityatama, and Ferdino R. Fadhillah

Optimization Strategies for Well Design and Drilling Operations in Low-Medium Temperature Geothermal Systems in Indonesia **500**
Brian Christiantoro, M. Rizqi Al Asyari, Daniel W. Adityatama, Dorman P. Purba, and Nadya Erichatama

ISSN 2986-1268
Volume 7, 2024

Operation and Maintenance of Dual Flash Binary Combined Cycle Geothermal Power Plant **513**
Adethia Lufti, Richard Alexander, Dedy Setiawan, and Terry Satria Indra

Successful Sidetrack for Fishbone Well in Geothermal Case Study Sorik Merapi Field, Indonesia **519**
Sarwono, Paulina Saraswati, Bambang Sigit, Yessica Fransisca, David Munoz, Ashadi, and Kiki Yustendi

The Impact of Tie Back Engineering on Geothermal Power Plant Production, Case Study: Change in Steam Production Phase WP-L Patuha Geothermal **527**
Mochammad Fa'iq Khasmadin, R. Bayu Wibowo, and Huda Nugraha

Prevention of the Silica Compounds at the Geothermal Power Plants with HYDRODIS® GE Products **539**
Mustafa EROGLU, Ayhan ERTEN, Irfan AVCI, and A.Talha BILGIN

RESOURCE AND MANAGEMENT

Geothermal Institute's Modelling Framework Application For Geothermal Resource Assessment of An Exploration Field **549**
Rony P. Nugraha, Michael Gravatt, Theo Renaud, Ken Dekkers, Ryan Tonkin, John O'Sullivan, and Michael J. O'Sullivan

Brine Pressure Management for Preventing Flashing in Sarulla GPP **559**
Saeful Romadhon

Steam Cap Development Monitoring of HCE-28A Well in the Dieng Geothermal Field Based on Fluid Geochemistry Data **566**
Aditya Yudha Kencana, Elfina, RA Julia Satriani Alibazah, Reza Jamil Fajri, Ichwan Agusta Elfajrie, Marchel Christian Supijo, and Zahratul Kamila

Analysis of Geothermal Field Development Scenario: A Case Study in the Ulumbu East Nusa Tenggara Geothermal Field as Efforts to Maintain National Energy Resilience **576**
Angela Benedicta Horta, Allen Haryanto Lukmana, Damar Nandiwardhana, Fefria Tanbar, and Soniawan R Temot

Existing Well Monitoring During Patuha-2 Drilling as a Preventive Action to Maintain Patuha Unit 1 PLTP Generation **584**
Wien Pratama Abi Wicaksono and Saltsa Prehtina Muryani

How Accurate Modeling of Superheated Steam Improves Field Management Strategy **590**
Minh T. Tran, Minh Pham, Ed Voge, and Dylan Esquivel

Successful Downhole pH Modification Facility Recovery: Case Study of Sokoria Geothermal Well **600**
Fabiola Pardede, Wishnu Triananda, Ryan Hidayat, and Junior Setiawan

ISSN 2986-1268
Volume 7, 2024

SOCIAL, POLITICS, ECONOMICS, AND COMMUNITY

Integrated Geothermal Operational Dashboard using Business Intelligence Platform as a Digital Transformation **607**
Fajar Khamim Mustofa, M. Vito Hamza, Hanifah Nur Azizah, Fransisco Simamora, R. Fuad Satrio Ajie, Muhammad Thasril, and Efrata P. Meliala

A Remote-Diagnostics and Predictive Maintenance Solution for Geothermal Power Plants **619**
Renato Papale, Roberto Parri, Luca Giancarlo Xodo, Doriano Pesenti, Giorgio Tori, Roberto Brogi, and Luca Giannecchini

Application of Drone Technology in Topography Mapping – Case Study at Star Energy Wayang Windu **632**
Adityaputera W., Fajar H., Toto J., and Mochamad R.

Critical Stress Analysis Based on 3D MEM in Geothermal Field Study Case: Utah FORGE, USA **640**
Mulyani S., Wisnubroto B., Aulia A.B., Widiatmoko W., Pradana A., Trikukuh J.S., and Puspa M.A.

Investigating the Performance of Ground Heat Exchangers with Nanoparticle-based Fluids using CFD **654**
Muhammad Indjra Dije, Syaharussajali, and Fikrul Jihad

Understanding Safeguard Requirements in Geothermal Exploration Projects: Insights from Lenders **665**
Eviyanti[1], Afandi, Desak Nyoman Inten Apriani, and Dorman Purba

Unlocking the Potential: A Preliminary Study on Geothermal Direct Use Business Models and Potential Applications in Indonesia **684**
M. Rizqi Al Asy'ari, Daniel W. Adityatama, Dorman Purba, Adika Bagaskara, and Nadya Erichatama

Social Safeguard Measures in Geothermal Exploration: Fulfilling Requirements for the Geothermal Resource Risk Mitigation Program **703**
Afandi, Chandra Hasudungan, Desak Inten, Eviyanti, and Dorman Purba

GENERAL

Acceleration of Geothermal Investment and Revenue **721**
Aditya Negara, Sepriandi Maulana, Richard Alexander, and Muhammad Andhika

Introducing the Business Model Approach to Manage and Handle Complexity during EPC Lumut Balai Project Unit 2 Development **733**
Erwandi Yanto, Rury Zonta Kusumah, Firman Johannes Simanullang, Hadi Suranto, Gatot Yudoko, and Meditya Wasesa

Assessing the Impact of Carbon Trading to Indonesia Geothermal Project Economic **744**
Serina Andiani Pongtuluran, Triwening Larasati, Ferdino R. Fadhillah, Johanes Timoty Jeremi Terok, Daniel Adityatama, Astri Indra Mustika, and Muhammad Ghassan Jazmi Shalihin

ISSN 2986-1268
Volume 7, 2024

Biodiversity Awareness at Geothermal Power Plant: Preliminary Study on Fauna around Geothermal Area **750**
Ryski D. Busta, Erwin P. Floris, and Muhammad A. Tarunaprawira

Building Reputation to Obtain Social License to Operate in Patuha's Geothermal Area **757**
Ilen Kardani, Rita Purwita I, Genny M Yudawinata, and Maria Rahmawati

Direct Large Scale Geothermal Field Development vs Smaller Staged Development: Considerations, Risk, and Impact to the Project Feasibility **766**
Daniel Adityatama, Ferdino R. Fadhillah, M. Rizqi Al Asy'ari, Agung W. Mukti, Dorman Purba, Nadya Erichatama, and V. Adven Brilian

Evaluating the Impact of Tariff Regulations on the Economic Performance of the "XYZ" Geothermal Project: An Analysis from Equity, Lender, and Government Perspectives **776**
Ferdino R. Fadhillah, Nadya Erichatama, William Jhanesta, Daniel W. Adityatama, and Dorman Purba

Inherent Risks of Simultaneous Operations (SIMOPs) and Associated Mitigations in Patuha Geothermal Operations **793**
Robertus Yulianto Kurniawan, Gilang Panatama Aziz, Galih Satria, Ilen Kardani, and Sandi Ahmad Nurrachman

Lesson Learned from Eco-friendly Oyster Mushroom Cultivation Pangalengan **801**
Ismail Hidayat, Firman Hidayat, Rahmat Hidayat, and Taufik Hidayat

Managing Social Risk and Impact Through Stakeholder Engagement and Social Empowerment Programs and its Impact Evaluation to the Society **809**
Erwin Patrisa Floris and Muhammad Roza

Addressing Geothermal Exploration Resource Risk in Indonesia: Introducing GREM as a Pioneer De-Risking Facility **817**
Desak Nyoman Inten Apriani, Rizka Chandra Amorini, Andreas Suseno[1], and Dorman Purba

Pentahelix Model in Forest Conservation Program on Patuha Geothermal Area **838**
Laurentia Mutiara Sani Widyawati, Muhammad Gantang Nugraha, Annisa Nadhilah, Agung Maulana, and Ilen Kardani

Roles of Geothermal Industries to Accelerate Talent Development and Build a Robust Well-Connected Ecosystem **846**
Rita Purwita I, Genny M Yudawinata, Hadhy M Fauzy, Robby Oka Y, and Ilen Kardani

Towards Sustainable Development: Evaluating the Environmental Impact of Renewable Energy Technologies Worldwide **853**
Adika Bagaskara, M. Rizqi Al Asyari, Daniel W. Adityatama, Dorman Purba[2], and Fatkhur Rahman

Exploring the Impact of Lender Procurement Guidelines on Geothermal Project Exploration Planning: Indonesia's GREM Perspective **862**
Aryani Amir, Agung Hardinugroho, Chandra Hasudungan Panjaitan, Dorman Purba, Desak Inten Nyoman Apriani, and Ery Surandaru

ISSN 2986-1268
Volume 7, 2024

Geothermal resource optimisation: Exergy's 500 MWe local production experience and know how in Turkey **876**
Erdogan Arpaci and Chee Aun Kok

Economic Assessment of Lithium Extraction from Geothermal Brine: Comparative Analysis Worldwide and Indonesia's Prospects **886**
Candra Sri Sutama, Ali Ashat, Desti Alkano, and Syarif Riyadi

Training for Geothermal Technician, Indonesia **899**
Kris Pudyastuti, Yudistian Yunis, Chris Stuart, and Tengku Alia

ISSN 2986-1268
Volume 7, 2024

This page is intentionally left blank

Part 1:
Earth Sciences

Identification of Permeable Zones Using Magnetotelluric Data and Gravity Data on the "ALPHA" Geothermal Area

Denny Simbolon[1], Yunus Daud[1], and Tony Rahadinta[2]

[1]Master Program in Geothermal Exploration, Graduate Program of Physical Science,
The University of Indonesia
[2]Center for Geological Resources, Geological Agency, Indonesia

Keywords: geothermal, magnetotelluric, gravity, magnetic

ABSTRACT

Surface manifestations in the form of hot springs with a temperature of 54-83ºC on granite rocks in the "Alpha" area indicate that there is a geothermal system. Hot water on the surface is tasteless, colorless, and the water pH is neutral. The distribution of geothermal subsurface temperature in "Alpha" area can be approximated by the resistivity value from magnetotelluric data, and the fault area can be identified by gravity data and the structure local geology. The Magnetotelluric (MT) method had measured about 35 points to form 6 paths in the southwest – northeast direction with a distance between points of about 500 – 1000 m which spread over the research area. In this MT method, several 3D cross-sections were made to see geothermal system of "Alpha" area and the correlation with density data.

1. INTRODUCTION

Alpha geothermal area is located in Masamba sub-district, North Luwu district, South Sulawesi. The Alpha geothermal field is classified as a type of non-volcanic system. In geothermal systems, there are four important parameters: cap rock, reservoir, heat source, and permeability associated with faults or fractures faults. The magnetotelluric method (MT) is one of the excellent geophysical methods for mapping conductive layers beneath the earth's surface. Particularly in the geothermal prospect area, the MT method is good in mapping geothermal systems because the method was usually sensitive to detect a conductive cap rock layer (Daud et al., 2021).

Non volcanic geothermal system usually has a hot rock, clay cap, and fracture structures. A reservoir is a permeable rock where hot fluids accumulate. A reservoir usually has low density relative to surrounding rocks. Alpha geothermal area is classified as type of non-volcanic system.

2. ALPHA GEOTHERMAL FIELD REVIEW

Based on Geology the Alpha Geothermal area is a continuation of the Palu and Central Sulawesi zones. The rocks exposed include: basic and ultra basic rocks (ophiolite); plutonic rocks (granitic/granite and granodiorite), gneiss and schists and Tertiary rocks of Palu zone (granodiorite, biotite-rich crystalline schists) and Barufu tuff of Plio-Plistocene age and Quaternary age alluvium (Bemmelen, 1949). In the alpha geothermal area, there are surface manifestations in the form of hot springs. The group of hot springs in Pincara Village at an altitude of 100 m above sea level with a temperature of 83°C, pH 7-8, clear color, fresh water taste with a weak sulfur smell and thin steam, no sinter and appear on andesite rocks.

Van Bemmelen divides this area into 5 formations, in order from oldest to youngest, among others: Latimojong Formation (Kls) of Cretaceous age, consisting of a mixture of slate, phyllite, wake, quartzite, limestone and siltstone with conglomerate and rijang inserts; Lamasi volcano (Tplv) of Paleocene age consists of basalt and andesite lava, volcanic breccia and tuff; Bonebone formation (Tmpb) of Middle Miocene age consists of sandstone, conglomerate, marl and tuffaceous clay: Kambuno Granite (Tpkg) of Upper Miocene age is a breakthrough rock of granite, granodiorite and schist, Aluvium (Qal) of Quaternary/Holocene age consists of silt, clay, sand, gravel and pebbles.

There are three main faults that control this area with the order from old to young is the north northeast-south southwest trending fault (N 20-30º E), Balease Faults. The second fault runs northeast-southwest (N 45-50ºE) and the youngest fault runs northwest-southeast (N 320- 340ºE), Balakala Fault, Masamba Fault and Kula Fault.

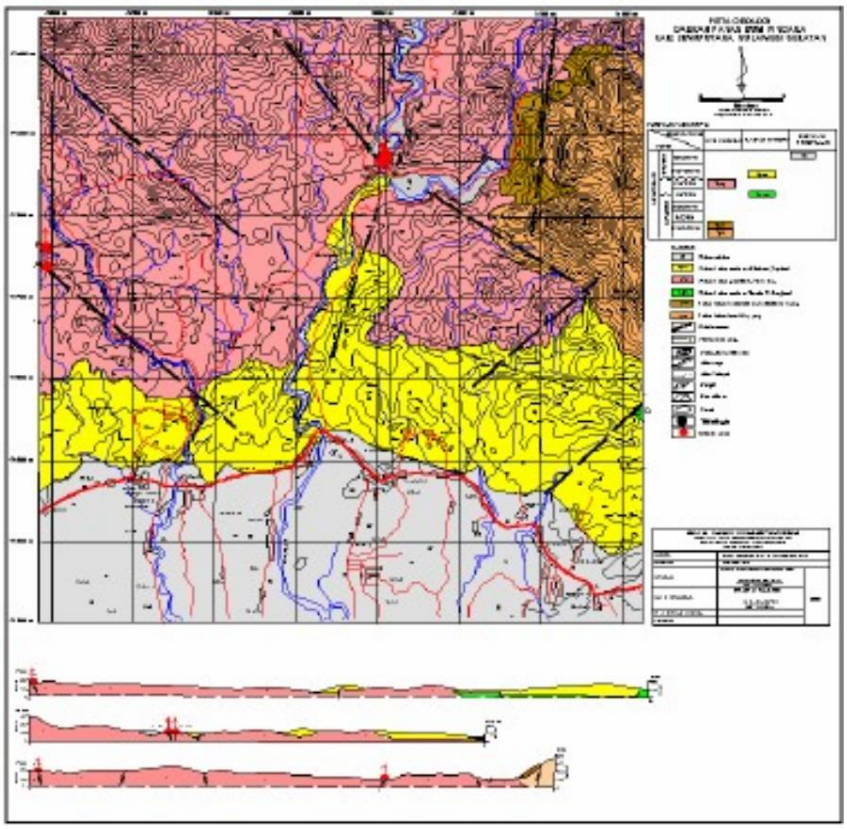


Figure 1: Geological Map of "Alpha" Geothermal Area, South Sulawesi, Indonesia (Sumardi et al., 2005).

3. GEOCHEMISTRY

Cl - SO4 - HCO3 triangle diagram can be used to determine the type of hot water. Anions in the form of CL, SO4 and HCO3 are solutes that are commonly found in geothermal fluids. One of the hot springs is suspected as bicarbonate water (Giggenbach, 1988).

Bicarbonate water is a type of geothermal fluid formed by the condensation of vapor and gas into oxygen-depleted surface water. This type of hot water consists of two types, the first type which has a low Chloride (Cl) and high Bicarbonate (HCO3) content. To determine the origin of geothermal fluids, Cl- Li-B diagram plotting is used. The content of Cl, Li and B can provide information about subsurface conditions due to their conservative nature. Plotting on this diagram can be used to determine the type of manifestation including upflow or outflow.

The Cl-SO4-HCO3 triangle diagram of Pincara 1 and Pincara 2 hot springs is a type of bicarbonate water with significant sulfate content with a temperature of 83.3ºC. Silica concentration of Pincara spring water is contaminated by dissolved and precipitated granite rocks. The Na-K-Mg diagram illustrates that Pincara Spring is located in immature water with close to partial equilibrium, indicating the possibility of rock interaction with hot fluids when the fluid reaches the surface before manifestation.

Hg values of more than 600 ppb are located south of the Pincara manifestation site and east of the Lero hot spring site. The lowest values of less than 200 ppb are located in the north. The area of the high Hg concentration anomaly is approximately 2.0 km2 which is thought to be geothermal related. Hg

concentration analysis is a common method to delineate permeable zones. High Hg anomaly values at the surface are indicative of a geothermal permeability zone (Kusnadi et al., 2005).

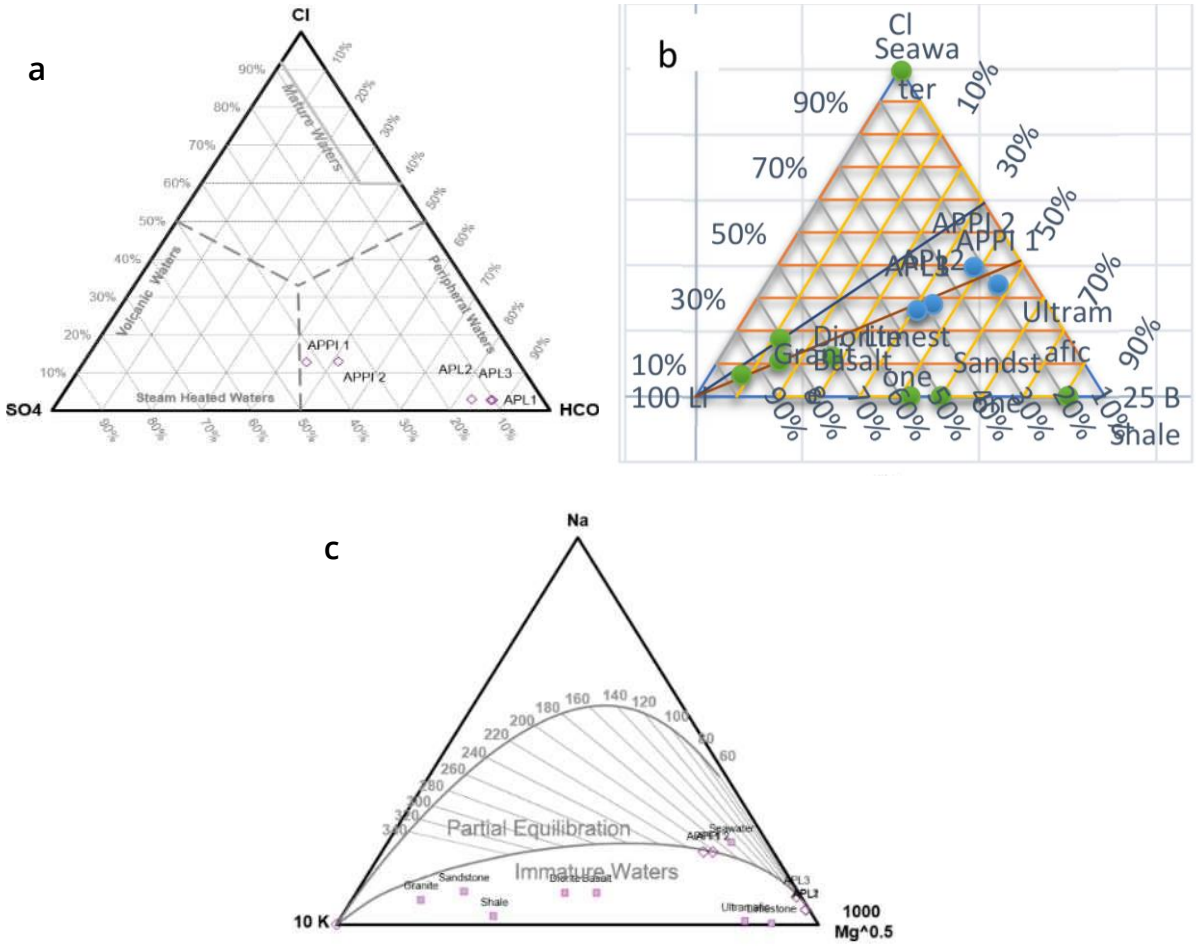


Figure 2: Geochemistry Diagram (a) Cl–SO4–HCO3 (b) Cl–Li–B (c) Na-K-Mg.

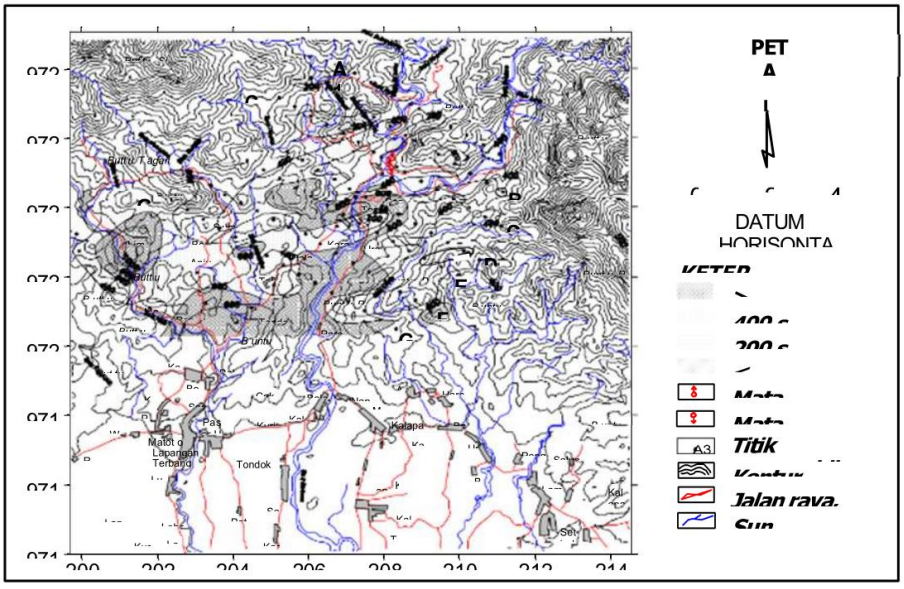


Figure 3: Hg Distribution Map of "Alpha" Geothermal Area (Kusnadi et al., 2005).

4. MAGNETOTELLURIK METHOD

The MT method is one of the geophysical methods that describes the electrical properties (density resistance distribution) of the subsurface utilizing variations in natural electromagnetic fields as the source. The frequency range of natural electromagnetic fields ranges from 10^{-4} - 10^{4} Hz (Vozoff, 1991).

Resistivity is the ratio of the value of the electric field and the magnetic field, which is referred to as the Cagniard equation. This equation is the result of Maxwell's equations assuming plane waves:

$$\rho_a = \frac{1}{5} f \; x \; \left|\frac{E}{H}\right|^2$$

where:

ρ : Apparent Resitivity (ohm.meter)
f : Frequency (Hz)
E : Electrical Field (mV/km)
H : Magnetic Field (nT)

The effective depth in the MT method depends on the rock's specific gravity and the frequency used. The effective penetration depth is obtained using the equation:

$$\delta = \frac{1}{\alpha} = \sqrt{\frac{2}{\mu_0 \delta \omega}}$$

where:

δ : Skin Depth (m)
ω : Angular Frequency
δ : Conductivity (S/m)

5. GRAVITY METHOD

The gravity method is one of the geophysical methods that can describe the shape or geology of the subsurface based on variations in the earth's gravitational field caused by differences in density or mass density between rocks. The gravity anomaly value can be obtained with the formula below:

$$CBA = g_{obs} - g_{\emptyset} + FA - BC + TC$$

where:

CBA : Complete Bouger Anomaly (mGal)
g_{obs} : Observe Gravity
$g_{\emptyset}$: Field Gravity
FA : Free Air Correction
BC : Bouguer Correction
TC : Terrain Correction

6. RESULT & DISCUSSIONS

6.1 Station Distribution Map

Magnetotelluric measurements were carried out at 35 points in the Pincara area, North Sulawesi and modelled on 3 lines. Line A - A' with a length of 3km is directed southwest to northeast passing MT 5, MT 11, MT 17, MT 23 and passing 1 fault. Line B - B' with a length of 7km is oriented north to south and passes through points MT 5, MT 10, MT 15, MT 20, MT 25, MT 30 and passes through 2 faults. Line C - C' with a length of 6 km is directed northwest to southeast and passes through points MT 24, MT 25, MT 20, MT 21, MT 17, MT 16, MT 11 and passes through 2 faults and 2 manifestations of hot springs.

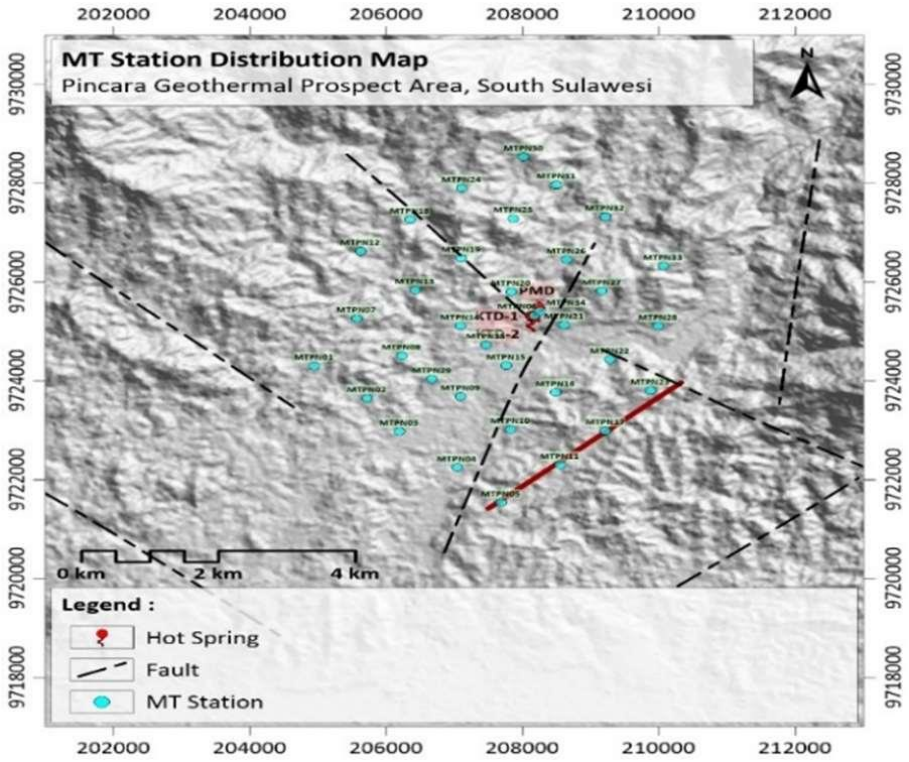


Figure 4: Magnetotelluric Distribution Map of "Alpha" Geothermal Area.

6.2 Line A-A' Modelling

The results of Magnetotelluric modelling show low to high resistivity values. These resistivity values correlate with permeability. Cumming mentions that low resistivity indicates the presence of many clay minerals resulting from alteration. Clay itself has a low permeability value and is impermeable so that it can trap water to rise upwards. Low resistivity values also indicate low temperatures because there is no gap for water to enter by impermeable clay alteration rocks. This also applied with the high resistivity which have a high permeability and thus is permeable and have a high temperature.

Line 1 has a length of 3 km which is directed southwest to northeast shows a low resistivity value of 6 - 38 ohm.meter with a depth of 200 - 800 m at each MT measurement point which is thought to be a clay cap or impermeable layer that is impermeable to water while in the middle of the modelling results show a high resistivity value of 40 – 398 ohm.meter with a depth of 800 - 3000 m where there are points MT 11 and MT 17 and is thought to be a place of permeable water accumulation or reservoir. The results of line 1 modelling can be seen in the Figure 5.

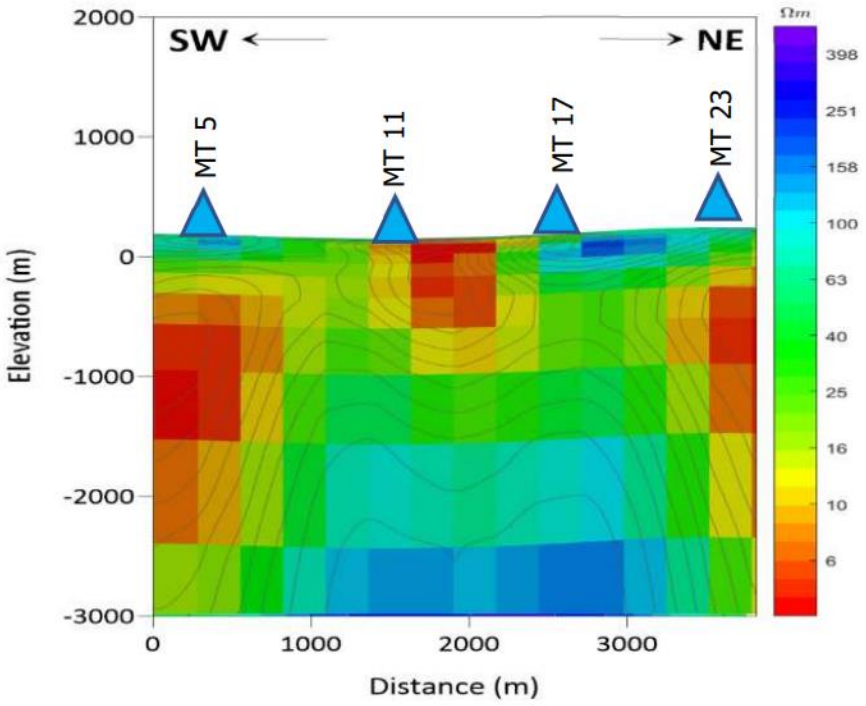


Figure 5: Magnetotelluric model of line A-A'.

The results of the magnetotelluric modelling of line A-A' were correlated with the 3-D gravity model which is in the same direction as the magnetotelluric model. The 3-D gravity modelling shows the presence of low density in the central and northeastern part of the model. Low density values ranging from 2.37 - 2.43 gr/cc indicate the presence of low density rocks as clay cap and are thought to correspond to the youngest geological formation, the Holocene-aged alluvium formation (Qal) consisting of silt, clay, sand and gravel. Meanwhile, high densities in the range of 2.46 - 2.95 are dominantly scattered in the southwest and northeast ends and are thought to be hard rocks as reservoirs and are thought to correspond to the upper Miocene-aged kambuno granite geological formation (Tpkg) consisting of granite intrusions, granodiorite and schist.

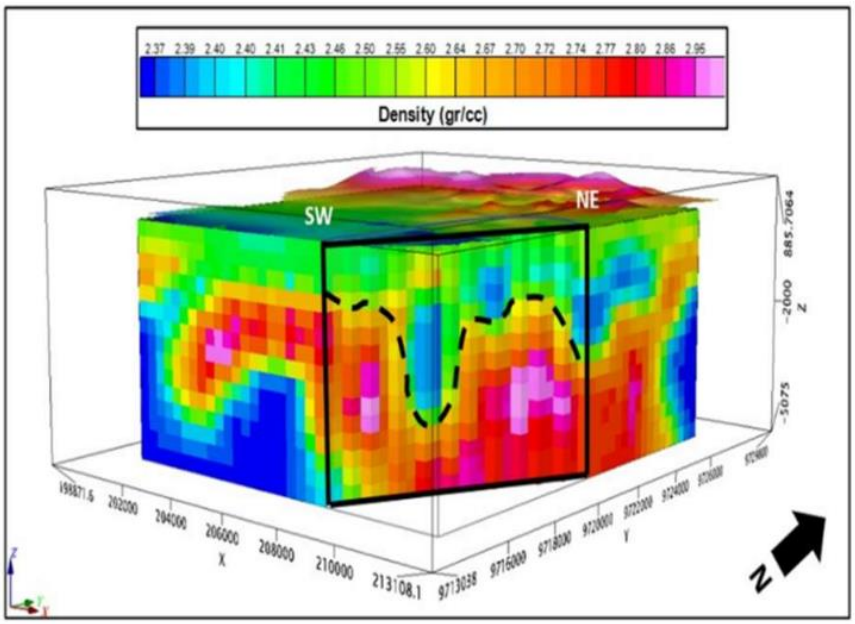


Figure 6: Gravity model of line A-A'.

6.3 Line B-B' Modelling

Line B - B' has a length of 7 km which is directed south to north showing a low resistivity of 6 – 38 ohm.meter with a depth of 100 - 1000 m in the southern and northern areas of the MT measurement point which is thought to be a clay cap or impermeable layer that is impermeable to water while in the southern and northern areas the modelling results show a high resistivity of 40 - 398 ohm.meter with a depth of 1000 - 3000 m where there are MT points 5, 10, 15, and 20 and is thought to be a place of permeable water accumulation or reservoir. The modelling results of line B - B' can be seen in the Figure 7.

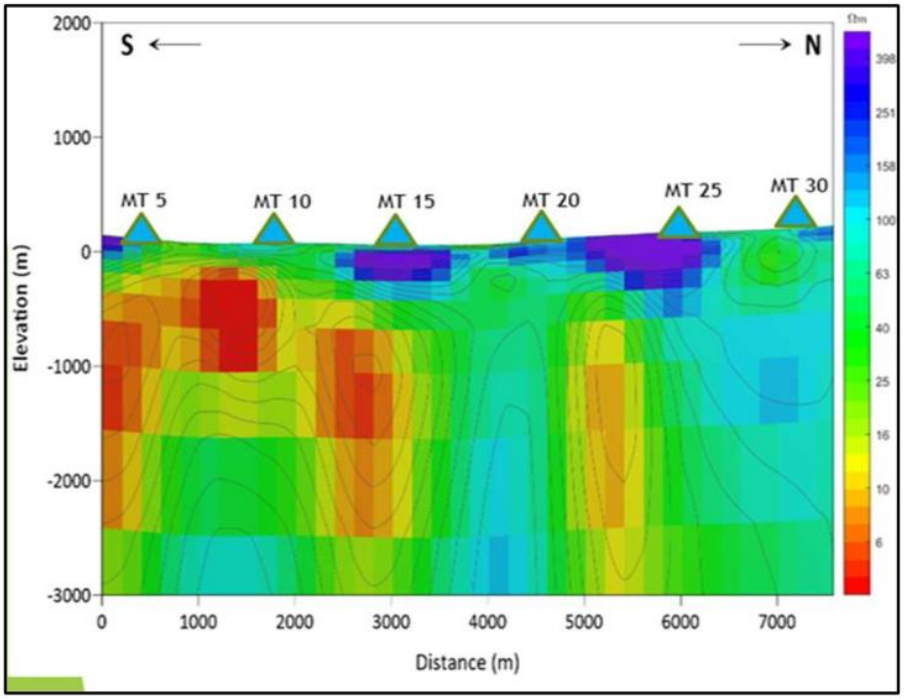


Figure 7: Magnetotelluric Model of Line B-B'.

6.4 Line C-C' Modelling

Line C - C' has a length of 6 km which is directed northwest to southeast showing a low resistivity of 6 - 38 ohm.meter with a depth of 100 - 1500 m in the central and southeastern areas just below the measurement points MT 21 and 16 and under the hot water "PMD" and "KTD" and is thought to be a clay cap or impermeable layer that is impermeable to water while at the southeast end of the modelling results show a high resistivity of 40 - 398 ohm.meter with a depth of 1000 - 4000 m where there is points MT 17, and 11 which are thought to be a place of accumulation of permeable water or reservoirs. upflow and outflow areas of geothermal areas can be seen in this C - C 'line modelling.

The upflow area is an area that has greater heat energy located in the southeast and gives rise to a dome shape. While the outflow area is an area that has less heat energy and appears as hot springs, namely hot water "PMD" and "KTD" and is located in the central region of the study. The results of line C - C' modelling can be seen in Figure 8.

The magnetotelluric modelling of line C-C' was then correlated with a 3-D gravity model in the same direction as the magnetotelluric model. The 3-D gravity modelling shows low density in the northwest and southeast parts of the modelling. Low density values ranging from 2.37 - 2.43 gr/cc indicate the presence of low density rocks as clay cap and are thought to correspond to the youngest geological formation, the Holocene-aged alluvium formation (Qal) consisting of silt, clay, sand and gravel. Meanwhile, high density with a range of 2.46 - 2.95 is dominantly spread in the middle and southeast end of the modelling which is suspected to be hard rock as a reservoir with the kambuno granite

geological formation (Tpkg) of upper Miocene age consisting of granite, granodiorite and schist intrusive rocks.

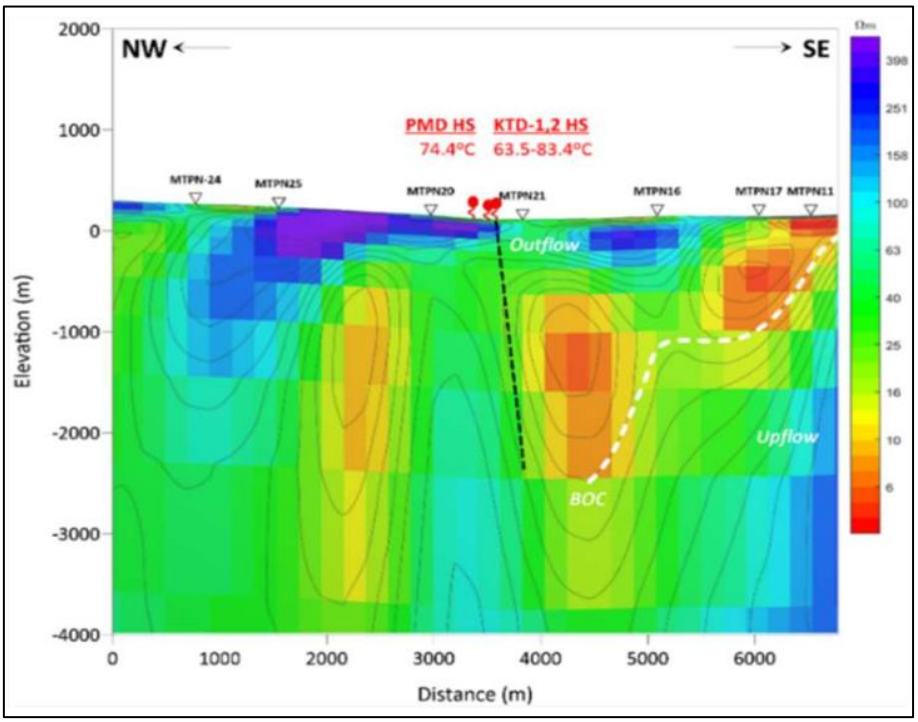


Figure 8: Magnetotelluric model of line C-C'.

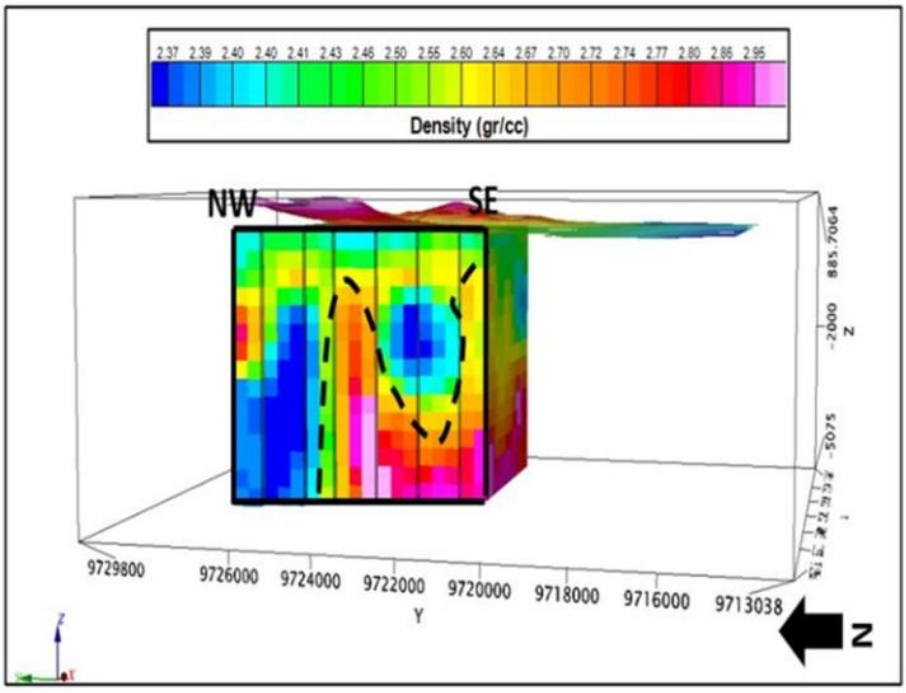


Figure 9: Gravity 3-D model of line C-C'.

6.5 Resistivity Distribution Map

The above modelling is reinforced by the distribution of resistivity values, especially on line C - C' which is northwest and southeast oriented. It can be seen that the possibility of an upflow zone or permeable reservoir is in the southeast area of the study area which has a large resistivity value and in the center of the study area there is a small resistivity and also hot springs "PMD" and "KTD" which are thought to be the outflow and clay cap of the reservoir or upflow zone in the southeast.

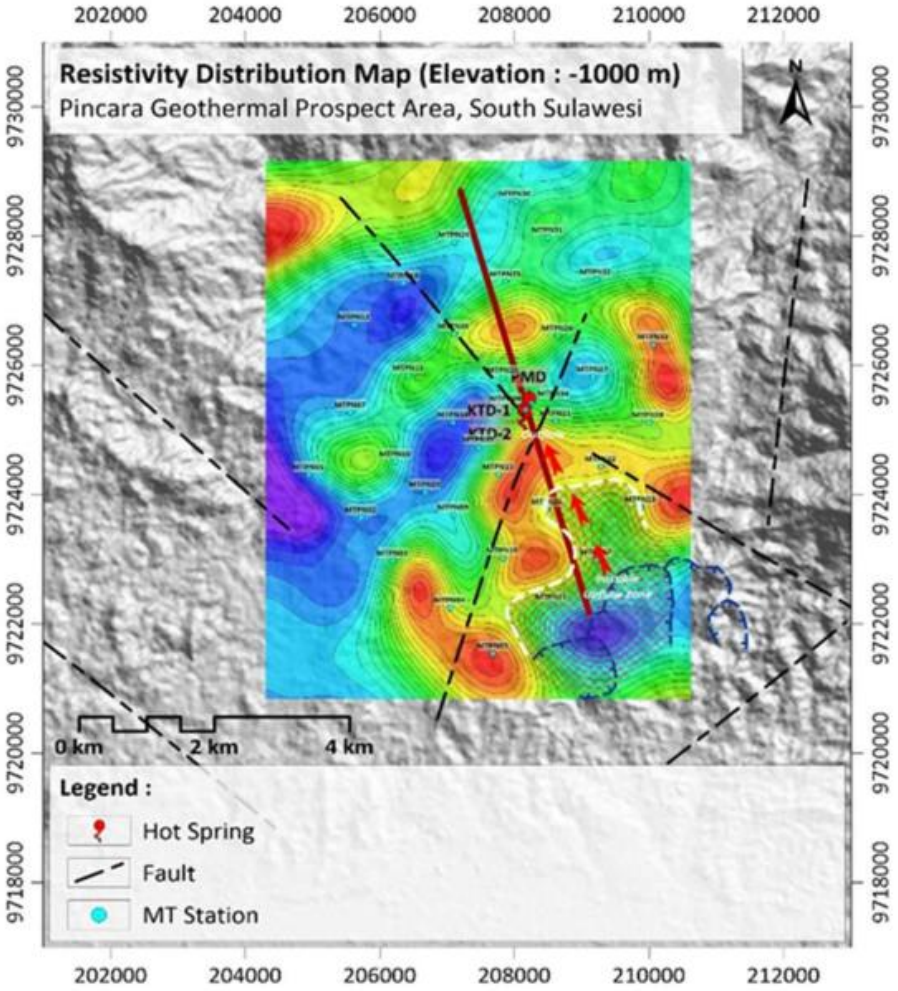


Figure 10: Resistivity Distribution Map of "Alpha" Geothermal Area.

7. CONCLUSIONS

Based on the results of data processing, analysis and modeling, the following conclusion points can be obtained:

1. In the three lines of 3-D Magnetotelluric. Modeling with a line length of 3 - 7 KM and a max depth of 4000 m, there is a layer of overburden/ clay cap located at an average depth of 100 - 1500 m and a resistivity value of 6 - 38 ohm.m and ends with a reservoir layer at an average depth of 800 - 4000 m and resistivity value of 40 - 398 ohm.m. This modeling is reinforced by 3-D Gravity Modeling which shows density values and estimated rock lithology.

2. Based on 3-D Gravity modelling with the same length and direction as magnetotelluric modelling and a max depth of 4000 m, there is a layer of cap rock / clay cap with an average density of 2.37 - 2.43 gr/cc and thought to be an alluvium formation (Qal) with lithology of silt, clay, sand and gravel and ends with a reservoir with an average density of 2.46 - 2.95 gr/cc and

thought to be the kambuno granite formation (Tpkg) with lithology of granite, granodiorite and schist intrusion rock lithologies.

3. The results of the resistivity distribution map show that the possible upflow zone is in the southeast direction because there is high resistivity and thought to be the center of the reservoir and leads to the northwest which shows low resistivity and hot springs "PMD" and "KTD" and thought to be the base of the conductor and the center of the clay cap.

REFERENCES

Bemmelen, R. W. V. The Geology of Indonesia 1A General Geology of Indonesia and Adjacent Archipelagoes. Solo Agents Martinus Nijhoff. (1949).

Daud Y., Nuqramadha, W. A., Fahmi, and Ismail. Optimising MT Imaging Technology for Reducing Geothermal Drilling Risks. Proceedings World Geothermal Congress 2021. (2021).

Dedi Kusnadi, Supeno, dan Sumarna. Penyelidikan Geokimia Panas Bumi Daerah Pincara, Masamba, Kabupaten Luwuk Utara, Sulawesi Selatan, Subdit Panas Bumi, Jakarta. (2005).

Giggenbach, W.F. Geothermal Solute Equilibria. Derivation of Na-K-Mg-Ca Indicators, Geochimica et Cosmochimica Acta, Vol. 52 No.12, pp. 27492765. (1998).

Sumardi, Eddy. dan Herry Sundhoro. Geologi Daerah Pincara, Masamba, Kabupaten Luwuk Utara, Sulawesi Selatan, Subdit Panas Bumi, Jakarta. (2005).

Vozoff, K. The Magnetotelluric Method. Electromagnetic Methods in Applied Geophysics-Applications Part A and Part B, 641-711. (1991).

Assessment of Hot Sedimentary Aquifer (HSA) Resources Potential in Central Sumatra Basin, Indonesia

Rismawan Nurhuda, Muhammad Kurniawan Agung Aristo,
Miftahul Jannah Nurul Azizah, and Suryantini

Jl. Ganesha No.10, Lb. Siliwangi, Coblong, Bandung, Jawa Barat, Indonesia 40132

rismawannurhuda@gmail.com

Keywords: Central Sumatra Basin, geostatistic, hot sedimentary aquifer, resources

ABSTRACT

A hot sedimentary aquifer (HSA) is part of permeable rock body that contains enough groundwater to be heated by conduction. These systems generally deal with large sedimentary basins that are thick and deep enough to generate heat for geothermal energy. This study aims to calculate the size of HSA resources based on several parameters such as aquifer thickness, heat flow, thermal conductivity, subsurface temperature, porosity, and rock density. The study was conducted in the Central Sumatra Basin, which has suitable geological conditions for HSA analysis. The stratigraphy of the study area consists of eight Formations with HSA potential in the Menggala Formation, which has a coarse-fine grain sandstone lithology. A total of 120 well data were used for resource calculation by creating model maps for each parameter. The calculation is based on a grid of 10' (18.5 km x 18.5 km), resulting in a total of 110 grids for HSA resource estimation. Subsurface temperature is determined based on drilled well depth data. Resource results will be modeled using geostatistics for each grid and interpolated to show the distribution of resources in the study area. The calculation parameters modeled include drilled well depth, heatflow, and thermal conductivity of rocks. Based on calculations, it is known that the average value of heat in place ranges from $3.68x10^{14}$ J/km2 per grid. With a lifetime of 30 years, it is known that the potential theoretical mean value is $1.23x10^{13}$ J/km^{2}yr. If the ultimate recovery factor value is 1%, the technical potential of the research area in the Central Sumatra Basin has the largest value of $2.02x10^{11}$ J/km^{2}yr and the smallest value of $4.245x10^{10}$ J/km^{2}yr per grid. The total energy from the technical potential is 146.5 MW in the research area. Geostatistical modeling using a variogram model with a lag distance of 18000 yielded a nugget value of 0.022, a sill value of 0.121, and a range value of 60000 for potential technical resource. The results of interpolation using ordinary kriging show that the largest potential value of HSA resources is in the center of the study area with a tendency towards the NW-SE. Henceforth, further HSA research and development can be carried out in the area.

1. INTRODUCTION

Indonesia is one of the countries that has significant geothermal energy potential. Indonesia holds 40% of the world's geothermal resources. The total potential of geothermal energy in Indonesia is estimated to reach 23.7 GW (Ministry of Energy and Mineral Resources, 2020). The Indonesian government plans for the renewable energy mix to reach 23% by 2025 and increase to 31% by 2050 (Coordinating Ministry for Economic Affairs of the Republic of Indonesia, 2023). Conversely, the energy mix from petroleum is projected to be reduced to 20% by 2050. However up until now, the utilization of geothermal energy potential has not been maximized.

At present, Indonesia is currently striving for progress in developing conventional geothermal systems, commonly associated with magmatism and volcanism. These systems have been implemented in specific areas, such as Kamojang, Darajat, Dieng, Ulubelu, among others. On the other hand, the progress in developing non-conventional geothermal systems in Indonesia is relatively limited or even absent. Despite Indonesia's favorable tectonic conditions that are conducive to the development of non-conventional geothermal systems, the exploration and utilization of such systems have not been fully explored in the country.

Furthermore, with the advancement of technology and geothermal systems, conventional drilling alone is not sufficient to extract non-conventional geothermal resources and handle the complexity of

geological conditions. This is because there is a possibility of encountering shallow heat flow that is not directly correlated with volcanic-magmatic activity. Additionally, non-conventional geothermal systems can be utilized as an additional potential for electricity generation, even with low or moderate temperatures. Therefore, there is a need for innovation in extraction methods, particularly for non-conventional geothermal systems. Non-conventional geothermal systems refer to geothermal systems that require non-conventional extraction methods to extract natural heat from beneath the surface to the top (Mustika et al., 2023). One promising non-conventional geothermal system in Indonesia is the Hot Sedimentary Aquifer (HSA) geothermal system.

A hot sedimentary aquifer (HSA) is a part of permeable rock body that contains enough groundwater to be heated by conduction. The term HSA refers to the existence of extensive aquifer systems containing large amounts of hot fluids and permeability in relatively deep conductive formations (Mijnlieff, 2020). The potential heat source of the system is controlled by conductive heat flow with gradient temperature and/or radiogenic activity. These systems generally deal with large sedimentary basins that are thick and deep enough to generate heat for geothermal energy. Unlike most volcanic-hydrothermal systems, HSA capping mechanisms are controlled by impermeable sedimentary rock formations (overburden) and fault traps (King R., 2010).

Indonesia has 128 potential basins, whether they have been produced for oil and gas or not (Ministry of Energy and Mineral Resources, 2022). Most sedimentary basins in Indonesia have been explored for petroleum prospecting at some stage. Although geothermal and petroleum exploration differ in the resources to be sought (high-temperature water and hydrocarbons), most of the data collected for petroleum exploration can be used for geothermal exploration (Deming, 1989 in Corbel & Griffiths, 2012). Therefore, an evaluation will be carried out on one of the potential non-conventional geothermal systems in Indonesia, namely the

This study aims to evaluate the potential non-conventional geothermal systems in the Central Sumatra Basin (CSB), which is considered to have suitable geological conditions for HSA analysis. The evaluation utilized open access data from 120 wells drilled in, provided by Royal Halloway – Southeast Asia Research Group. This study calculates the size of HSA resources using equation in Limberger (2018) based on several parameters such as aquifer thickness, heat flow, thermal conductivity, subsurface temperature, porosity, and rock density. Sensitivity analysis was done to determine the most influential parameters in the calculation of geothermal resource potential.

The calculation of the potential of geothermal resources in the research area carried out in this paper will be different from the calculation of the potential of previous geothermal resources, based on Sihotang and Alam (2019), the calculation uses the assumption that the research area has an Enhanced Geothermal System (EGS) system. Sihotang and Alam (2019) calculated geothermal resources in basements, this study calculated resources in sedimentary basins.

2. REGIONAL GEOLOGICAL SETTING

The Central Sumatra Basin (CSB) is one of the back-arc basins formed along the Sumatra Island due to subduction Indo-Australian plate and Eurasian plate. The Central Sumatra Basin was formed in the Early Tertiary (Eocene - Oligocene), with series of half-graben structures separated by horst blocks (Eubank and Makki, 1981 in Irhamsyah, 2018). Structures in CSB are influenced by transtensional to transpressional systems, followed by compressional folding and uplift (Mertosono and Nayoan, 1974 in Fardiansyah et al., 2021). The research area has a dominant structural orientation in the NW-SE direction and some in the N-S as shown in Figure 1 (Barber et al., 2005).

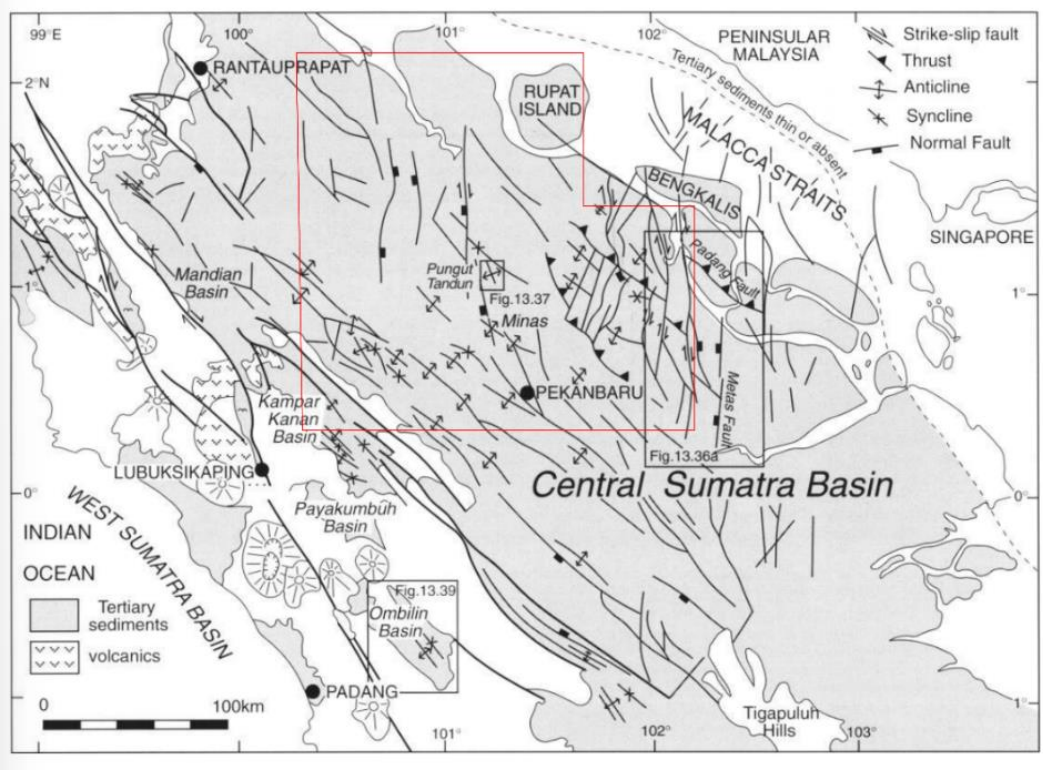


Figure 1: Regional structure map of Central Sumatra Basin (Barber et al., 2005). The structure of CSB is largely influenced by the Semangko main fault. Red line square is the study area of Hot Sedimentary Aquifer.

CSB has a high geothermal gradient due to crustal faults that penetrate into the upper mantle (Eubank and Makki, 1981 in Sihotang & Alam, 2019). The Central Sumatra Basin consists of a succession of Tertiary sediments deposited over complex pre-Tertiary lithology. The succession is bounded by the Barisan Mountains to the west and southwest, Malaysia to the east, and the Asahan Arch to the north (Choanji et al., 2017). In general, the tectonostratigraphy of the Central Sumatra Basin area is grouped into four phases (Figure 2):

1. Early Synrift (Late Eocene to Oligocene)
   This stage forms Pematang and Kelela Formation. The Formations are deposited in alluvial, shallow to deep lacustrin, and fluvio-delta environments. The Pematang and Kelela Formations have lithology in the form of shale, silt, and laminated sand with coal inserts and conglomerates (Doust & Noble, 2008). The lacustrine facies of the Pematang Formation are known as Brown Shale Formation (Sefein et al., 2017).

2. Late Synrift – Early Postrift (Late Oligocene to Early Miocene)
   The sequence is deposited by transgression, covering several facies, such as the Menggala, Bekasap, and Bangko Formations. The Menggala Formation is a fluvial deposit, overlapped by shallow sea sandy facies (Bekasap Formation) and argillaceous (Bangko Formation), until finally forming coastal deposits (Doust & Noble, 2008). The Menggala Formation is characterized by fine to coarse grained sandstones with conglomerates of gravel, tuff, coal, and shale dating from fluvial to deltaic. The Menggala, Bekasap, and Bangko sandstones of the Sihapas Group are known as the main reservoirs in CSB (Willis and Fitris, 2012 in Fardiansyah et al., 2021).

3. Early Postrift (Early to Middle Miocene)
   This sequence consists of the distal marine facies of the Sihapas Group. This phase is the end of

the transgression process (Duri Formation), until it is finally continued with the maximum Tertiary flooding period (Telisa Formation). The Duri Formation consists of delta front sand deposits and shale. The Telisa Formation consists of shale and silt (Doust & Noble, 2008).

4. Late postrift (middle Miocene to Quaternary)
   This phase represents the filling of sedimentary basins in the late Tertiary. In this phase, regression processes occur, and sediments of deltas and rivers are deposited incongruously (Doust & Noble, 2008). The Petani Formation, the earliest formation of this stage, consists of claystone, siltstone, thin sandstone, and limestone (Barber et al., 2005). The Plio-Pleistocene Minas Formation was the final phase of deposition (Barber et al., 2005).

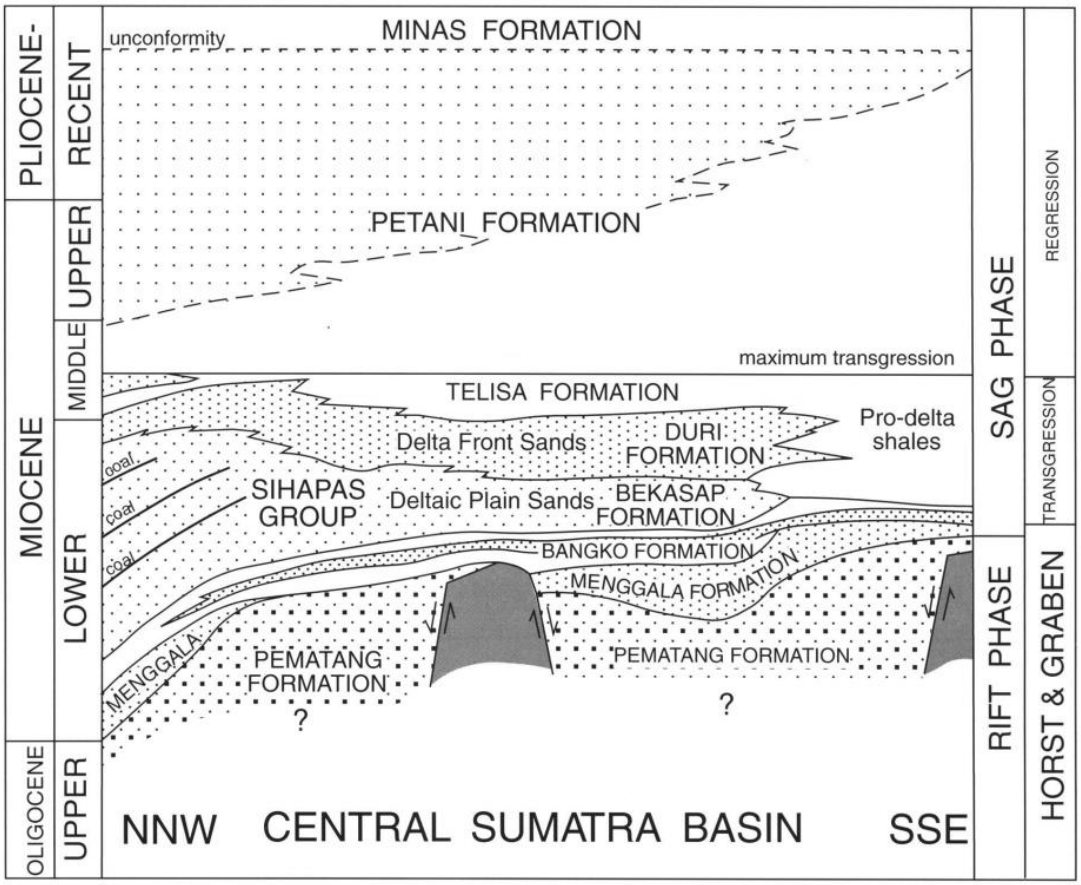


Figure 2: Regional stratigraphy formation of Central Sumatra Basin (modified from Wongsosantiko, 1976). The aquifer used in this study is the Menggala Formation.

3. DATA AND METHODOLOGY

3.1 Aquifer Size

This study limits the maximum depth of sediment to 3 km because in general, the permeability of sedimentary rocks decreases with depth due to decreased porosity (Limberger et al., 2018). The greatest reduction in porosity for siliciclastic sediments occurs within the first few kilometers (Figure 3), making deeper geothermal production quite difficult. This depth limit is also determined by economic factors because the cost of drilling on land will increase exponentially with depth (Lukawski, 2014).

The resource calculation was based on a grid of 10' (18.5 km x 18.5 km), which resulted in 110 grids (342,25 km^2) for HSA resource estimation. The thickness of the aquifer is 1800 feet (548.74 meters) based on Sukmono (2007). This thickness will be used for calculating the energy in the reservoir (heat in place). In this study, the aquifer used was the Menggala Formation, which has fine-grained quartz sandstone lithology (Fardiansyah et al., 2021; Sukmono, 2007). The porosity used is an assumption of a fixed conservative porosity value of 10% in the entire aquifer. This value is representative of sandstone sedimentary formations in the study area.

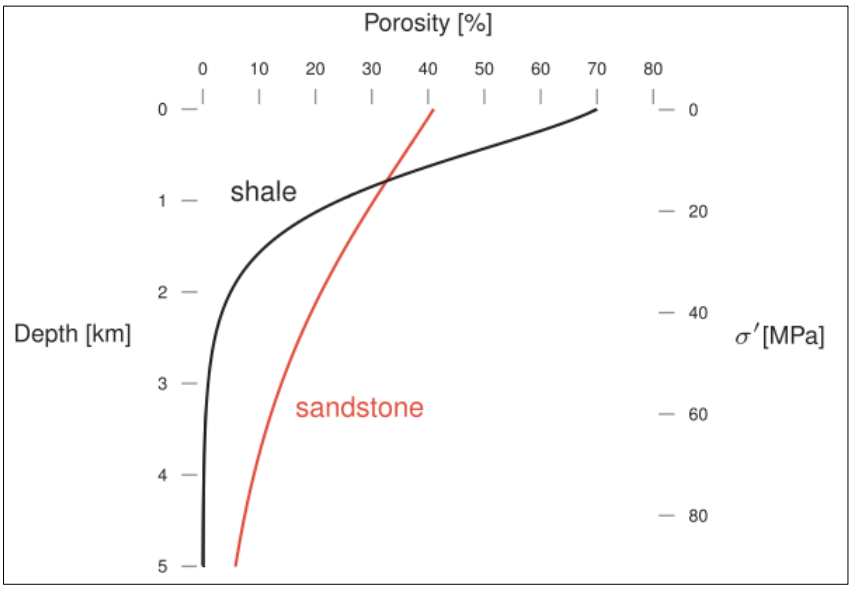


Figure 3: An example of compaction curves for shale (black line) and sandstone (red line) sediments (Hantschel et al., 2009). Porosity (x-axis) in the plot with respect to depth and effective pressure (y-axis).

3.2 Aquifer Temperature

All geothermal systems have specific applicative requirements for production temperatures and require different minimum heat rates to operate economically (Lund, 2010). The thermal properties of rocks, crustal thickness, and heat transfer control earth's heat flux and cause most of the observed subsurface temperature variations. Conductive heat transfer is dominant within the earth's lithosphere, while large-scale convective heat transfer is limited to tectonically and volcanically active regions (Limberger et al., 2018).

Equation (1) shows the calculation of subsurface temperature conductively using several parameters of thermal properties of rocks and aquifer depth (z) based on drilling data.

$$z \leq 3km : T(z) = T_0 + \frac{Q_0}{k} z - \frac{A}{2k} z^2 \approx T_0 + \frac{Q_0}{k} z \quad (1)$$

The calculation of temperature at this depth is based on several parameters, such as surface heat flow (Q_0), thermal conductivity of rocks (k), depth (z), and surface temperature (T_0). In this study, the

presence of *radiogenic heat production* (A) can be ignored because it has no major effect on subsurface temperatures above 3 km (Limberger et al., 2018). The specific parameters can be found in Table 1.

Surface heatflow, cyclation (z), and rock thermal conductivity (k) are obtained from drilled well data. The surface temperature value is obtained from average temperature data for 2019 – 2021 at the SSK Pekanbaru Meteorological Station in BPS Riau (2022). Next, interpolation is carried out to produce a model of surface heat flow values, rock thermal conductivity, and depth for calculating the parameter values of each grid.

Table 1: HSA calculation parameters.

Output variable	Input variable	Symbol	Unit	Value
subsurface temperature		T	℃	
	surface heat flow	Q_0	$M\ Wm^{-2}$	
	surface temperature	T_0	℃	27.5
	bulk thermal conductivity	k	$Wm^{-1}K^{-1}$	
	depth	z	km	
heat in place		H	$J\ m^{-2}$	
	aquifer thickness	h	km	0.5
	production temperature	T_{prod}	℃	
	re-injection temperature	T_{inj}	℃	37.5
	aquifer bulk heat capacity	γ	J	
	porosity	$\emptyset$		10%
	water heat capacity	C_w	$J\ kg^{-1}K^{-1}$	1000
	aquifer rock heat capacity	C_r	$J\ kg^{-1}K^{-1}$	3772
	water density	ρ_w	$kg\ m^{-3}$	1042
	aquifer rock density	ρ_r	$kg\ m^{-3}$	2600
theoretical potential		P_{theory}	$J\ km^{-2}yr^{-1}$	
	economic lifetime	t	yr	30
technical potential		$\rho_{technical}$	$J\ km^{-2}yr^{-1}$	
	ultimate recovery factor	UR		1%

3.3 Resource Estimation

Estimation of geothermal resources in the study area using theoretical potential calculations and technical potential calculations. The calculation of theoretical potential is a theoretical calculation with several parameters based on the equation of Limberger et al. (2018), while the calculation of technical potential is a calculation of potential that uses multiplication between the results of theoretical calculations with an *ultimate recovery factor*.

The calculation of estimated resources in the study area covers a land area of 110 grids (342,25 km^2). Equation (2) shows the theoretical value of heat energy capacity in an aquifer (heat in *place*, H) using the heat capacity parameter (γ) in equation (3).

$$H = h\left(T_{prod} - T_{inj}\right)\gamma \tag{2}$$

$$\gamma = \emptyset.c_w.\rho_w + (1-\emptyset).c_r.\rho_r \tag{3}$$

This heat capacity (γ) is determined by rock density (ρr), water density (ρw), rock heat capacity (c_r), aquifer fluid (c_w) and porosity of aquifers ($\emptyset$)(Limberger et al., 2018). Next, heat *in place* (H) is determined based on aquifer thickness (h), the bulk heat capacity of the aquifer that has previously been calculated (γ), and the difference between production temperature and injection temperature. In this

study, the production temperature (T_{prod}) is defined as the temperature at the depth of the well (T(z)), while the injection temperature (T_{inj}) is assumed to be the surface temperature plus 10°C (H_0+10°C) (Limberger et al., 2018).

Heat in place (H) that can be utilized or expelled is influenced by technical and economic conditions. This includes surface and subsurface conditions, such as production facilities and drilling technology (Rybach, 2015). Therefore, this study used a *recovery factor* (UR) of 1% against *heat in place* for the calculation of technical potential ($P_{technical}$). The calculation of potential is carried out assuming a utilization time (t) of 30 years against the theoretical potential (P_{theory}) in equation (4) and the technical potential ($P_{technical}$) in equation (5).

$$P_{theory} = \frac{H}{t} \tag{4}$$

$$P_{technical} = P_{theory}.UR \tag{5}$$

Heat production sites should be located in nearby areas where thermal energy is utilized. To better assess economic feasibility, technical potential can be matched to energy capacity and demand locally.

3.4 Geostatistical Analysis

The calculation of technical potential for each grid is then treated as a geostatistical analysis to see the distribution of potential in the research area. The distribution of technical potential is determined by the ordinary kriging method to see the interpolation of potential values. The ordinary kriging method is preceded by exploratory data analysis, exploratory spatial data analysis, and semi variograms to make spatial modeling. Exploratory data analysis (EDA) is used to determine data distribution, outliers, and anomalies (Komorowski et al., 2016). Exploratory spatial data analysis (ESDA) is a continuation of EDA, which is useful for detecting spatial properties, including spatial patterns in data and correcting spatial models (Haining et al., 1998).

Experimental semi variograms are basic geostatistical tools used to visualize and model spatial correlations between data points in the form of error variants at locations (s) and locations separated by distance (s+h) (Guskarnali, 2016). According to Armstrong (1998), experimental variograms are expressed in the following equation (6):

$$\gamma(h) = \frac{1}{2N(h)} \sum_{i=1}^{N} [Z(s_i) - Z(s_i + h)^2] \tag{6}$$

The semi variogram parameter consists of three parameters that determine the success rate of spatial analysis. The parameters are nugget, sill, and range effects.

Ordinary kriging *(*OK) is a method used to assume unknown population averages and spatial data that do not contain trends (Deutsch, 2003). Ordinary kriging can be done after obtaining a semi variogram model which is considered an isotrope (Kitanidis,1997). There are several parameters in OK, such as maximum and minimum values, pixel size, georeference, semi variogram model, nuggets, values, thresholds, and ranges. This process uses analysis from the Ilwis Academic 3.3 software.

All the steps in this study are listed in the simple flowchart in Figure 4.

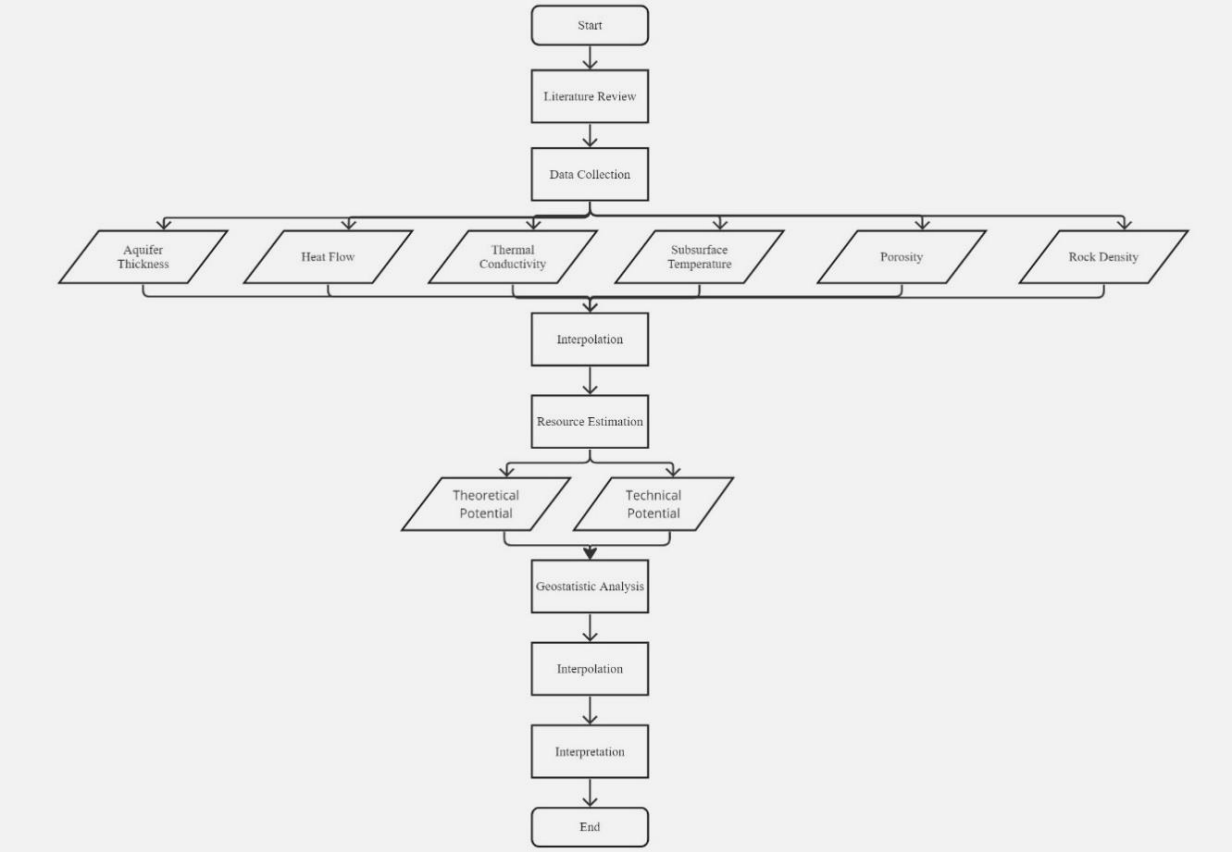


Figure 4: Research flowchart.

4. RESULT AND DISCUSSION

4.1 Heatflow, Depth, and Thermal Conductivity Distribution

The results of heatflow modeling, drill well depth, gradient temperature, and thermal conductivity of rocks are presented in Figure 5. The depth value of the drilled well ranges from 375 – 2000 meters, the heat flow is around 103.1 – 189 mW/m^2, the thermal conductivity of 1.9 – 2.2 W/m.K, and the temperature gradient values range from 47 – 97 °C/km that represent each grid (Table 2). Other parameters used in resource calculations are the surface temperature value of 27.5°C, the aquifer thickness of 548.64 m, the porosity of 10%, the water heat capacity value of 1000 J/kg. K, the value of the heat capacity of rocks is 3772 J / kg. K, and the rock density of 2600 kg/m^3. We assume that the depth of the well drilled as the measurement depth of the HSA resource as an implication of the aquifer depth.

From the modeling results, high heatflow, depth, and thermal conductivity values are characterized by red on the map (Figure 5), medium values are yellow-green, and low values are colored blue. High heatflow values are in the East-Southeast of the study area, high aquifer depth values are in the Middle-West of the study area, and high thermal conductivity values are in the Northwest and East research areas. The value of thermal conductivity and thermal gradient has a positive correlation with the value of heatflow, while the value of drilled well depth has a negative correlation with the value of heatflow, thermal conductivity, and thermal gradient. This is because based on equation 1, the value of heatflow depends on the value of thermal gradient and thermal conductivity, while the value of drilled well depth has not influence on thermal conductivity and thermal gradient.

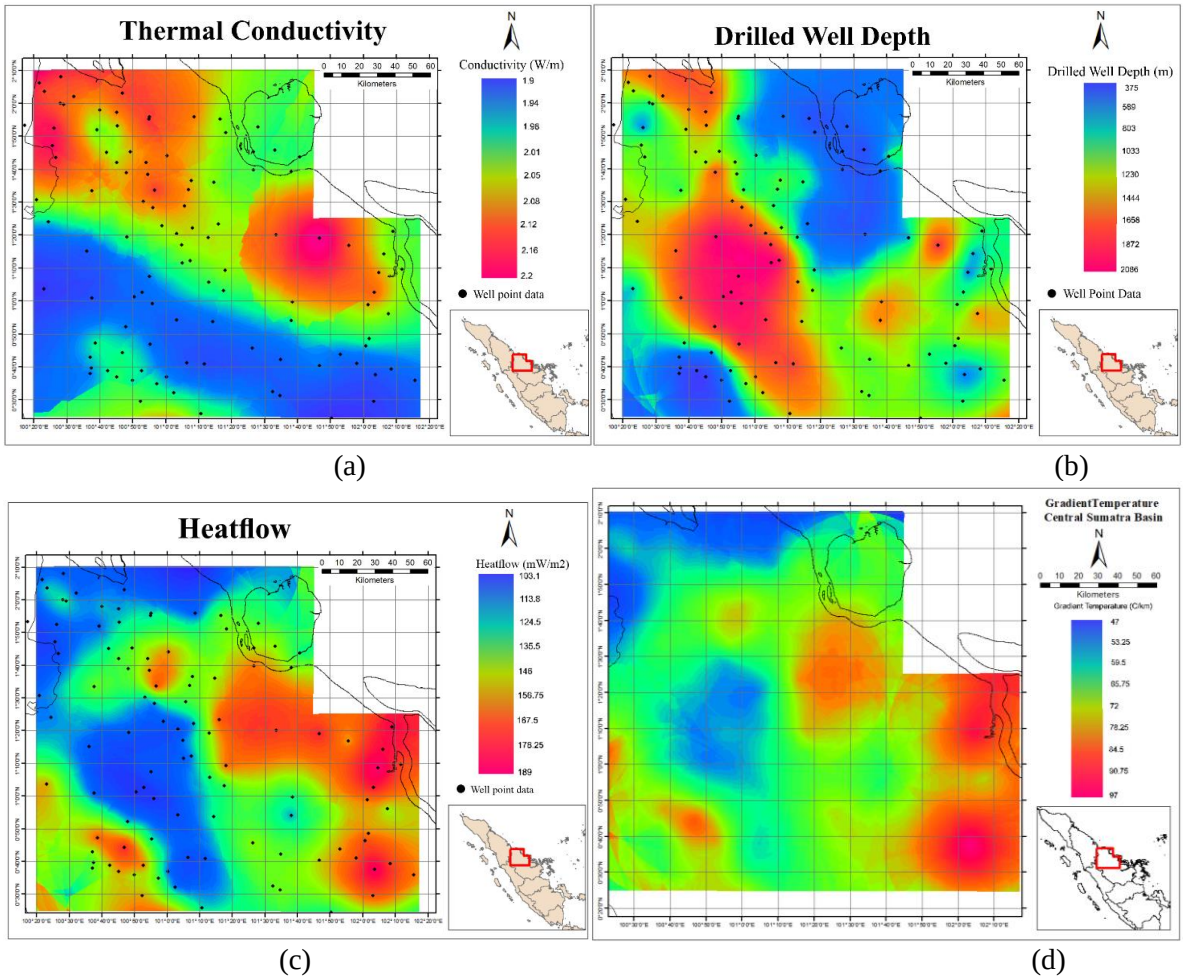


Figure 5: Model distribution of thermal conductivity parameters of rocks (a), drilled well depth (b), heatflow (c), and gradient temperature (d).

Table 2: Heat flow and conductivity values of each grid.

Grid	Drill well depth; z (m)	Heat flow; Qo (mW/m2)	Conductivity; k (W/mK)
1	1231	127	2.07
2	1850	107	2.05
3	1872	110	2.2
4	1190	103	2.08
5	800	103	2.08
6	680	125	2.03
7	590	125	2.03
8	634	130	2.03
9	788	109	2.2
10	1129	117	2
11	1549	123	2.1
12	1002	125	2.2
13	643	117	2.1
14	401	148	2
15	400	130	2
16	690	128	2

Grid	Drill well depth; z (m)	Heat flow; Qo (mW/m2)	Conductivity; k (W/mK)
17	705	135	2.02
18	1180	106	2.2
19	1192	125	1.98
20	1392	133	2.07
21	1173	156	2.08
22	780	147	2.05
23	700	147	2.03
24	500	151	2.02
25	402	135	1.95
26	1200	125	2.1
27	1192	138	2.1
28	1567	138	2.1
29	1300	175	2.3
30	1190	133	2.08
31	1014	148	1.95
32	720	155	2.08
33	700	150	2.12
34	800	130	2.05
35	1324	115	1.9
36	1457	118	1.9
37	1761	114	1.95
38	1796	110	2
39	1401	125	2.01
40	710	150	2.05
41	400	160	2.1
42	400	165	2.12
43	1230	175	2.5
44	1153	175	2
45	1230	120	1.85
46	1614	105	1.89
47	2000	100	1.96
48	2050	100	1.94
49	1900	118	1.98
50	1150	165	2
51	721	158	2.08
52	803	156	2.1
53	803	158	2.2
54	1658	145	2.05
55	836	170	2.02
56	1000	158	2
57	950	160	1.87
58	1730	102	1.87
59	1900	100	1.91
60	2050	115	1.9
61	1872	123	1.9
62	1200	130	1.93
63	1150	132	2.05
64	1200	130	2.08
65	1250	135	2.1

Grid	Drill well depth; z (m)	Heat flow; Qo (mW/m2)	Conductivity; k (W/mK)
66	1178	145	2.1
67	1100	170	2.1
68	1000	150	2
69	1121	143	1.88
70	1340	160	1.9
71	1772	97	1.91
72	1921	104	1.95
73	1819	108	1.92
74	1294	128	1.89
75	1180	131	1.9
76	1444	110	1.92
77	1444	125	1.95
78	1150	133	1.98
79	1250	128	1.98
80	1320	128	1.98
81	900	144	1.9
82	800	150	1.98
83	1000	200	2
84	1658	120	1.95
85	1730	113	1.9
86	1700	118	1.88
87	1037	145	1.89
88	1039	130	1.9
89	1034	145	1.9
90	893	160	1.91
91	845	150	1.91
92	920	145	1.91
93	890	135	1.92
94	450	144	1.95
95	400	152	2
96	1112	130	1.98
97	1401	103	1.95
98	1480	110	1.93
99	1287	130	1.9
100	1100	142	1.9
101	1120	144	1.89
102	1000	155	1.89
103	940	170	1.89
104	1154	150	1.89
105	890	145	1.95
106	589	150	2
107	1444	120	2
108	1278	105	1.88
109	1100	120	1.82
110	1245	115	1.9

4.2 Geothermal Resources

Based on equations (2) and (3), it is found that the average value of heat in place of the study area is $3.68x10^{14}$ J/km^2. Therefore, with a lifetime of 30 years, it is known that the theoretical potential value of the research area is $1.23x10^{13}$ J/km^2.yr. If the ultimate recovery factor value is 1%, the technical potential value of the research area in the Central Sumatra Basin has the largest value of $2.03x10^{11}$ J/km^2.yr and the smallest value of 4.24x10 10 J/km^2.yrs with an average of $1.227x10^{11}$. If it is assumed that the surface area of the aquifer is equal to the surface area of the grid, the aquifer area for each grid is 342.25 km^2. So, it is known that the research area has a total energy potential of 146.52 MW with an average of 1.33 MW of each grid.

The calculations obtained have different results from the results of geothermal resource calculations according to Sihotang and Alam (2019). Based on Sihotang and Alam (2019), a technical potential value of 103.5 MW was obtained at a depth of 3.5 km. This happens because there are different concepts of geothermal resource potential calculation formulas. Sihotang and Alam (2019), performed calculations using the Breadsmore protocol formula, which assumes that the study area has a tectonic order as an Enhanced Geothermal System (EGS).

Enhanced Geothermal Systems (EGS) is a geothermal reservoir system that allows economical utilization of low-permeability conductive rocks by creating fluid connectivity in low-permeability rocks through hydraulic, thermal, or chemical stimulation at depths of more than 3 km (Huenges, 2016). The research area has a tectonic order as a basin filled with fairly thick sediments in a location that is not too deep and has a large enough porosity. The study area is also an active subduction area where EGS tends to be in ancient subduction (stable) with crystalline rock basements (Mustika et al., 2023). Mustika et al. (2023) said the Central Sumatra Basin has the potential for hot sedimentary aquifers. Therefore, it will be easier to accept if the calculation uses the concept of the HSA calculation formula.

4.3 Resources Geostatistic Analysis

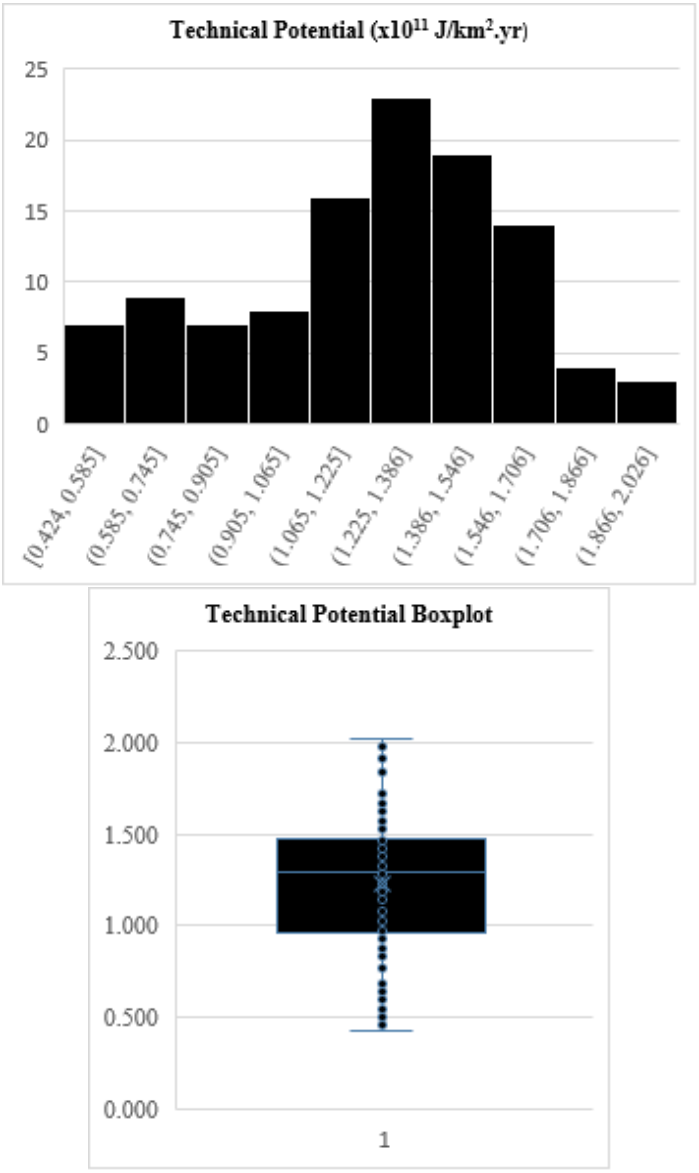
The results of calculating the resources of each grid will be analyzed with geostatistical treatment. Geostatistical analysis processing using Ilwis 3.3 Academic software to obtain semi variograms and visualization of ordinary kriging interpolation. These results were then adjusted to create a map of the hot sedimentary aquifer's geothermal resources.

Table 3: Summary statistic of technical potential.

Technical Potential ($x10^{11}$ J/km^2.yr)	
Mean	1.2273933
Standard Error	0.0355954
Median	1.2893678
Mode	1.2247687
Standard Deviation	0.3733277
Sample Variance	0.1393736
Kurtosis	-0.45943
Skewness	-0.349916
Range	1.6018673
Minimum	0.4244798
Maximum	2.0263471
Sum	135.01327
Count	110

In exploratory data analysis, summary statistics (Table 3) show a fairly normal distribution of data characterized by mean, mode, and median values that are almost the same at a value of 1.2 x 10 11 J / km $^{2.yr}$. In addition, normal data are also characterized by moderate skewness which is in the range of -

0.5 – 0.5 (Bulmer, 1979). Normal data distribution is also shown by histogram plots that form or almost resemble bell shapes and boxplots that do not show any "outlier" data, as shown by (Figure 6).



(a) (b)

Figure 6: Histogram (a) and box plot (b) of the technical potential. The histogram shows a fairly normal distribution of data, while the boxplot shows the absence of "outlier" data.

In exploratory spatial data analysis, there are 110 ten spatial points that represent each grid and its technical potential. Each point is placed regularly and spread out at a uniform distance. The results of technical potential values that have previously been normally distributed will be processed using variogram analysis. In spatial analysis using variogram plots, it is known that the variogram fittings are carried out by the try and error method with direct observation or by eye (Guskarnali, 2016). Based on the results of the semi variogram fitting (Figure 7), it shows that the semi variogram model that is close to the model is a spherical type. Spherical models with a lag distance of 18000 have nuggets of 0.022, sill values of 0.121, and a range of 60000. The spherical model with a lag distance of 18000 was chosen because it has small nuggets, can clearly show spatial dependence and spatial independence, and the shape is non-erratic. Then, the value of the variogram model will be used for interpolation processing using ordinary kriging.

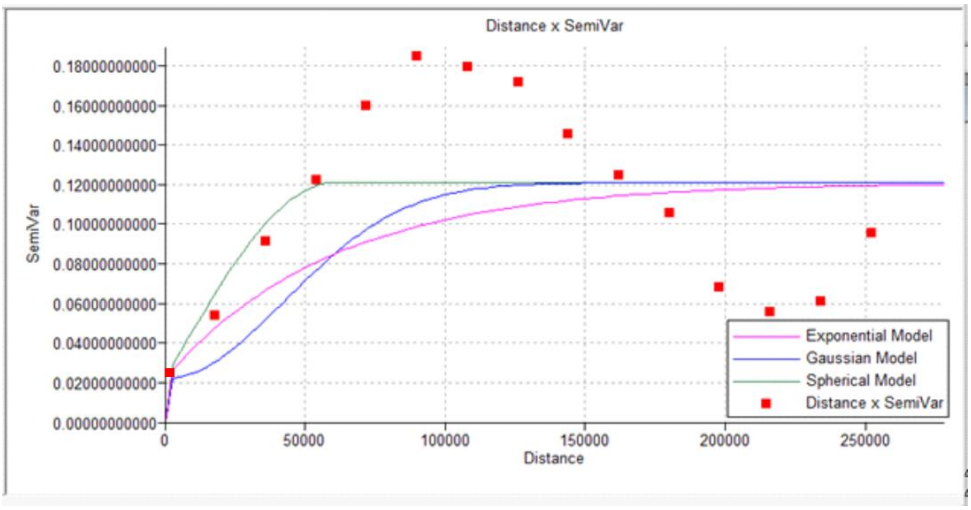


Figure 7: Semi variogram model of technical potential data. From the diagram model, it can be seen that the spherical model is the most suitable model.

Based on the results of interpolation using ordinary kriging, it was found that the high technical potential value anomaly was in the center parts of the study area with a tendency towards NW - SE. It is based on the interpolated color, which tends to be red- pink on the map (around 1.94×10^{11} J/km$^{2.yr}$) (Figure 8). Large value anomalies are generally influenced by the depth of the borehole as a representation of the z value. Meanwhile, the trend of the NW – SE direction is influenced by the amount of thermal conductivity of rocks and heatflow values.

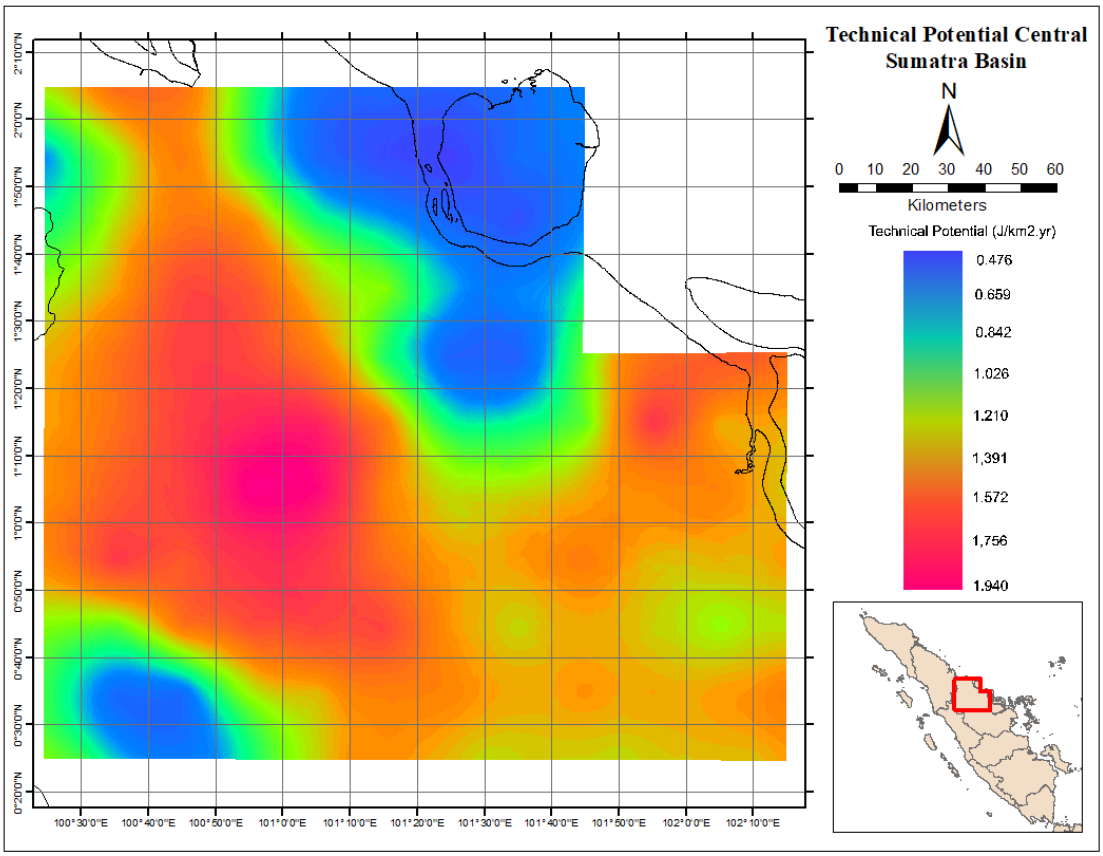


Figure 8: Technical potential distribution.

5. CONCLUSION

- The tectonic setting of the Central Sumatra Basin is suitable for the calculation of hot sedimentary aquifers (HAS) because they have thick sedimentary basins, porosity, and not ancient subduction (unstable).
- This study uses the Menggala Formation as an aquifer that has a fine-grain quartz sandstone lithology and a thickness of 548.74 meters.
- A total of 120 drilled wells data will be processed with a 10' (18.5 x 18.5 km) grid system of 110 grids.
- Based on the model, the depth value of the drilled well ranges from 375 – 2000 meters, the heat flow is around 103.1 – 189 mW/m 2, the thermal conductivity of 19 – 2.2 W/m.K, and the temperature gradient value ranges from 47 – 97 °C/km. Other parameters used in resource calculations are the surface temperature value of 27.5°C, the aquifer thickness of 548.64 m, the porosity of 10%, the water heat capacity value of 1000 J/kg. K, the value of the heat capacity of rocks is 3772 J / kg. K, and the rock density of 2600 kg/m3
- Based on calculations, the average value of heat in place ranges from $3.68x10^{14}$ J/m^2 per grid. The potential theoretical mean is $1.23x10^{13}$ J/m$^{2.yr}$., while the technical potential of the research area in the Central Sumatra Basin has the largest value of $1.85x10^{11}$ J/m 2.yr and the smallest value of 4.24x10 10 J/m $^{2.yr}$ for each grid.
- If each grid has an aquifer area of 342.25 km^2, it is known that the study area has a total geothermal resource energy of 146.52 MW.
- Geostatistical analysis shows a normal distribution of resource data. The results of processing using semi variograms and ordinary kriging interpolation show that areas with large resource value anomalies are in the middle area of the research area with directional potential trends NW – SE. Large value anomalies are generally influenced by the depth of the borehole as a representation of the z value. Meanwhile, the trend of the NW – SE direction is influenced by the amount of thermal conductivity of rocks and heatflow values.

DATA AVAILABILITY

All excel format table datasets can be accessed via the following link:
https://bit.ly/DataAvailabilityIIGCE2023

All map images can be accessed via the following link: https://bit.ly/DataAvailabilityIIGCE2023

REFERENCES

Armstrong, M.: Basic Linear Geostatistic. *Springer*. (1998)

Barber, A.J., Crow, M.J., Milsom, J.S.: Sumatra: Geology, Resources, and Tectonic Evolution. *Geological Society Memoir*, No. 31, (2005).

Bulmer, M. G: *Principal of Statistics*. Dovers. (1979).

Choanji, T., Yuskar, Y., Good, D., Son, E., Faiez, Z., &; Habibi, M.: Sandstone Reservoir Characteristic Based on Surficial Geological Data of Sihapas Formation in Bukit Suligi Area, Southwest Central Sumatra Basin, (2017). https://www.researchgate.net/publication/322962579.

Coordinating Ministry for Economic Affairs of the Republic of Indonesia: The Government Continues to Accelerate the Energy Transition in the Country to Achieve the Net Zero Emission Target by 2060 [Web Page], (2023, March 7). Retrieved from https://www.ekon.go.id/publikasi/detail/4996/.

Deutsch, C. V.: Geostatistics (R. A. B. T.-E. of P. S. and T. (Third E. Meyers (ed.); pp. 697– 707). Academic Press. (2003). https://doi.org/10.1016 B0-12-227410-5/00869-3.

Doust, H., & Noble, R. A.: Petroleum systems of Indonesia. *Marine and Petroleum Geology*,*25*(2), (2008), 103-129.

Fardiansyah, I., Wiyono, A., &; Talib, A. F.: The Massive Fluvial Channel System in The Balam Graben: New Insight and Future Expectation from Menggala Formation in The Northern Rokan

Block, Central Sumatra Basin. *Indonesian Association of Geologists Journal*, *1*(2), (2021), 103–110. https://doi.org/10.51835/iagij.2021.1.2.34.

Guskarnali: metode point kriging untuk estimasi sumberdaya bijih besi (Fe) menggunakan data Assay (3D) pada daerah Tanjung Buli Kabupaten Halmahera Timur. *Promine Journal*, *4 (2)*(December), (2016). 13–20.

Haining, R., Wise, S., & Ma, J.: Exploratory Spatial Data Analysis. Journal of the Royal Statistical Society: Series D (The Statistician), 47(3), (1998). 457–469. https://doi.org/10.1111/1467-9884.00147.

Huenges, E.: Enhanced geothermal systems: Review and status of research and development. *Geothermal Power Generation*, Woodhead Publishing, (2016), 743-761. ISBN 9780081003374. https://doi.org/10.1016/B978-0-08-100337-4.00025-5.

Hantschel, T., Kauerauf, A.I.: Fundamentals of Basin and Petroleum Systems Modeling, (2009). doi : 10.1007/978-3-540-72318-9.

Irhamsyah, F. M.: Comparison of Petrophysical Characteristics of a Shaly Sand Reservoir Using Shale Volume and Double Layer Models, (2018). https://doi.org/10.29118/ipa.50.17.419.se

King, R., & Miller, M.: Multiuse "Triple Play" Hot Sedimentary Aquifer (HSA) Potential of Victoria, Australia. In World Geothermal Congress, Bali, (2010).

Kitanidis, P. K.: Introduction to Geostatistics: Applications in Hydrogeology. Cambridge University Press. (1997).

Komorowski, M., Marshall, D., Salciccioli, J., & Crutain, Y: . Exploratory Data Analysis. In Secondary Analysis of Electronic Health Records, (2016), 185–203. https://doi.org/10.1007/978-3-319-43742-2_15.

Limberger, J., Boxem, T., Pluymaekers, M., Bruhn, D., Manzella, A., Calcagno, P., Beekman, F., Cloetingh, S., & van Wees, J. D:. Geothermal energy in deep aquifers: A global assessment of the resource base for direct heat utilization. In Renewable and Sustainable Energy Reviews, 82, (2018), 961–975. https://doi.org/10.1016/j.rser.2017.09.084\.

Lukawski M, Anderson B, Augustine C, Capuano L, Beckers K, Livesay B: Cost Analysis of Oil, Gas, and Geothermal Well Drilling. Journal Petroleum Science and Engineering,118, (2014),1–14. doi:10.1016/j.petrol.2014.03.012.

Lund J: Direct utilization of geothermal energy. Energies, 3, (2010). 71

Mijnlieff, H.: Introduction to the geothermal play and reservoir geology of the Netherlands. *Netherlands Journal of Geosciences*. 99, (2020). 10.1017/njg.2020.2.

Ministry of Energy and Mineral Resources: Geothermal Energy Development Potential in Indonesia [Web page], (2020, December). Accessed from https://ebtke.esdm.go.id/lintas/id/investasi-ebtke/sektor-panas-bumi/potensi.

Mustika, A.I., Permadi, B.P., Shalihin, M.G.J., Nugraha, R.P., Pratama, A.R., Purwanto, E.H., & Nazif, H.: Discovering The Potential of Unconventional Geothermal System in Indonesia. *PROCEEDINGS, 48th Workshop on Geothermal Reservoir Engineering*. California: Feb 6-8. (2023). SGP-TR-224

Rybach, L.: Classification of geothermal resources by potential. *Geothermal Energy Science*, *3*(1), (2015), 13-17.

Sefein, K. J., Nguyen, T. X., & Philp, R. P.: Organic geochemical and paleoenvironmental characterization of the Brown Shale Formation, Kiliran sub-basin, Central Sumatra Basin, Indonesia. *Organic Geochemistry*, *112*, (2017), 137-157. doi:10.1016/j.orggeochem.2017.06.017

Sihotang, J. W., &; Alam, S.: Applied Geostatistics to The Assessment of Enhanced Geothermal System (Egs) In Central Sumatra Basin. *Geological Resources Bulletin*, *14*(2), (2019), 113–125. https://doi.org/10.47599/bsdg.v14i2.284.

Sukmono, S.: Application of multi-attribute analysis in mapping lithology and porosity in the Pematang-Sihapas groups of Central Sumatra Basin, Indonesia. The Leading Edge, 26(2), (2007), 126–131. doi:10.1190/1.2542435.

Wongsosantiko, A.: Lower Miocene Duri Formation Sands, Central Sumatra Basin. *Proceedings, The 5th Indonesian Petroleum Association Annual Convention & Exhibition*. 133-150. (1976).

Preliminary assessment of the Pentadio geothermal prospect, Gorontalo, Indonesia

M. Ghassan Jazmi Shalihin, Ferdino R. Fadhillah, and Astri Indra Mustika

PT. Geoenergi Solusi Indonesia (Geoenergis), Jakarta, Indonesia

muhammad.ghassan235@gmail.com

Keywords: Remote sensing analyses, lineament, FFD, fault fracture density, low-medium geothermal system, geothermal, Indonesia

ABSTRACT

Pentadio Geothermal Prospect located in Telaga Biru, Gorontalo, Indonesia. The prospect can be categorized as low to medium geothermal resource associated with Gorontalo graben on the northern arm of Sulawesi Island. To identify geothermal potential on the low to medium geothermal resource might be challenging due to less vigorous thermal features compared to the high-temperature fields. Remote sensing analyses are considered to be a powerful tool for preliminary assessment of this geothermal resource potential. This paper is part of our preliminary study to assess geothermal prospect in Pentadio by remote sensing techniques to identify those structures which considered have strong correlation to indicate the geothermal presence in a geothermal field. The research conducted using digital elevation model (DEM) sourced from DEMNAS with varies lightning azimuth and certain altitude. Field checking will be conducted to confirm the anomaly resulted from the remote sensing analyses. It is expected that the anomalies recorded on the remote sensing analyses will have positive correlation with the field observation (i.e., the presence of active thermal manifestations).

1. INTRODUCTION

The Gorontalo section of the northern arm of Sulawesi Island which is traversed by a longitudinal median depression is volcanically extinct (van Bemmelen, 1949). Notwithstanding, it still hosts one of the geothermal prospects located in Gorontalo, namely Pentadio. According to the Directorate of New and Renewable Energy (EBTKE), Pentadio can be categorized as low to medium geothermal resource which controlled by the fault system (EBTKE, 2017). The prosect currently having 25 MWe speculative resource and has included in the Preliminary Survey and Exploration Assignment Geothermal Area (WPSPE) by the Ministry of Energy and Mineral Resources, Indonesia (MEMR). Although several studies shows that low-medium geothermal systems have abundant prospects in Indonesia, none of those prospects are developed due to inadequacy data and information (Wibowo, et al., 2021; Putriyana, et al., 2022) including Pentadio.

To date, the low-medium geothermal resources in Indonesia are still considered less attractive. One of the reasons may be related to its characteristic that still is not well understood. For example, the active thermal features (i.e., warm and/or hot springs) that may not as appealing as in the high-temperature geothermal field (i.e., fumarolic/solfataric steam discharge, boiling hot pool, etc.). In addition, some of the field may lack surface thermal features (also known as blind/hidden geothermal systems). Conventional exploration and/or extraction concepts such as applied in the high-temperature system may not be fully suitable on those conditions. These kinds of things will lead to very high resource risk that also will have an impact to its economic value. The understanding of exploration strategy for this type of field is critical to accelerate its development in Indonesia.

The main factor that controls the distribution of geothermal manifestations usually is the geological structure. The structural indication can be preliminary identified by remote sensing imagery such as that has been done in Mokai Field, New Zealand (Soengkono, 2010). This paper is part of our preliminary study to assess geothermal prospect in Pentadio by remote sensing techniques to identify those structures which is considered have strong correlation to indicate the geothermal presence in a geothermal field. Pentadio prospect is chosen due to its low-medium resource characteristic and non-volcanism setting which may shed light if similar techniques will be applied on the other comparable fields in Indonesia.

2. METHODS

The research conducted using digital elevation model (DEM) sourced from DEMNAS that has 8-meter spatial resolution. It utilized to create hill shade representations with 0°, 45°, 90°, 135°, 180°, 225°, 270°, and 315° angle with altitude 45. The diverse range of illumination angles ensures comprehensive visibility of all slopes from distinct perspectives. The elevation model used as basis of surface lineament that automatically extracted using software to construct the Fault Fracture Density (FFD) map.

3. GEOLOGY

3.1 Physiography

The north arm of Sulawesi is part of the Sangihe volcanic arc, which according to Hamilton (1979) was formed due to the subduction of Molucca Sea plate to the west, and the Halmahera volcanic arc resulted from the subduction of the Molucca Sea plate to the east. According to van Bemmelen (1949), the north arm of Sulawesi has a sinuous outline which can be distinguished into three parts, the eastern end, with a NE-SW trend is highly volcanic (Minahasa area); the central part, where the main trend rotates from a NE-SW to E-W trend of the longitudinal depression and volcanically extinct (Gorontalo section); and the N-S trending part.

The North Sulawesi Trench ends at the east where the northeast tip of the Nort Arm of Sulawesi curves from an easterly trend to a northerly. Some volcanoes that become extinct in Quaternary time continue westward some distance from this bend, while the still active volcanoes on Sulawesi are now confined to the northeast tip of the North Arm (Hamilton, 1979). Pentadio is situated within the central arm of the Gorontalo physiographic section. This section is longitudinal median depression which stretches between the mountain ranges on the North coast on the E-W direction called Limboto Zone where the volcanism is entirely extinct (van Bemmelen, 1949). This depression zone is the prominent feature which can be seen around Pentadio prospect. EBTKE (2017) expected that this depression structure is controlling the geothermal system in Pentadio.

3.2 Stratigraphy

Following the geological map presented by EBTKE (2017), based on its relative age and rock type, generally the stratigraphy in Pentadio can be grouped into Old Volcanic Products, Intrusion Rocks, Sedimentary Rocks, Young Volcanic Products, and Surficial Deposit. Pentadio geological map is presented on Figure 1.

a) Old Volcanic Products consist of basaltic lavas which is locally distributed on the southwestern coast of the interest area, pyroclastic rocks at the eastern part of the prospect, and andesitic lavas which cover most of the field in the northern and southern part.

b) Intrusion Rocks which partly can be seen in the NW, NE, and S of the field. There is no information related to the composition of the intrusion rocks.

c) Sedimentary Rocks consist of sand-silt stones which is partly distributed on the NW and S part of the Limboto Lake. Limestones is dominantly covering the western part and partly exposed on the south coast.

d) Young Volcanic Products resulted from two young volcanoes namely Lampotoo and Pilomba which can be found at the eastern and western edges on the interest area, respectively.

e) Surficial Deposit which is expected derived from the lake deposits and distributed along the E-W direction around the Limboto Lake.

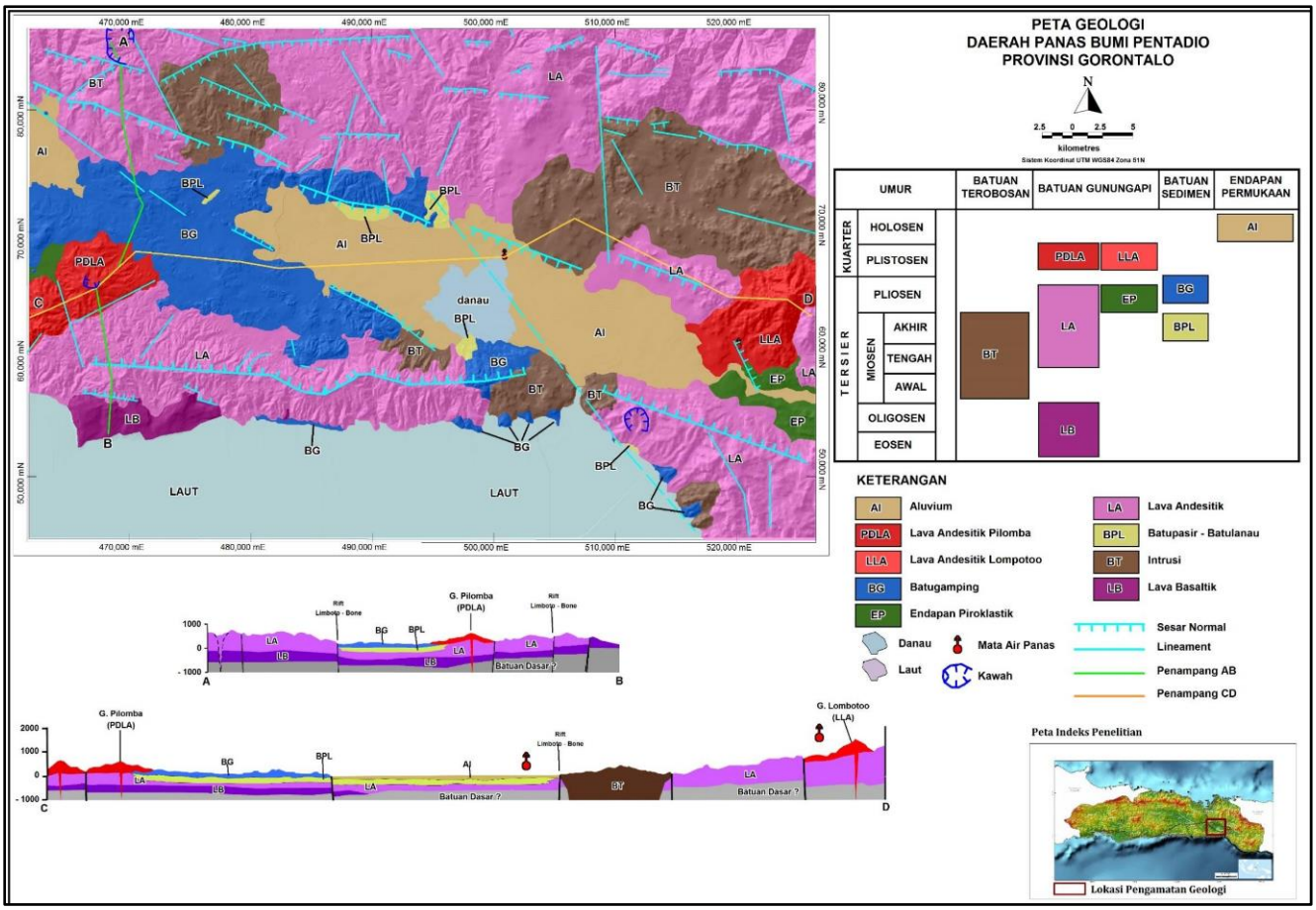


Figure 1: Geological map of Pentadio geothermal prospect (EBTKE, 2017).

3.3 Geological structures

The geological structures that were interpreted from DEMNAS showed that the main structures in Pentadio are the E-W trending. Two major dip-slip faults bounded the depression zone which was interpreted by van Bemmelen (1947) as Limboto Zone. The thermal manifestations in the Pentadio prospect are situated within this depression zone. However, that thermal feature is not precisely located in adjacent to the fault, thus the role of the structure as permeability provided still needs to be studied further

Lineament density or fault and fracture density defined as the total length of lineament per unit area (Soengkono, 1999). The lineament density in the research area was divided into a 1 km grid system. The total length of lineaments inside each grid (in km) was measured and the result was used to compute a representative value of FFD (in km/km^2) at the center of the grid (Soengkono, 2010). The lineament density value in research area has range from 0 to 4.89 km/km^2 and was classified into 3 class namely high (> 4.3 km/km^2 km/km^2), medium (2.1-4.3 km/km^2), and low density (< 2.1 km/km^2). The digital elevation map of Pentadio area shown in

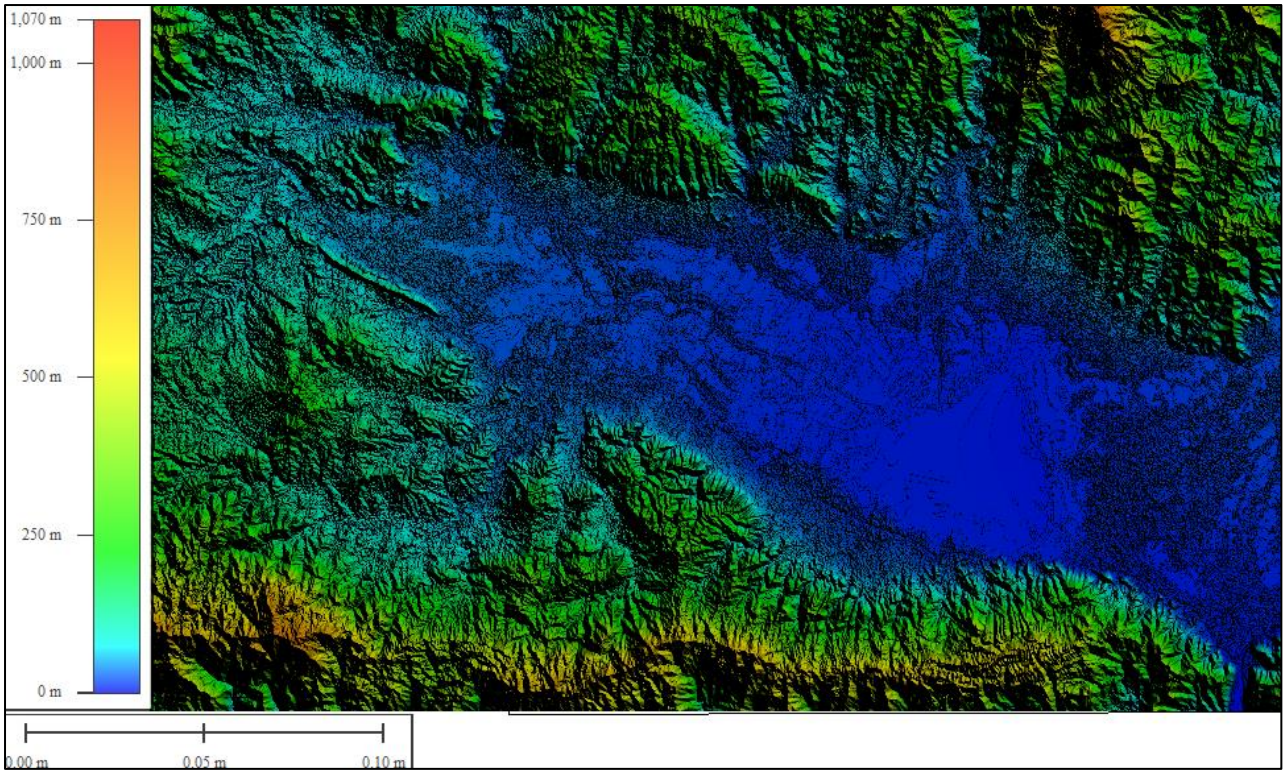


Figure 2: Digital elevation model of Pentadio area based on DEMNAS (2023).

3.4 Thermal manifestation

Thermal manifestations in Pentadio lie at about 9 to 15 mRL. The thermal manifestations emerged on the alluvial plain and only occur in one location at the NE part of the Limboto lake. They are manifested as hot spring and hot pools with temperature ≥70°C (EBTKE, 2017). Further investigations related to the physical characteristic of the thermal manifestations will be conducted on the future site visit by Geoenergis including altered ground observation, sampling and analysis to better understand thermal characteristic/evolution which may be presence in Pentadio.

4. CONCLUSION

Lineament density in research area is divided into 3, which are high (> 4.3 km/km^2), medium (2.1-4.3 km/km^2), and low density (< 2.1 km/km^2). High lineaments density is distributed at southern and northern part of Pentadio area, however, there is no clear association between lineament density and thermal features in Pentadio. Further advance remote sensing such as Land Surface Temperature (LST) will be conducted to be overlayed to the lineament density expecting to the strong correlation of those features which indicate the geothermal presence in a Pentadio. Field checking will also be conducted to confirm the anomaly resulted from the remote sensing analyses.

REFERENCES

Apandi, T., & Bachri, S. (1997). Geological Map of the Kotamobagu Sheet, Sulawesi. Geological Research and Development Centre, Indonesia.

Bachri, S., Sukidon, & Ratman, N. (1993). Geological Map of the Tilamuta Sheet, Sulawesi. Geological Research and Development Centre.

EBTKE. (2017). Potensi Panas Bumi Indonesia Jilid 2. Directorate of Geothermal, Directorate General of New and Renewable Energy, and Energy Conservation of the Ministry Energy and Mineral Resources, Indonesia.

Hamilton, W. (1979). Tectonics of the Indonesian Region. US: US Geological Survey Professional Paper 1078.

Putriyana, L., Daud, T., Saha, B., & Nasruddin, N. (2022). A comprehensive data and information on low to medium temperature geothermal resources in Indonesia: a review. Geomechanics and Geophysics for Geo-Energy and Geo-Resources.

Soengkono, S. (1999). Te Kopia geothermal system (New Zealand) - The relationship between its structure and extend. 28, 767-784.

Soengkono, S. (2010). Assessment of fault and fractures at the Mokai Geothermal Field, Taupo Volcanic Zone, New Zealand. World Geothermal Congress 2010.

van Bemmelen, R. (1949). The Geology of Indonesia vol. 1A. The Hague.

Wibowo, A., Hadi, M., & Risdianto, D. (2021). Sistem Panas Bumi Temperatur Rendah-Sedang pada Cekungan Kutai dan Rekomendasi Pemanfaatannya. Buletin Sumber Daya Geologi, 16(2), 133-151.

Fluid Chemistry Evolution after one year production at Sokoria Geothermal Field

Radhitya E Pradipta and Ryan Hidayat

KSORKA

radhitya.pradipta@ksorka.com, ryan.hidayat@ksorka.com

Keywords: Corrosion, Acid, Chemistry Evolution, Production Monitoring

ABSTRACT

Sokoria Geothermal Indonesia (SGI) produces ~8 MW of electricity from 4 production wells. The first COD was conducted in March 2022 and the second was conducted in July 2023. The initial stage of production fluid shows pH below 5. Thus, the downhole pH modification was applied by injecting NaOH to increase the pH to 4.8-5.2 to avoid the corrosion potential.

After a year, two production wells show an increase of pH overtime; hence the NaOH dosage for treatment is decreasing. The evolution is in line with Na-K-Mg and Cl-SO_4-HCO_3 diagrams from initial stage to the latest sampling. The diagrams show the shifting from immature waters to partial equilibrium as the effect of increasing the pH of produced brine. Moreover, the Cl-B cross plot diagram also suggests there is no direct connection to Mt. Kelimutu. The benign liquid at deep reservoir is present based on the appearance of Epidote, Wairakite, and Neutral Cl Spring. The downhole sampling indicates the acid fluid entries are from shallow zones through Lowongopolo fault as the acid fluid pathway. Geochemistry samples corroborate that the wells drilled towards the Lowongopolo fault have lower pH compared to the wells that were drilled further away from the fault.

1. INTRODUCTION

Sokoria Geothermal is located at Ende, Flores Island, East Nusa Tenggara Province, Indonesia. The late Quaternary volcanism is located on the south side of Flores with eight active volcanoes including Kelimutu Volcano which in the vicinity of Sokoria project. Sokoria prospect is situated within the large collapse features and NNE-SSW Lowongopolo fault (Sarmiento, at al. 2019). Four exploration wells have been drilled, encountered three formations and more than two feed zones. Brine sample at the wellhead shows all the wells originally have pH <5 and showing an increasing trend over time. This paper will evaluate the improvement of brine in Sokoria Geothermal.

2. GEOLOGY

2.1 Lithology

The main rock composition of the drilled wells is composed of andesitic rock, tuff breccia, and lithic-crystal tuff. The rock units are part of the Mutubusa volcanic formation in the upper part, Kelinabe volcanic formation in the lower part, and The Old Sokoria volcanic formation as the main reservoir rock in the bottom part (Siagian, et al. 2018). The reservoir rock is characterized by altered lithic tiff interstratified by altered andesite tuff breccia.

2.2 Geology Structure

Detailed remote sensing analysis was conducted using a combination of LiDAR and DEMNAS (detail resolution in 1 meter and 8 meters) in the prospect area and integrated with surface structural mapping. The study result shows that the local structural framework in Sokoria corresponds to the regional structural patterns where major NE-SW, NW-SE and E-W faults were outlined. The study area is also characterized by structurally controlled major collapsed features. The inferred structures are more dominant around surface manifestation area with NW-SE and N-S trends and continue to the south. The NS fault has the highest confidence based on supported surface geology and subsurface geophysics, especially from the drilling results of the well that intersected the NS fault.

Lithologic Column	Rock Unit and Type	Thickness (m)	Age (Ma)	Geothermal Significance
	Mutubusa volcanic: interlayered lava & pyroclastic, consist of lithic tuff, tuff breccia, andesite, dacite and rare basalt	700	Not yet determinated, Holocene	Cap Rock
	Kelinabe volcanic: dominantly pyroclastic altered, consist of lithic tuff and crystal lithic tuff	300-500	0.36 (K-Ar)*, Late Pleistocene to Early Holocene *Abbott & Chamalaun, 1978; 1981	Shallow Reservoir
	Old Sokoria volcanic: contact of altered pyroclastic rocks, consist of lithic tuff – tuff breccia, andesite breccia altered	≥ 700	Not yet determinated, Pleistocene	Deep Reservoir

Figure 1: Simplified subsurface stratigraphy of Sokoria (Siagian et al., 2018).

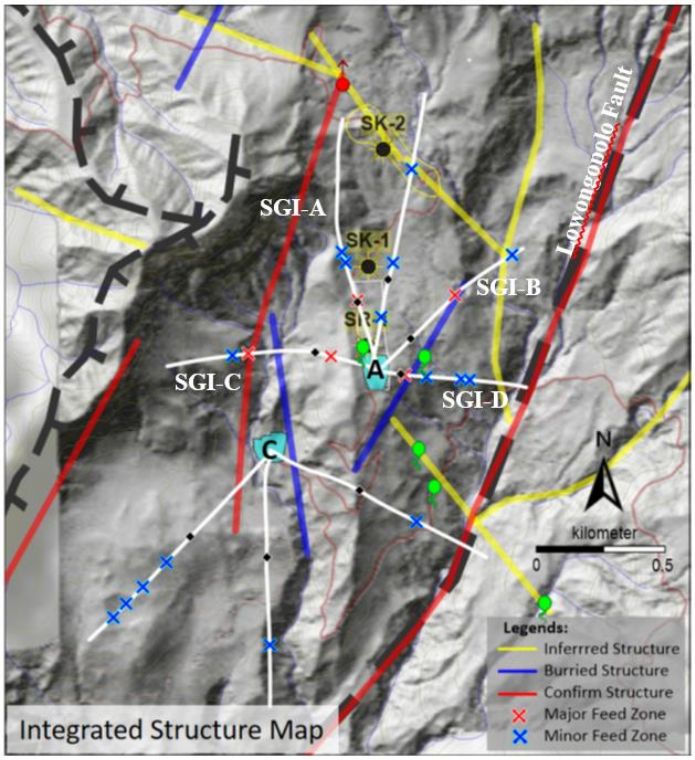


Figure 2: Integrated Structure Map of Sokoria (Siagian et al., 2022).

2.3 Alteration

Drilled cuttings from all production wells in Sokoria namely SGI-A, SGI-B, SGI-C, and SGI-D show a similar pattern of lithology alteration. SGI has identified three (3) alteration zones namely argillic alteration, phyllic alteration, and prophylitic alteration. The argillic alteration zone (clay cap) is identified by the dominance of smectite rich and swelling clay minerals, with rare amounts of quartz and calcite. The bottom of argillic zone is indicated by an increase of chlorite, followed by decreasing in smectite.

Phyllic alteration (transition zone) is characterized by illite with increasing amounts of pyrite and quartz. The appearance of anhydrite is the main distinguisher in this zone. This mineral is normally abundant

in permeable zone especially where the acid and neutral fluid are mixed. Propylitic alteration occurred at the deep reservoir section. The mineral assemblage consists of epidote minerals, an increase of chlorite, coinciding with quartz, calcite, pyrite, illite, and anhydrite.

The mineral assemblages indicate the presence of acidic minerals such as anhydrite, diaspore and pyrophyllite from ~600 to ~1200 meters. However, the appearance of acid mineral index is decreasing and changes to neutral mineral index such as epidote started from ~1110 and changed to crystalline epidote at ~1357 m and wairakite at depth ~1700 m up to total loss circulation (TLC).

3. INITIAL STAGE OF FLUID CHEMISTRY

Discharge flow test was performed in all production wells between 2018-2019. All wells showed similar low pH at their initial stage. SGI-A has average pH 5.5 at temperature 82^0C, SGI-B average pH was 3.7 with temperature 78^0C, SGI-D has pH 3.5 and SGI-C showed pH 4.1. Figure 3 summarizes the fluid chemistry in the initial stage.

Downhole sampling taken in SGI-B showed that the shallowest feedzone at 1270 m has the smallest pH (3.9) and the deepest feed zone at 1755 m shows the highest pH (4.6), indicating that the acid fluid comes from the shallow feedzone (Figure 3a)

The Na-K-Mg ternary diagram shows all brine samples are immature water and Cl-B cross plot suggest all the samples are not directly connected to Kelimutu Crater (Figure 3b and 3c). The isotope plot of deuterium and oxygen 18 indicate the origin of SGI fluid comes from meteoric water. The closest well to Lowongopolo fault has the highest enrichment of deuterium and oxygen 18 (Figure 3d). The SGI-D is the well that intersects Lowongopolo fault and has the highest enrichment of isotope. This is supporting the hypothesis that the low pH in Sokoria comes from the shallow acid carry over from Lowongopolo fault from Kelimutu Volcano.

4. BRINE EVOLUTION AFTER ONE YEAR PRODUCTION.

Downhole pH modification was implemented to avoid corrosion risk at production casing and all surface facilities. The capillary tube was installed in all the production wells above flashing point to avoid corrosion in production casing before Unit-1 commissioning. The pH target after modification is 4.8-5.2 in surface two-phase line to avoid the corrosion.

Figure 4 illustrates the evolution of pH levels in production wells after one year of production. Notably, Well SGI-A, which was oriented to the north, did not undergo downhole pH modification due to observed pH fluctuations during various well discharges. At the commencement of Unit-1 commissioning (U-1 COD), the initial pH of this well was recorded at 4.5. Over time, Well SGI-A exhibited a steady increase in pH, eventually reaching a neutral pH of 7 within five months of production. Subsequently, there was a gradual slowdown in the pH increase, taking four additional months to attain a final pH level of approximately 8.

SGI-B initially required an injection of NaOH at a rate of 155 ml/min, which was later reduced to 110 ml/min to achieve the desired pH target. The decreasing NaOH consumption hinted at changes within the pH reservoir. However, a significant shift occurred in mid-September 2022 when the injection point was relocated from the downhole position to the wing valve. This transition had a notable impact, causing NaOH consumption to drop from 110 ml/min to approximately 45 ml/min, which continued to decrease over the subsequent four months, reaching as low as 10 ml/min. This shift in NaOH consumption patterns strongly suggested alterations in the pH reservoir. In late February 2023, the injection point was reverted back to the downhole location. Surprisingly, NaOH consumption did not return to its initial levels; instead, it continued to decrease until no further treatment was required to achieve the pH target. This intriguing trend in NaOH consumption indicated a complex interplay of factors affecting the pH dynamics within SGI-B. Further observations revealed that SGI-B's NaOH consumption experienced an increase when production in SGI-D was halted in mid-March 2023. This suggested that SGI-D's production activities were impacting the composition of SGI-B's production fluid.

SGI-D was brought online in October 2022, oriented to the east, and intersecting with the Lowongopolo fault. It had an initial pH of 3.2. The NaOH consumption data exhibited no clear pattern, but the average trend indicated a gradual decrease in NaOH consumption from October 2022 to March 2023.

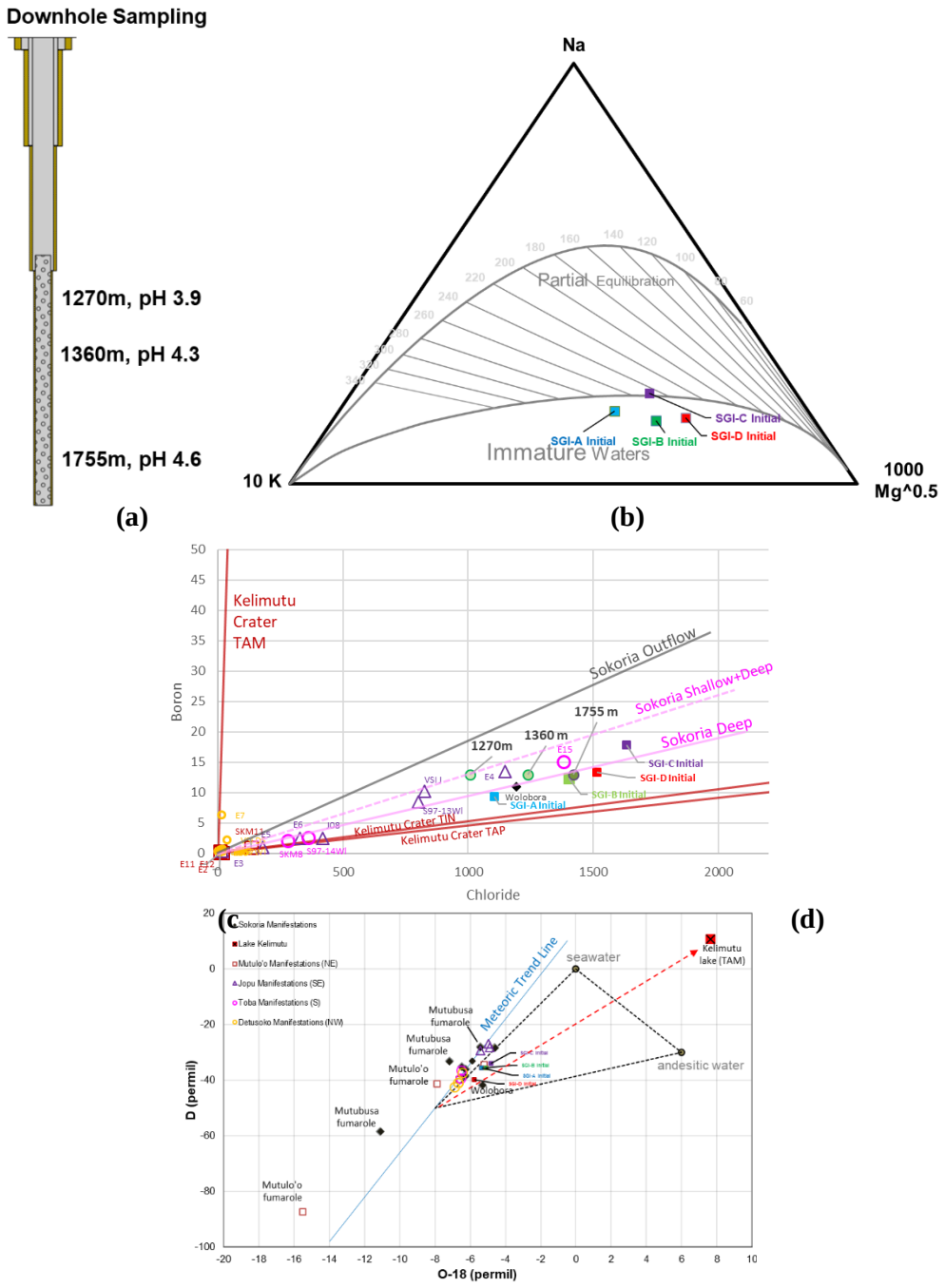


Figure 3: Downhole sampling location in SGI-B (a), Na-K-Mg Tr diagram (b), Cl-B Cross plot of downhole sampling and initial well (c), Isotope cross plot initial well (d).

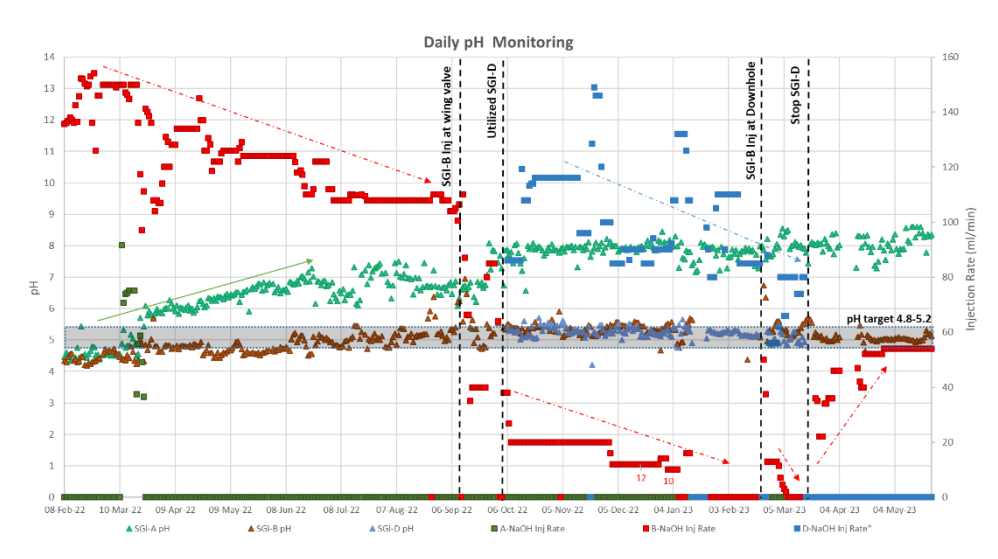


Figure 4: pH daily monitoring.

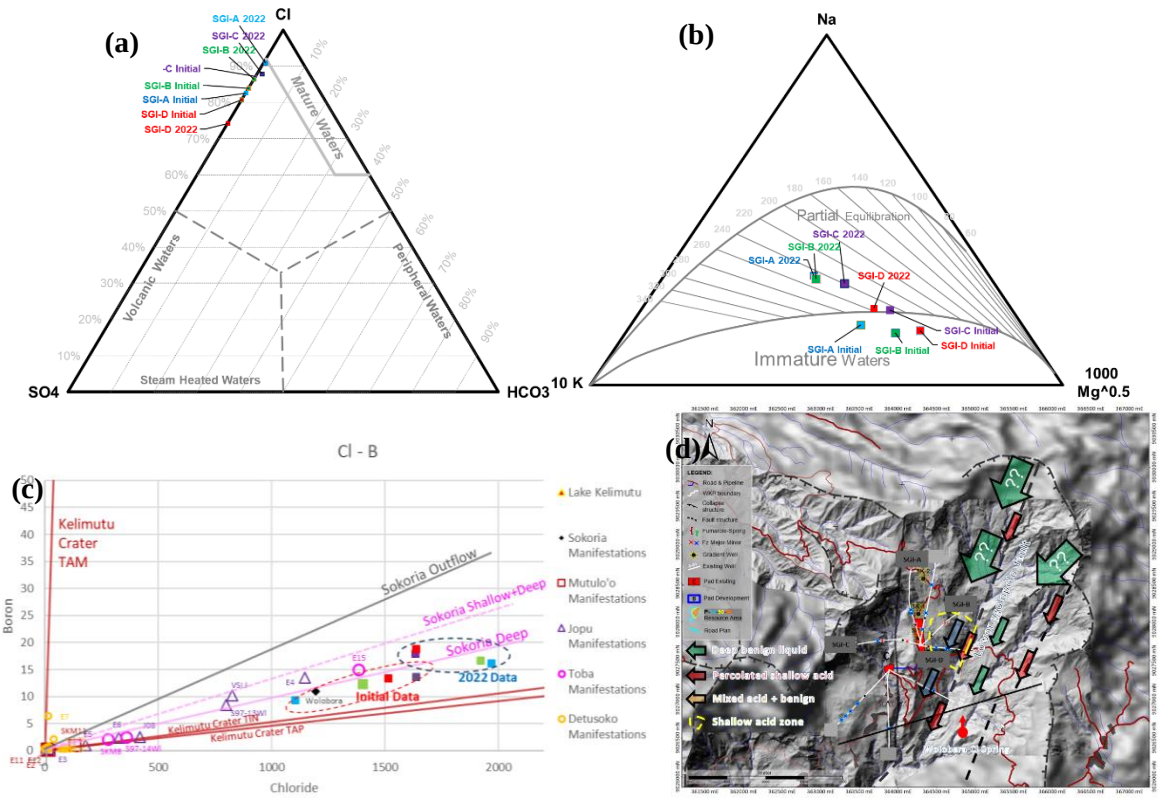


Figure 5: SO_4-Cl-HCO_3 ternary diagram (a), Na-K-Mg ternary diagram (b), Cl-B Cross Plot diagram (c), and Conceptual model of Fluid acid path way (d).

5. DISCUSSION

The heat extraction operations at Sokoria Geothermal have had a discernible impact on the reservoir fluid dynamics. Broadly, the trends observed indicate a positive transformation in fluid properties. Examining the SO_4-Cl-HCO_3 diagrams (Figure 5a), it becomes evident that the fluid chemistry of all wells has been evolving towards proximity to the Cl apex. This shift suggests a maturing fluid composition, with the exception of SGI-D, which appears to be trending towards a more volcanic water composition. Similarly, when analyzing the Na-K-Mg trends (Figure 5b) for all wells, they exhibit a notable improvement characterized by a shift towards partial equilibrium. However, it's worth noting that SGI-D experienced a less pronounced shift in comparison to the other wells. The Cl-B cross plot diagram (Figure 5c) reveals an enrichment of boron and chloride concentrations over time. This phenomenon is a natural response to reservoir fluid extraction and signifies that the deep reservoir is transitioning into a significant source of benign fluid production.

Geochemical monitoring has revealed a distinct anomaly in the behavior of SGI-D when compared to the other wells. Notably, SGI-D was drilled in a manner that traverses the Lowonggopolo fault, a geological feature interpreted as a pathway for shallow acid fluids (as depicted in Figure 5d). The presence of this shallow acid pathway is strongly supported by downhole sampling data. Remarkably, the shallowest downhole sampling point, located at approximately 1270 meters, exhibited the lowest pH in comparison to the other feed zones.

Daily pH monitoring data further confirms that the source of the acid fluid can be attributed to the Lowonggopolo fault. When both SGI-B and SGI-D wells are in simultaneous operation, it becomes evident that the well closest to the Lowonggopolo fault, SGI-D, predominantly produces acid fluid, while SGI-B produces only a minimal amount. This intriguing phenomenon results in the pH of SGI-B rising above the threshold of five, a departure from the norm observed in the other wells.

6. CONCLUSION

After one year of production, the reservoir's response indicates a notable transformation in the composition of the produced fluid, with the Lowonggopolo fault emerging as a significant contributor to this evolution. Wells located farther from the fault discharge deep benign reservoir fluid, while those in close proximity to the fault blend acid fluid from the fault with the benign fluid, resulting in the production of sub-neutral fluid.

All key brine properties are affected in these production fluid changes, reflecting a shift towards more mature water. The observed responses of the reservoir during one year of production are a natural manifestation of the behavior of a produced reservoir. This insight underscores the dynamic nature of geothermal reservoirs and the importance of ongoing monitoring and analysis for sustainable energy production.

REFERENCES

Sarmiento, Z. F., Sagala, B. and Siagian, H., The Sokoria Geothermal System, Flores Island, Indonesia. Geothermics 82, 282–295, (2019)

Siagian, H., Sanjaya, D., Sagala, B., Rafli, Jul.: Hydrothermal Alteration Mineralogy of Well Mtb A, Sokoria Geothermal Field, Flores, Indonesia, *Proceedings*, 6Th Indonesia International Geothermal Covention & Exhibition (2018)

Siagian, H., Sanjaya, D., Pradipta, R., Ferdinan, T., Triananda, W., Simamora, S.: Structure Characterization and Its Implication to Assets Development at Sokoria Geothermal Field, Flores, Indonesia, *Poster*, Indonesia International Geothermal Convention & Exhibition (2022)

Identification of Geothermal Potential in the Sangkar Oil and Gas Working Area Using Landsat-9 with a Gravity and Geomagnetic Approach

Dwandari Ralanarko[1], Fadhlur Rahman[2], Nanda Ridki Permana[3], Dhika Faiz Fadrian[2], Fardhan Rafshan Zani[2], Dennya Angeline[4], Muhammad Sulhan[5], and Hafid Rizki Nur Rohman[6]

[1]Pertamina Hulu Energi Offshore South East Sumatra (PHE OSES), Standart Chartered Tower, Prof. Dr. Satrio Street No. 164, Kuningan, South Jakarta, Indonesia, 12950
[2]GeoXplore, Indonesia Kincir Air Street, Pondok Manggis Block B6, Bojong Baru, Bojonggede, Bogor, West Java, Indonesia 16920
[3]PT Minelog Service Indonesia, Industrial Zone Taman Tekno BSD Blok G1 Sector XI Bumi Serpong Damai, South Tangerang, Banten, Indonesia 15314
[4]Department of Production and Industrial Technology, Sumatera Institute of Technology Lampung
[5]Faculty of Exploration and Production Technology, Pertamina University Jakarta
[6]Departement of Geophysical Engineering, Faculty of Mineral Technologies, Pembangunan Nasional "Veteran" University Yogyakarta

dwandari.ralanarko@pertamina.com

Keywords: Andesite Intrusion, Landsat-9, TOPEX, NOAA

ABSTRACT

The North East Java Basin area is an area that has considerable geothermal potential. However, the identification of geothermal potential in this area is still not maximized. Due to the lack of knowledge and data, in-situ investigation of geothermal potential has various disadvantages and significant risks in the early stages, and the expenses incurred are relatively expensive. Therefore, research is needed that can identify geothermal potential in this area more effectively and efficiently. This research will combine Landsat 9 satellite imagery, gravity, and magnetic data to identify geothermal potential in the North East Java Basin area. This research uses Landsat-9 satellite data recorded on February 12, 2023, TOPEX gravity data, and NOAA magnetic data. The application of these data is divided into several processes, for Landsat-9 satellite data, band ratio, and band composite are carried out to identify the distribution of rock alteration at the research site. Then, for TOPEX gravity data, 2D and 3D modeling processes are carried out to determine intrusive rocks' depth, density value, and shape. Meanwhile, the NOAA magnetic data was separated using reduce-to-pole magnetic to eliminate one pole so as not to cause ambiguity during interpretation. Based on the processing of Landsat-9 data, it is found that there is rock alteration in the study area caused by high CO2 levels. In the gravity processing of TOPEX data, it is found that there is a suspected andesite intrusion rock association around the sub-basin as the research target. The distribution of gravity field anomalies in the study area ranges from -4.859 - 6.176 mGal. Then, in the processing of NOAA magnetic data, it is found that the distribution of magnetic anomalies ranges from -3,705 - 4,752 nT at low susceptibility values dominated by sedimentary rocks while high anomaly values are thought to be associated with andesite intrusive rocks. After that, geophysical data correction and 2D and 3D inversion modeling were carried out with 7-section models that validated the previously obtained results that there were indeed andesite intrusive rocks in the eastern and western parts of the study area with an average depth of 1000-4000m.

1. INTRODUCTION

The North East Java Basin is an area with significant geothermal potential. However, the identification of geothermal potential in this area is still not maximized. Due to a lack of knowledge and data, in-situ exploration of geothermal potential has significant limitations and risks in the initial stages, and the expenses involved are relatively high (Witter et al., 2019). Remote sensing-based exploration would be more effective as it can reduce costs and hazards. Remote sensing can provide geological information that can be used as a basis for further regional investigations (Noorollahi et al., 2005).

Therefore, research is needed to identify the geothermal potential in this area more effectively and efficiently. This study will integrate Landsat 9 satellite imagery, gravity, and magnetic data to identify the geothermal potential in the North East Java Basin. Satellite imagery data can be used to characterize geological objects based on their ability to reflect and absorb electromagnetic waves on the Earth's surface, enabling the identification of intrusive rock locations. Gravity and magnetic data can be used to identify structures that control the geothermal system, such as faults and the distribution of rocks based on density contrasts (Huenges, 2010).

1.1. Regional Geology

1.1.1. Physiography

The research area is located in the northern part of East Java province, according to Van Bemmelen (1949) the northern part of East Java has a physiography in the form of the Northern Mountains Zone, the Rembang - Madura Zone, the Randublatung Depression Zone, and also the Kendeng Zone. The Northern Mountains Zone itself is composed of andesitic igneous rocks which are volcanic products of Mount Lasem and Mount Butak, as well as rocks from Mount Muria in the form of leucite rocks. In the Holocene Mount Muria was the only mountain in the area (standing alone), but at present Mount Muria is connected by an alluvial plain that stretches from Semarang - Demak - Kedu - Pati - Rembang. In the Rembang - Madura Hills Zone there are areas that have the intensity of anticline distribution or what we often call the anticlinorium area. The anticlinorium is located in the northern part (North Rembang), and also in the southern part (Cepu). The anticlinorium is separated by the Depression located at Blora - Kening, the anticlinorium is the result of tectonic movements in the late tertiary period that can be identified until the Madura Strait.

The next zone that is part of the Physiography of this research is the Randublatung Zone. At the Plistocene time, a west-east trending depression was formed, which caused the Randublatung Zone itself to be included in the physiographic depression zone as well as tectonic movements that stretched from the Kendeng Zone to the Rembang Zone and had the narrowest zone in the Cepu area and then widened eastward to the Madura Strait area. This zone is a syncline composed of several sedimentations so that there are several sedimentary rocks that are quite thick in the area. The last zone of the regional physiography of the study area is the Kendeng Zone where there is a fairly long anticlinorium, ranging from 200 - 250 kilometers, about 50 kilometers wide, and the height of this anticlinorium is about 500 meters. The Kendeng Zone covers several areas including Mount Ungaran to the east to the Mojokerto area, even after further exploration the area reaches Madura. This anticlinorium is not just a straight anticlinorium, there are several areas that prove that this anticlinorium is cut by the Solo River that runs from south to north. In the eastern part of the Kendeng Zone, Mount Pandan penetrates the Tertiary age strata. Starting from this area, all the large sizes gradually decrease, both in width and height to become lower and then the anticline disappears in the deposits of the Brantas delta in the Mojokerto area.

1.1.2. Structural Geology

Based on ONEMAP ESDM (2023) n the study area there are several structural patterns that develop, including active horizontal faults oriented southwest - northeast in the west, and Lasem horizontal faults oriented southwest - northeast in the western part of the study area that cut the Ngrayong Formation, Mundu Formation, Wonocolo Formation, Ledok Formation, Paciran Formation, and there is also a southwest - northeast oriented horizontal active fault, as well as a Tuban horizontal fault located in the eastern part of the study area that cuts the Tongue Formation, Mundu Formation, Ngrayong Formation, Wonocolo Formation, Paciran Formation, Mundu Formation. In addition to horizontal faults, the study area also contains 3 ascending faults that have a west-east orientation that cut the Ngrayong Formation, Tuban Formation, Mundu Formation, Paciran Formation, Ledok Formation, Bulu Formation, Wonocolo Formation. The existing faults in the study area can be characterized based on the development of anticlinorium areas that have a west-east to northwest-southeast orientation.

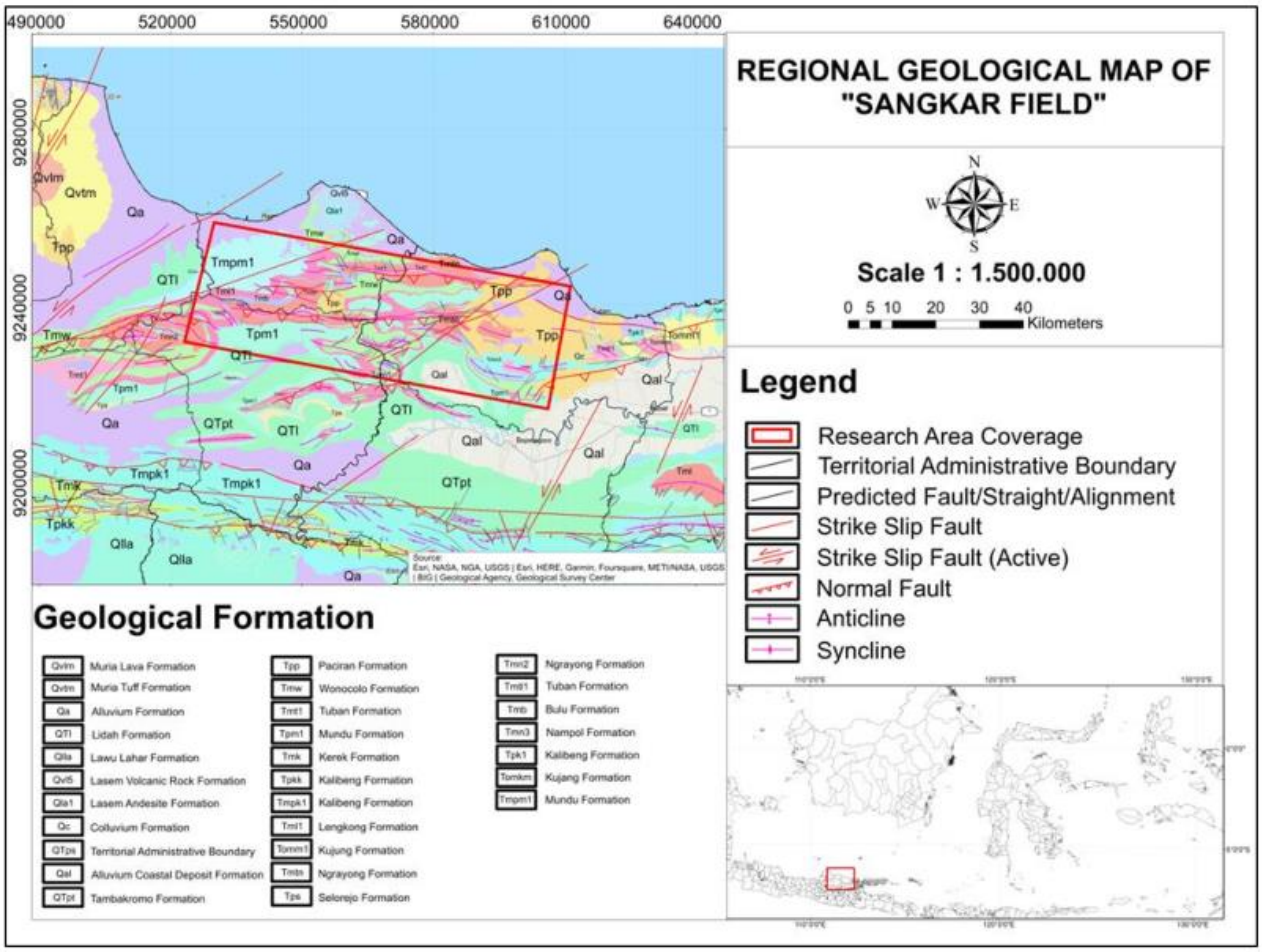


Figure 1: Regional Geological Map Of "Sangkar Field" (https://geoportal.esdm.go.id/emo/).

2. BASIC THEORY

2.1 Gravity

The gravity method is one of the geophysical exploration methods. This method is based on Newton's law, which states that there is an attractive force (F) between two objects with certain masses (m1 and m2) separated by a certain distance (r) (Telford et al., 1990). The equation for Newton's law is as follows:

$$F = G\frac{m_1 m_2}{r^2} \quad (1)$$

Where F represents the magnitude of the gravitational force measured in Newtons (N), G is the gravitational constant with a value of approximately 6.67 x 10^{-11} Nm^2/kg^2, m1 is the mass of the first object measured in kilograms (kg), and m2 is the mass of the second object measured in kilograms (kg) (Telford et al., 1990).

2.2. Geomagnetic

The geomagnetic method is a potential method in geophysical exploration. This method works by calculating the susceptibility values of rocks beneath the Earth's surface. The geomagnetic method can provide insights into the subsurface based on the magnetic characteristics or susceptibility of rocks (Saffarzadeh and Noorollahi, 2005; Duhri et al., 2019). The basic principle of the geomagnetic method follows Coulomb's law, with the equation as follows:

$$F = G\frac{p_1 p_2}{\mu_0 r^2}\hat{r} \quad (2)$$

With p1 and p2 representing the magnetic poles separated by a distance r (m), μ_0 is the permeability of free space (4π x 10^{-7} N/A^2), and $\hat{r}$ is the unit vector (Huenges, 2010; Permana et al., 2022).

2.3. Landsat 9

Altered rocks are one of the manifestations of geothermal activity. There are three types of alterations: mineral replacement, filling of space, and rock dissolution (Browne, 1998; Utami, 2015). The presence of altered rocks is caused by the interaction between geothermal fluids and the rocks they pass through. The presence of altered rocks can be an indication for mapping geothermal potential, especially in areas surrounding manifestations that indicate the presence of an active geothermal system (Van Bemmelen, 1949; Browne, 1970).

One way to obtain information about the Earth's surface and subsurface conditions is by using data obtained from satellites orbiting in space. An example of a satellite used in geophysical exploration is Landsat 9, which is a continuation of NASA's Landsat program, previously represented by Landsat 8. Landsat 9 will continue the data processing system based on established data collection and distribution strategies by the USGS (Kementrian ESDM, 2017; Masek, 2020).

Landsat 9 can assist in identifying altered rocks because different objects on the Earth's surface have varying reflectance characteristics, including the minerals resulting from hydrothermal alteration, which also exhibit different reflectance characteristics. Therefore, the distribution of alteration minerals in an area can be detected using Landsat 9 imagery. This can help determine regions with high potential for geothermal activity. Through initial surveys using remote sensing applications, the distribution of hydrothermal alteration minerals, which are often associated with the presence of geothermal manifestations, can be observed (Telford et al., 1990; Pratama et al., 2020).

2.4. Inversion Method

In geophysical exploration, the inversion method is a mathematical or statistical approach. This method takes observed data and directly generates a model or reconstruction based on that data. The main objective of the inversion method is to obtain physical information that was previously unknown or not directly visible through the available observation data. (Duhri et al., 2019; Octavia et al., 2021).

2.5. Geothermal

In general, geothermal energy, also known as heat from the Earth, originates from the Latin root’s 'geo' meaning earth and 'thermal' meaning heat. Geothermal energy can be defined as the natural heat generated beneath the Earth's surface. Geothermal energy can be understood as the amount of heat stored within the Earth, forming the geothermal system that has existed since the formation of the Earth. The geothermal system includes the water system, hydrothermal system, heating processes, and the conditions where hot water accumulates, thus encompassing the availability of water, heating of rocks, rock reservoirs, shallow soil layers, and other requirements.

Geothermal resources are generally associated with mechanisms of magma formation and volcanic activity. High-temperature geothermal systems are typically found along volcanic belts, continental ridges, and in subduction zones and intraplate melting anomalies, such as in Indonesia. Moving plate boundaries are central sites for the formation of hydrothermal magmatic systems. The conductive transfer of heat energy in the tectonic plate environment is enhanced by the movement of magma and hydrothermal circulation. The main requirements for the formation of a geothermal system consist of a large heat source, heat reservoirs, and heat-bearing rocks. In this hydrothermal system, heat is transferred through conduction and convection. Conduction occurs through rocks, while convective heat transfer occurs at the contact between water and the heat source. Convection heat transfer is inherently driven by buoyancy. Water always tends to move downward due to gravity, but when water touches the heat source, heat transfer occurs, raising the water temperature and making it lighter. This condition causes hot water to flow upward and cooler water to flow downward, creating a circulation or convection of water (Permana et al., 2022; Anshory, 2010).

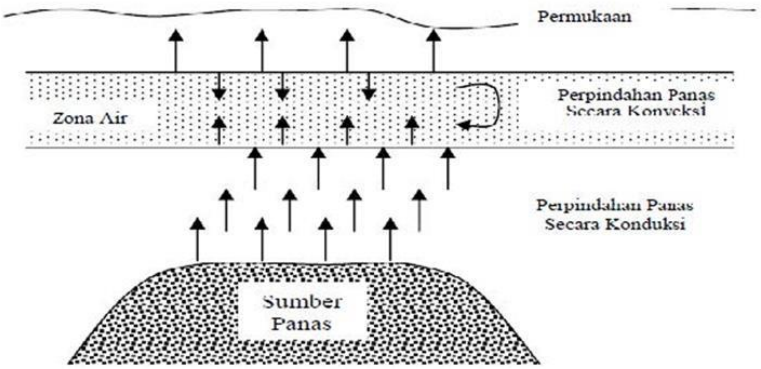


Figure 2: Geothermal System (Browne, 1970).

3. METHODOLOGY

This study utilizes satellite imagery data. The Landsat-9 data was obtained from the USGS website, recorded on February 12, 2023, consisting of bands 2, 4, 5, 6, and 7. Band ratio processes were conducted on bands 4/2 and 6/7, followed by band compositing (4/2, 6/7, and 5) to identify the distribution of rock alterations in the research area.

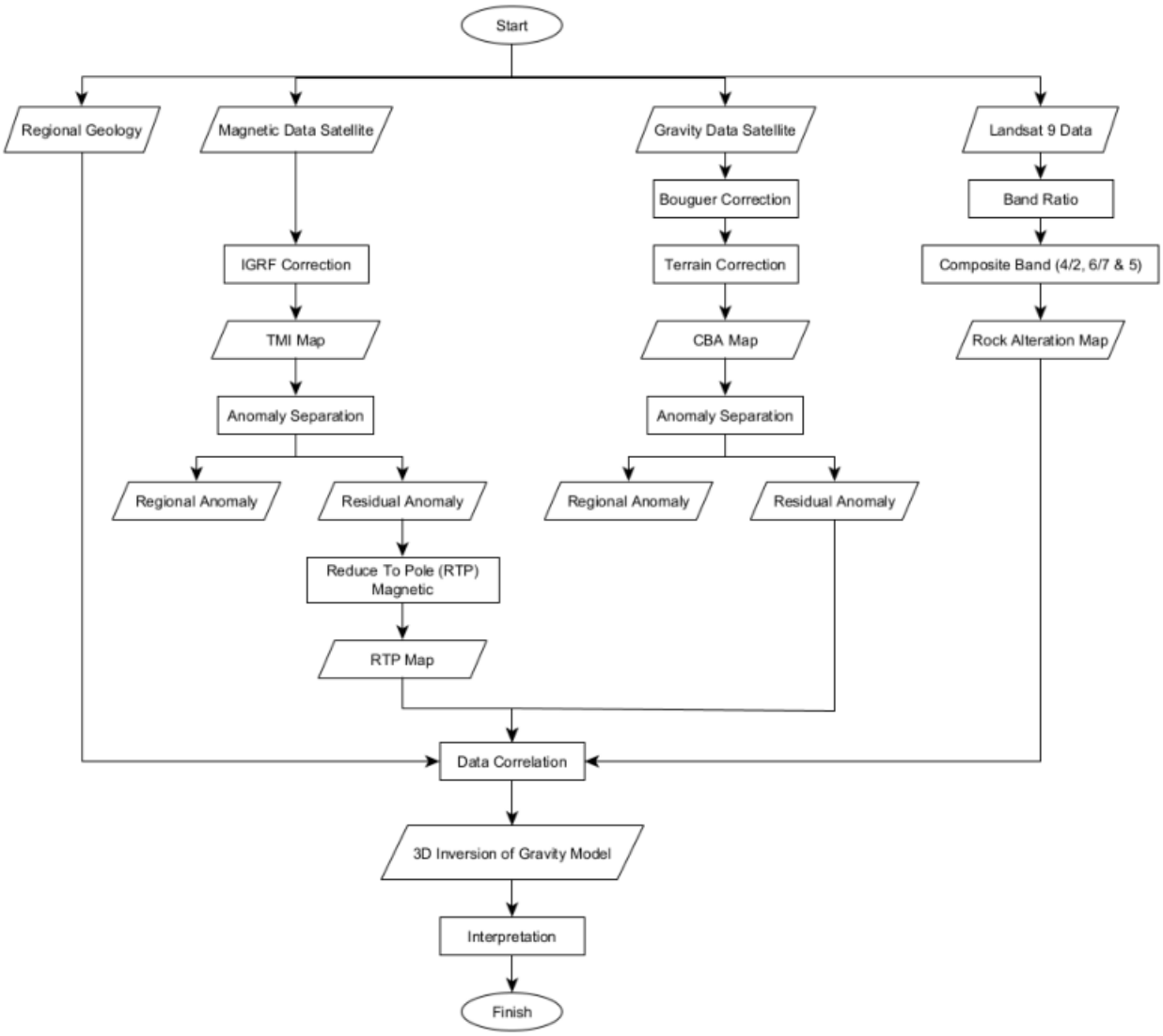


Figure 3: Research Flowchart.

Next, gravity data was collected from the TOPEX website, consisting of 705 data points of Free Air Anomaly (FAA) and topography. Bouguer correction and terrain correction processes were applied to obtain the Complete Bouguer Anomaly (CBA). Then, anomaly separation was performed using a bandpass filter to obtain the residual anomaly. Inversion modeling was carried out in 2D and 3D to assess the depth, density values, and shape of intrusive rocks.

Furthermore, magnetic data was collected from NOAA, comprising 2197 magnetic readings at the research location. The International Geomagnetic Reference Field (IGRF) correction was applied to obtain the total magnetic anomaly. The anomaly was then separated using a bandpass filter to obtain the residual anomaly. To eliminate high ambiguity during interpretation, the residual anomaly, which still exhibited dipole magnetic characteristics, underwent a reduce-to-pole magnetic process to remove one pole.

4. RESULT

4.1. Composite Band (4/2, 6/7 & 5) Landsat 9

In the band composite (4/2, 6/7 & 5) of Landsat 9, a rock alteration map was generated for the research area. In the map below, several color variations resulting from the band composite can be observed. The red and purple colors are likely indicative of settlements and drainage systems. The light green and turquoise colors are indicative of vegetation distribution in the research area. The gold color (white polygon) represents the research target, which is the scattered rock alterations in the eastern, central, and western parts of the research area. It is suspected that these rock alterations contribute to the high CO2 content in the generated hydrocarbons (Figure 4).

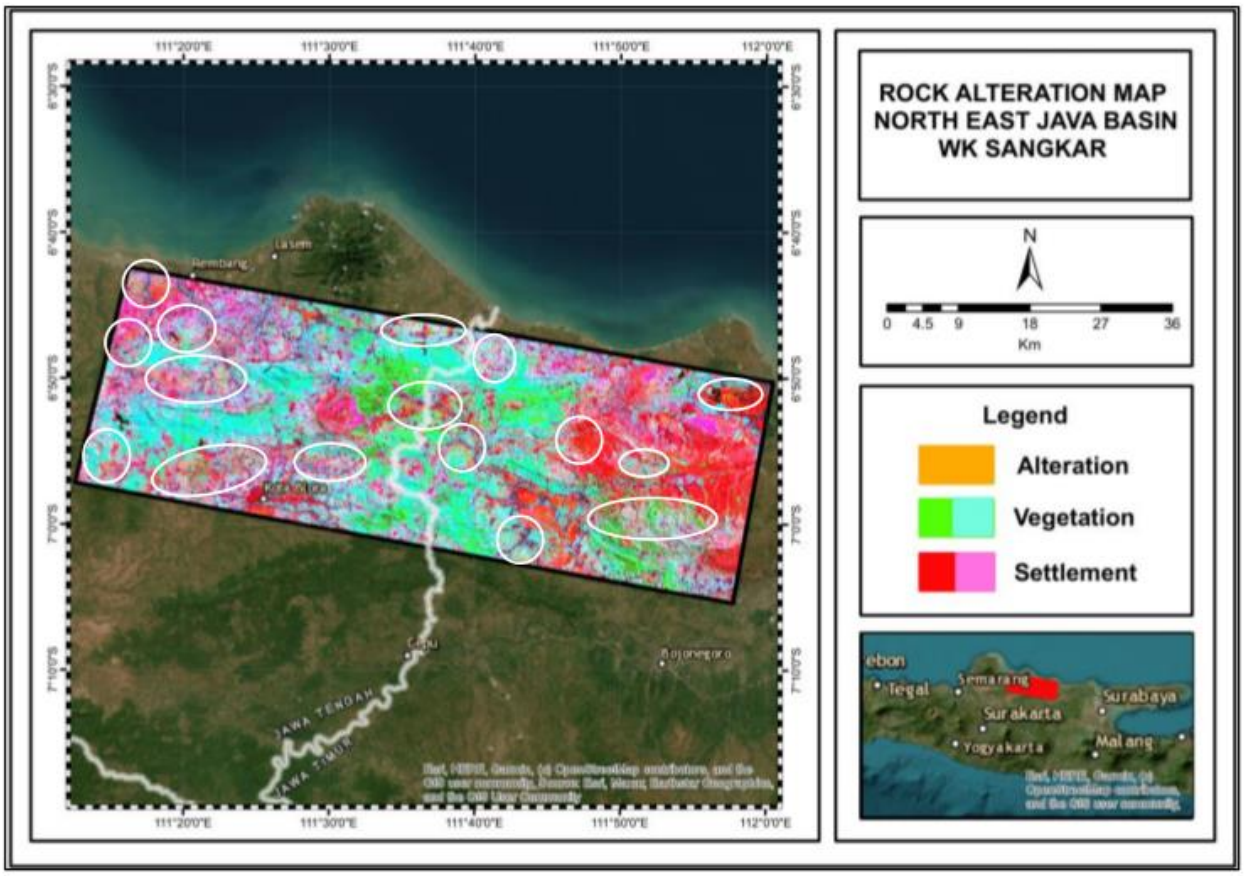


Figure 4: Rock Alteration Map North East Java Basin WK Sangkar.

4.4. Residual Gravity Map

In the gravity data results of the research area, after several corrections and anomaly separations, a map of residual anomalies was obtained. In the residual anomaly map, the distribution of gravity field anomalies in the research area ranges from -4.859 to 6.176 mGal. Low gravity anomalies in the research area range from -4.859 to -2.252 mGal and are evenly distributed in the central part of the research area. These low anomalies are suspected to be associated with sub-basins dominated by sedimentary rocks. High gravity anomalies in the research area range from 3.949 to 6.176 mGal and are scattered in the eastern, central, and western parts of the research area. These high anomalies (white polygon) are suspected to be associated with andesite intrusive rocks located around the sub-basins, which serve as the research target (Figure 5).

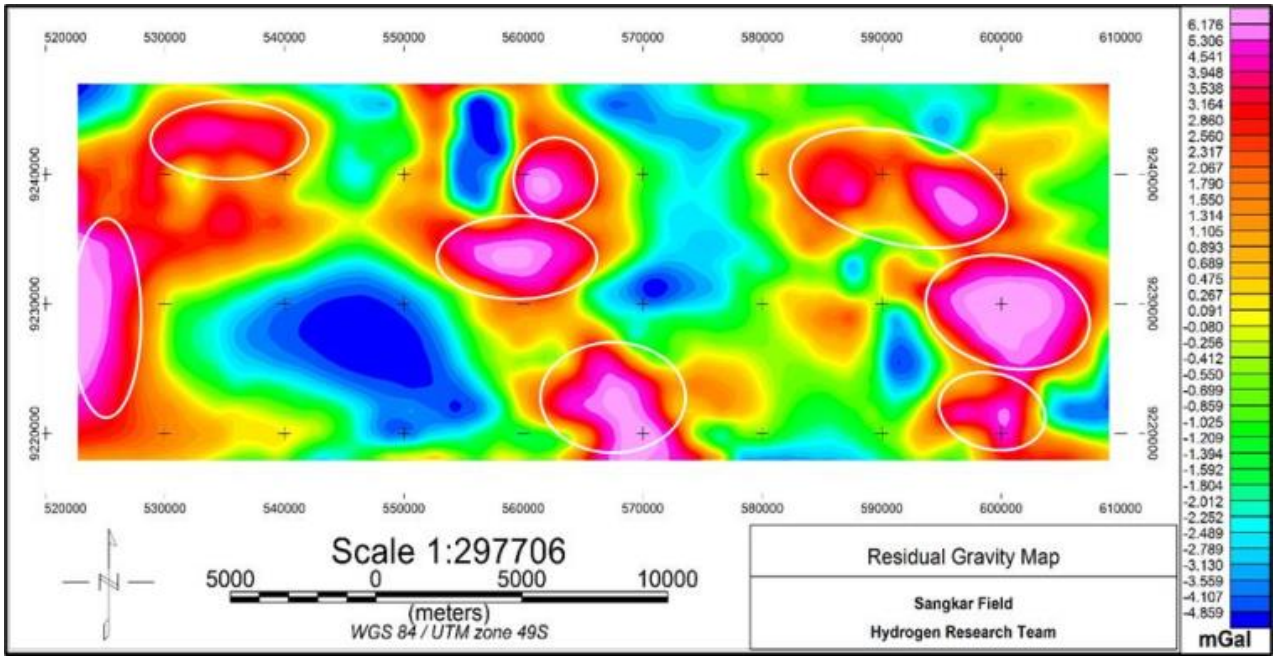


Figure 5: Residual Gravity Map.

4.3. Reduce To Pole (RTP) Magnetic Map

In the magnetic data results of the research area, after several corrections and anomaly separations, a map of residual anomalies was obtained. Subsequently, a pole reduction process was conducted to eliminate the two poles present in the residual anomaly map, as they can lead to high ambiguity during further interpretation. In the pole reduction map, the distribution of magnetic field anomalies in the research area ranges from -3.705 to 4.752 nT. Low magnetic field anomalies in the research area range from -3.705 to -1.007 nT and are evenly distributed throughout most of the research area. These low anomalies are suspected to be associated with subbasins dominated by sedimentary rocks, which have low magnetic susceptibility values. High magnetic field anomalies in the research area range from 2.861 to 4.752 nT and are scattered in a small western portion and predominantly in the far western part of the research area. These high anomalies (blue polygon) are suspected to be associated with andesite intrusive rocks located around the sub-basins, serving as the research target (Figure 6).

4.4. Correlation of Geophysical Data Results

After obtaining the inferred areas of intrusion and alteration using the three aforementioned methods, a correlation and overlap analysis was conducted to generate a zoning map of intrusion zones in the research area. This map was further examined to assess the depth and shape of the intrusive rocks as potential geothermal resources through 2D and 3D inversion modeling (Figure 7(a), (b), (c)).

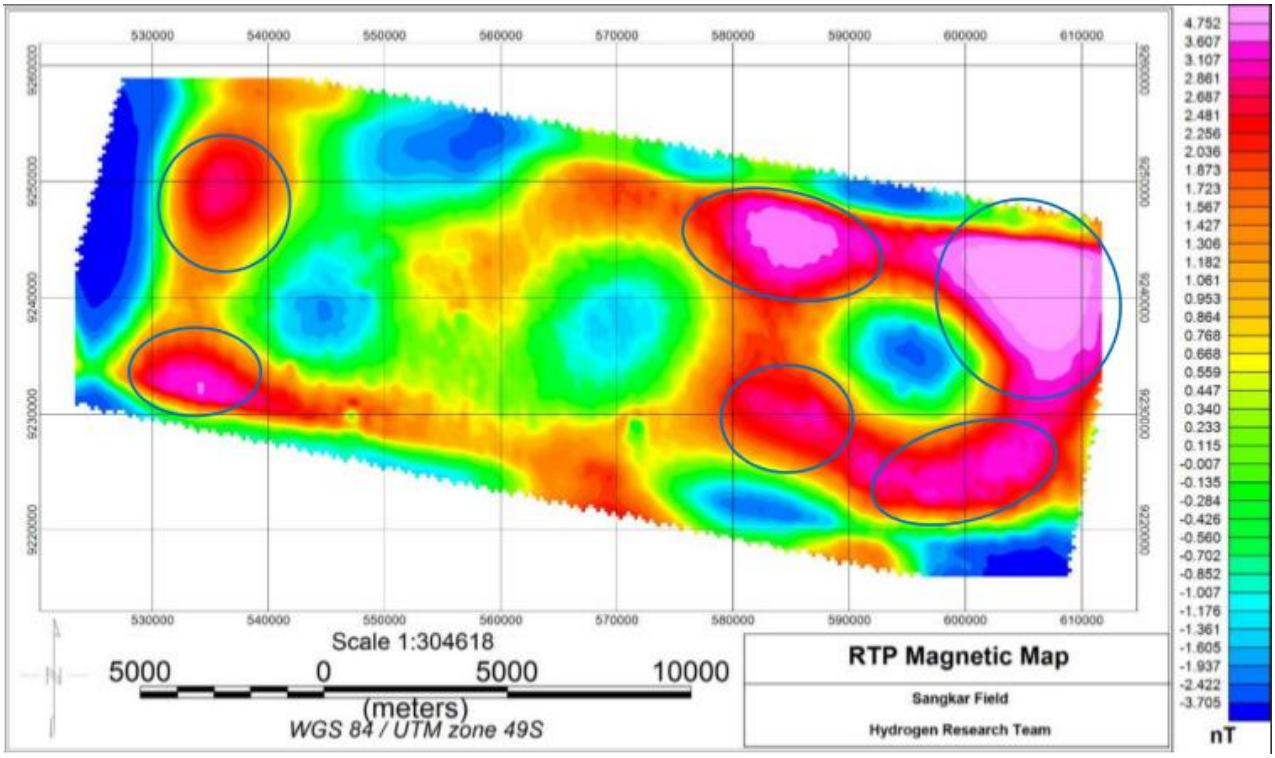
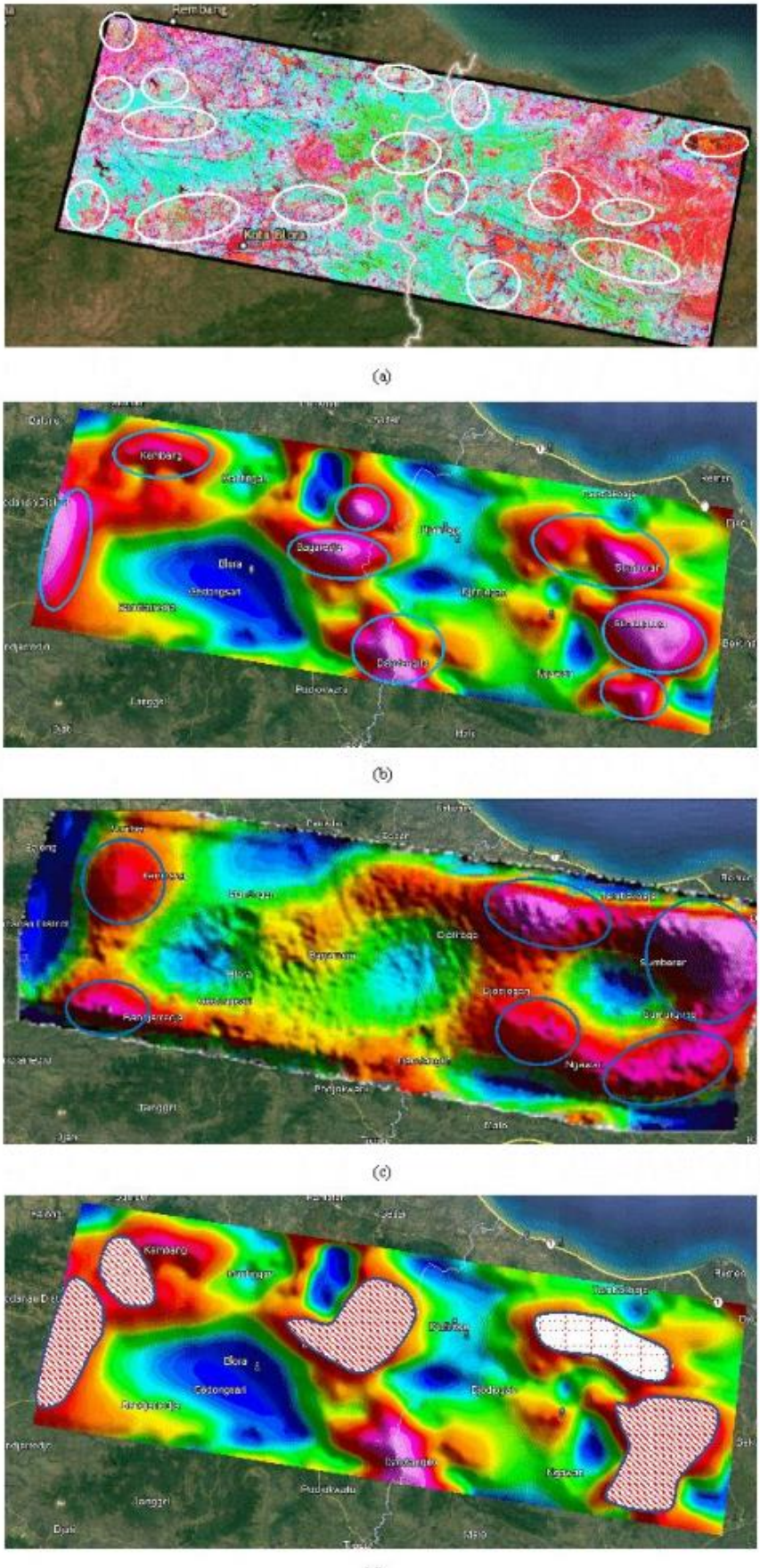


Figure 6: RTP Magnetic Map.

4.5. 2D and 3D Inversion Models

After correlating the results from the three methods, the next step involved conducting 2D and 3D inversion modeling on the residual gravity map to visualize the subsurface intrusive rocks based on density parameters as an indication of geothermal potential. In the 2D inversion models, seven cross-sectional models were created in a north-south direction.

In the A-A' cross-sectional model, it can be observed that the andesite intrusive rocks are located at depths ranging from 1000 to 4000 m, predominantly in the northern and southern parts of the research area, with density values ranging from 2.5 to 3 g/cc (Figure 8(a)). In the B-B' cross-sectional model, the andesite intrusive rocks are observed at depths ranging from 800 to 4000 m, with density values ranging from 2.5 to 3 g/cc (Figure 8(b)). In the C-C' cross-sectional model, the andesite intrusive rocks are observed at depths ranging from 500 to 4000 m, with density values ranging from 2.5 to 3 g/cc (Figure 8(c)). In the D-D' cross-sectional model, the andesite intrusive rocks are observed at depths ranging from 1000 to 4000 m, predominantly in the northern and central parts of the research area, with density values ranging from 2.5 to 3 g/cc (Figure 8(d)). In the E-E' cross-sectional model, the andesite intrusive rocks are observed at depths ranging from 1000 to 4000 m, predominantly in the northern and southern parts of the research area, with density values ranging from 2.5 to 3 g/cc (Figure 8(e)). In the F-F' cross-sectional model, the andesite intrusive rocks are observed at depths ranging from 1000 to 4000 m, predominantly in the northern and southern parts of the research area, with density values ranging from 2.5 to 3 g/cc (Figure 8(f)). In the G-G' cross-sectional model, the andesite intrusive rocks are observed at depths ranging from 800 to 4000 m, with density values ranging from 2.5 to 3 g/cc (Figure 8(g)).



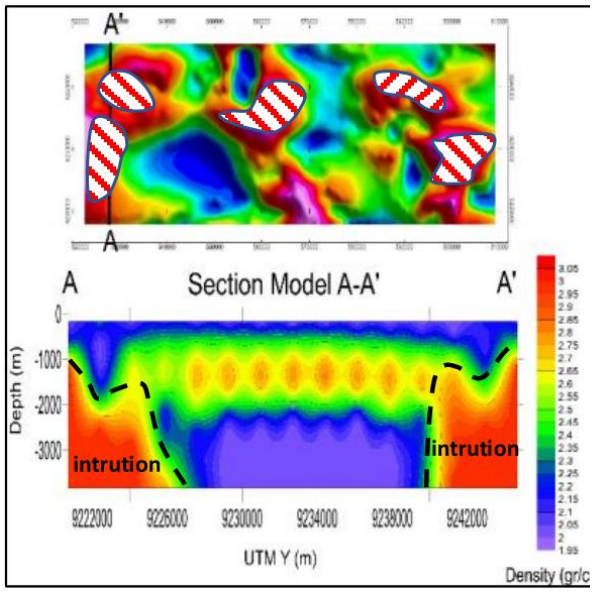
(a)

(b)

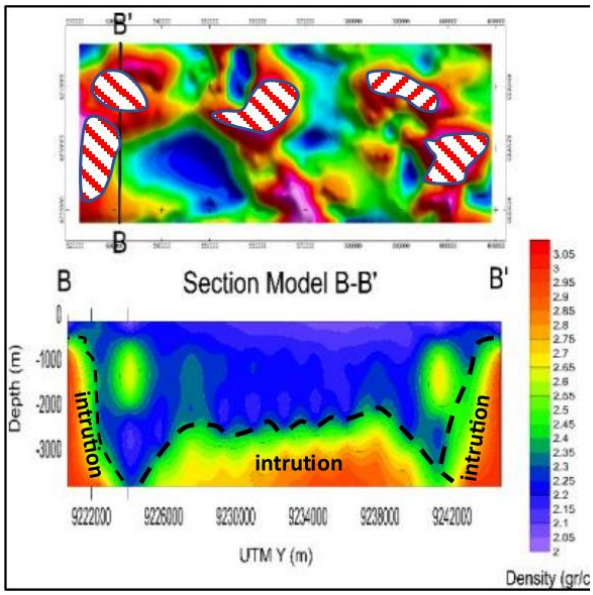
(c)

(d)

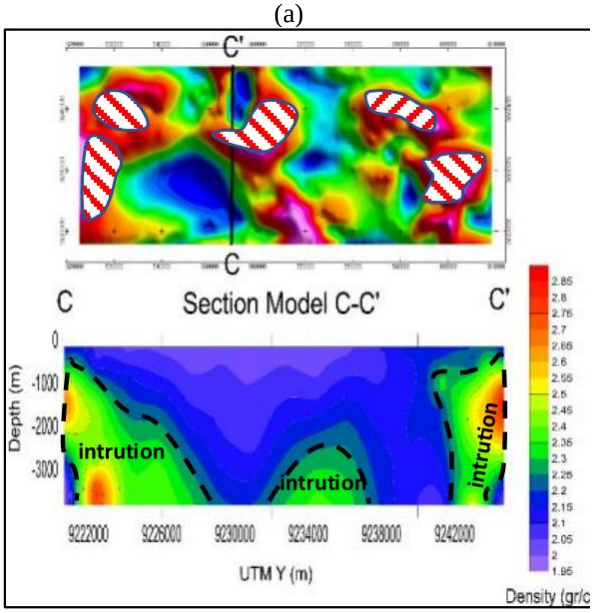
Figure 7: Correlation of Geophysical Data Results.


A'
A
A
Section Model A-A'
A'
Depth (m)
0
-1000
-2000
-3000
intrution
intrution
9222000
9226000
9230000
9234000
9238000
9242000
UTM Y (m)
Density (gr/c

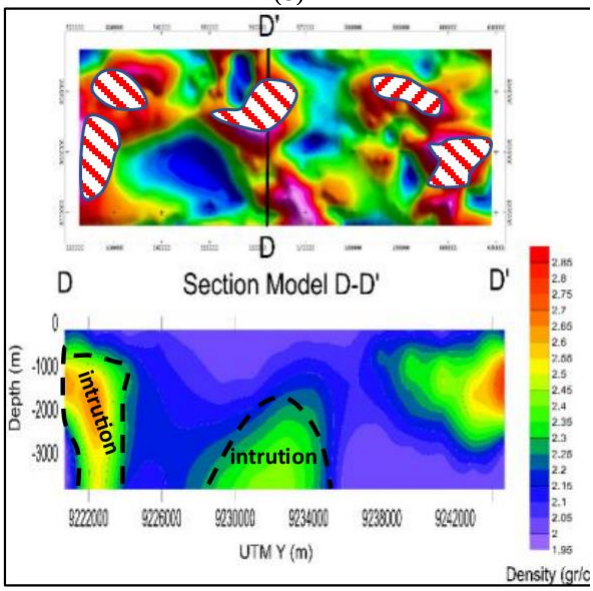
(a)


B'
B
B
Section Model B-B'
B'
Depth (m)
0
-1000
-2000
-3000
intrution
intrution
intrution
9222000
9226000
9230000
9234000
9238000
9242000
UTM Y (m)
Density (gr/c

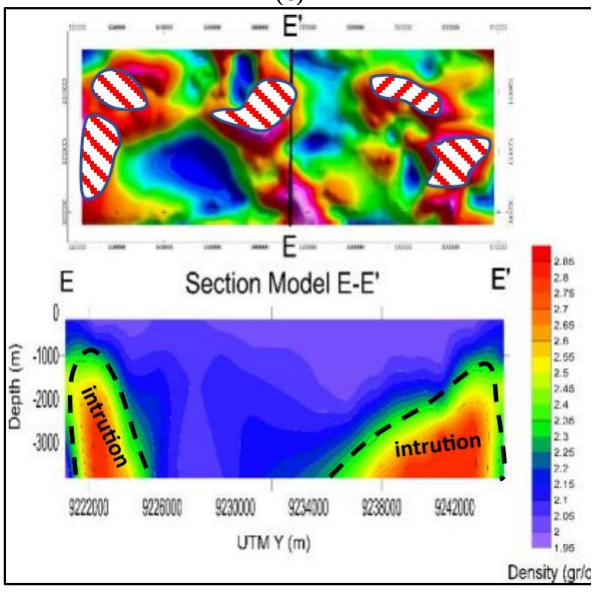
(b)


C'
C
C
Section Model C-C'
C'
Depth (m)
0
-1000
-2000
-3000
intrution
intrution
intrution
9222000
9226000
9230000
9234000
9238000
9242000
UTM Y (m)
Density (gr/c

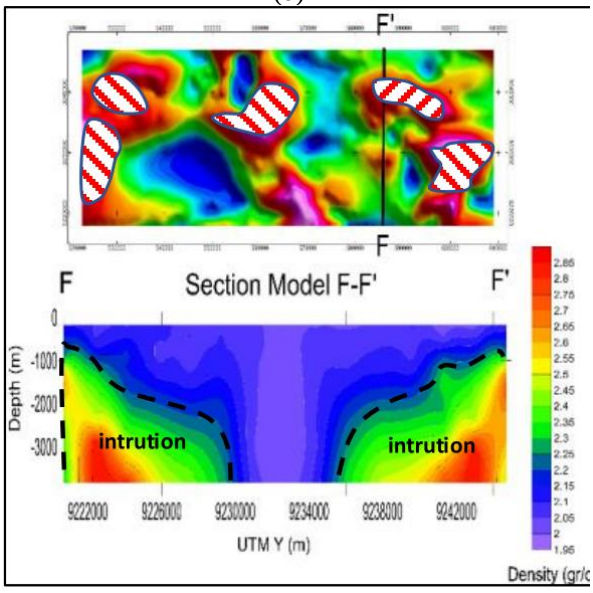
(c)


D'
D
D
Section Model D-D'
D'
Depth (m)
0
-1000
-2000
-3000
intrution
intrution
9222000
9226000
9230000
9234000
9238000
9242000
UTM Y (m)
Density (gr/c

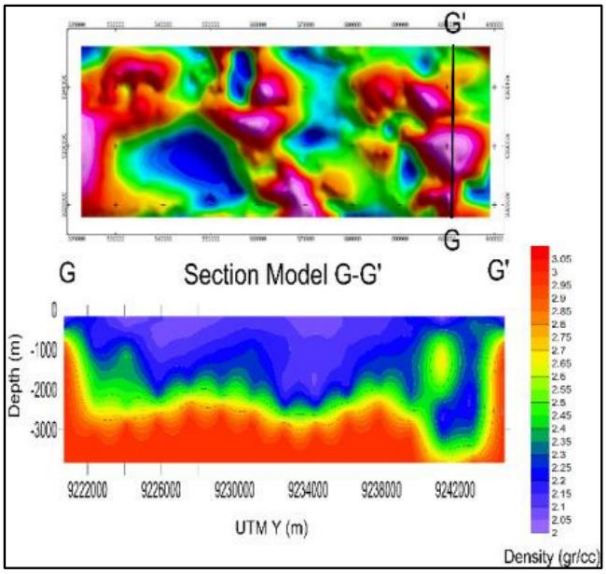
(d)


E'
E
E
Section Model E-E'
E'
Depth (m)
0
-1000
-2000
-3000
intrution
intrution
9222000
9226000
9230000
9234000
9238000
9242000
UTM Y (m)
Density (gr/c

(e)


F'
F
F
Section Model F-F'
F'
Depth (m)
0
-1000
-2000
-3000
intrution
intrution
9222000
9226000
9230000
9234000
9238000
9242000
UTM Y (m)
Density (gr/c

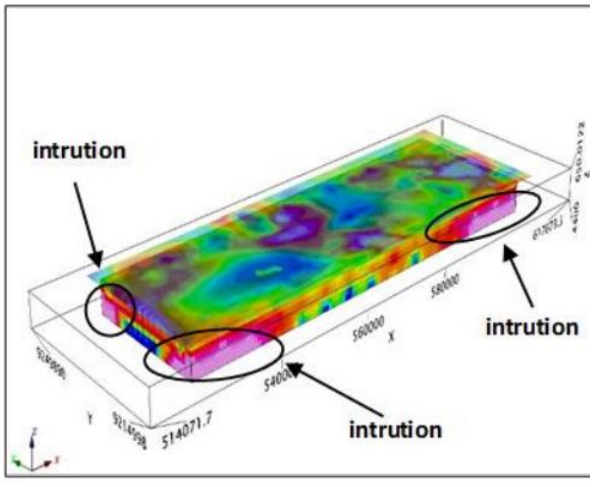
(f)



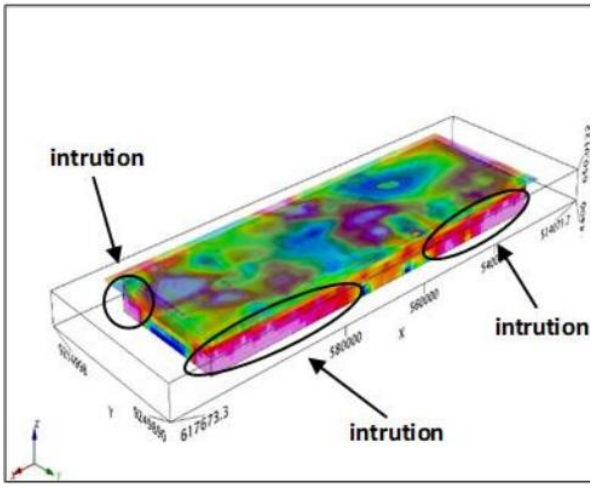
(g)

Figure 8: Section Model A-A' (a), Section Model B-B' (b), Section Model C-C' (c), Section Model D-D' (d), Section Model E-E' (e), Section Model F-F' (f), Section Model G-G' (g) of Residual Map.

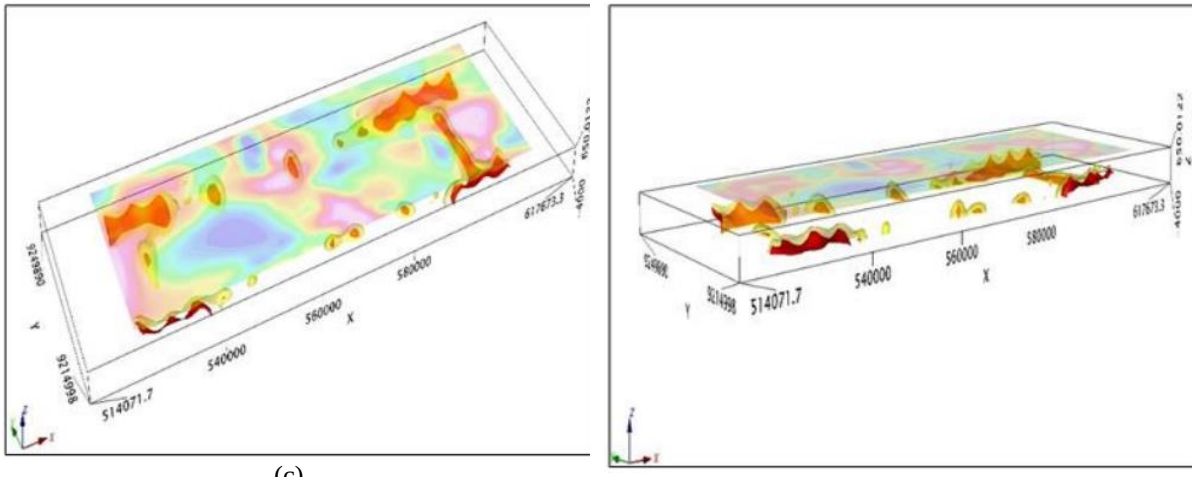
After conducting the 2D section modeling, a 3D modeling was performed to visualize the distribution of andesite intrusive rocks in a three-dimensional representation. It is evident that the intrusions are predominantly scattered in the eastern and western parts of the research area (Figure 9(a), (b)). Subsequently, isosurfaces were generated at density values of 2.7 g/cc and 2.9 g/cc to observe the shape and distribution of the subsurface andesite intrusive rocks. It can be observed that the andesite intrusions are dominantly scattered in the eastern and western parts of the research area, with an average depth ranging from 1000 to 4000 m (Figure 9(c), (d)).



(a)



(b)



(c) (d)

Figure 9: Model 3D Gravity (a) Southwest View, (b) Northeast View, Intrusion Rock Model (c) Top View, (d) Southwest View.

5. CONCLUSION

Based on Result and Discussion we can get a conclusion as it follows:

1. Based on Rock Alteration Map it shows that the gold color (white polygon) represents the research target, which is the scattered rock alterations in the eastern, central, and western parts of the research area. It is suspected that these rock alterations contribute to the high CO2 content in the generated hydrocarbons.

2. The Gravity result shows that in residual map shows the distribution of gravity field anomalies in the research area ranges from -4.859 to 6.176 mGal. Low gravity anomalies in the research area range from -4.859 to -2.252 mGal and are evenly distributed in the central part of the research area. These low anomalies are suspected to be associated with sub-basins dominated by sedimentary rocks. High gravity anomalies in the research area range from 3.949 to 6.176 mGal and are scattered in the eastern, central, and western parts of the research area. These high anomalies (white polygon) are suspected to be associated with andesite intrusive rocks located around the sub-basins, which serve as the research target. This result is reinforced with magnetic anomaly result

3. Magnetic result shows that in Reduce to Pole (RTP) map shows the distribution of magnetic field anomalies in the research area ranges from -3.705 to 4.752 nT. Low magnetic field anomalies in the research area range from -3.705 to -1.007 nT and are evenly distributed throughout most of the research area. These low anomalies are suspected to be associated with sub-basins dominated by sedimentary rocks, which have low magnetic susceptibility values. High magnetic field anomalies in the research area range from 2.861 to 4.752 nT and are scattered in a small western portion and predominantly in the far western part of the research area. These high anomalies (blue polygon) are suspected to be associated with andesite intrusive rocks located around the sub-basins, serving as the research target. This resulted correlated with the gravity and shows a good correlation between each other's

4. 2-D Inversion Gravity Modelling Results between A-A' to G-G' shows that the andesite intrusive rocks are located at depths ranging from 500 – 4000 m in the northen and southern part of research area. This Modelling is reinforced with 3-D Modelling isosurface that shows that the andesite intrusions are dominantly scattered in the eastern and western parts of the research area, with an average depth ranging from 1000 to 4000 m

6. RECOMMENDATION

Based on the results and conclusion. The writers want to recommend making a Sangkar field to become a Probability of Discovery (POB) of the Geothermal field. This recommendation is made because we predict the oil well can't always produce. So, in the further plan, the Sangkar Field can be the POB Field of Geothermal.

REFERENCES

Amirhomayoun Saffarzadeh and Younes Noorollahi. 2005. Geothermal Development in Iran: A Country Update. Proceedings World Geothermal Congress 2005 Antalya, Turkey, 24-29 April 2005

Browne, P. R. L., 1970, Hydrothermal Minerals as an Aid in Investigating Geothermal Field. Journal of Geothermics, 2 (1), pp 564 – 570. Browne, P. R. L., 1998, Hydrothermal Alteration, Geothermal Institute, The University of Auckland.

Duhri, N.I,m et.al. 2019. Identifikasi Material Bawah Permukaan Kecamatan Bontocani Kabupaten Bone Menggunakan Metode Geomagnet. Jurnal Sains dan Pendidikan Fisika (JSPF), Jilid 15 No. 2, Hal: 76-83.

H. Al Anshory, Pemodelan Sistem Geothermal Daerah X Menggunakan Metode Magnetotelluric. Pp. 1–71. 2010.

Huenges, E. 2010 Geothermal Energy Systems: Exploration, Development, and Utilization. Wiley-VCH, Weinheim.

Jeffrey B. Witter, Whitney J. Trainor-Guitton, Drew L. Siler 2019, Uncertainty and risk evaluation during the exploration stage of geothermal development: A review, Geothermics, Volume 78, 2019, Pages 233-242

Kementrian ESDM. 2017. ESDM ONE MAP

Masek. 2020. Landsat 9: Empowering Open Science and Applications Through Continuity. Jurnal E l Remote Sensing Environment.

Melani, Octavia., et.al. 2021. Penerapan Metode Inversi Dalam Pendugaan Nilai Resistivitas. Jurnal Teknika Sains, Vol. 6 No. 2.

Permana, N., Gunawan, B., Primastika, A., Shafa, D., Fadrian, D., & Zani, F. 2022. Identification of alteration zone and gold mineralization based on magnetic anomaly and 3D model of geomagnetic satellite data inversion of Mount Pongkor Area, West Java. Journal of Natural Sciences and Mathematics Research, 8(2), 94-102. doi:https://doi.org/10.21580/jnsmr.2022.8.2.13177

Telford, W. M., Geldart, L. P. & Sheriff, R. E. 1990. Applied geophysics. Cambridge, UK: Cambridge University Press

Van Bemmelen, R.W. 1949. General Geology of Indonesia and Adjacent Archipelagoes. In van Bemmelen (Ed.), The Geology of Indonesia. The Haque Martinus Nijhoff.

Yusuf Arico Pratama., Rifaldy., Anggun Mutika. 2020. Identifikasi Alterasi Hidrotermal Menggunakan Citra Landsat 8 Oli/Tirs: Studi Kasus Gunung Patuha, Kabupaten Bandung, Jawa Barat. BULLETIN OF GEOLOGY, VOL. 5, NO. 1, 2021, DOI: 10.5614/bull.geol.2021.5.1.3.

Identification of Geothermal System Based on 3D Inversion Gravity, Land Surface Temperature, and Landsat 9 at Cubadak - Panti, Pasaman, West Sumatera

Muhammad Wildi Nurul 'ilmi[1], Fadhlur Rahman[2], Fardhan Rafshan Zani[2], Ferdian Budi ar-rouf[3], Dhika Faiz Fadrian[2], and Baiq Yola Wahyu Febryanty[4]

[1]Pertamina University, Geophysical Engineering, Standard Chartered Tower,
Teuku Nyak Arief Street, RT.7/RW.8, Simprug,
Kec. Kby. Lama, Kota Jakarta Selatan, Daerah Khusus Ibukota Jakarta 12220
[2]GeoXplore, Indonesia Kincir Air Street, Pondok Manggis Block B6, Bojong Baru, Bojonggede,
Bogor, West Java, Indonesia 16920
[3]Padjajaran University, Geological Engineering, Bandung Sumedang Street KM 21, Jatinangor 45363.
[4]UPN "Veteran" Yogyakarta, Geophysical Engineering, Padjajaran Street No. 104 (Ringroad Utara) Condong Catur, Sleman, Daerah Istimewa Yogyakarta, Indonesia 55283

muhammadwildinurulilmi@gmail.com

Keywords: Gravity, Landsat-9, GGMPlus, Geothermal, Cubadak

ABSTRACT

Indonesia is located at the confluence of three tectonic plates. In addition, the geological conditions through which many volcanoes pass make the potential for geothermal energy in Indonesia quite large. Indonesia alone has 299 geothermal prospects scattered along volcanic lines, which have a potential of 29 GWe (about 40% of all world reserves). Based on data from PSDG in 2009, geothermal potential areas are scattered in 265 locations with an estimated potential of around 28.1 GWe. To face the energy crisis that will occur in the future, a solution is needed to overcome dependence on fossil fuels, one of which is renewable energy, namely geothermal energy. One area that shows indications of a potential geothermal energy source is the Cubadak and Panti area, Pasaman, West Sumatra. This research was conducted in May 2023 which aims to identify geothermal systems and map the temperature and mineral alteration of the study area. The data used are gravity anomaly data from the Bureau Gravimetrique International website, GGMPlus and Landsat 9 data from USGS Earth Explorer totaling 13906 data. The gravity anomaly data is subjected to Bouguer correction, free air correction, and terrain correction to obtain Complete Bouguer Anomaly (CBA) data. Meanwhile, the Landsat 9 data was subjected to a raster calculator to obtain composite bands corresponding to temperature and alteration. The Digital Elevation Model (DEM) map shows that the study area is located in a green to orange medium plain area ranging from about 466.1 - 885.2 meters. This indicates the presence of a fault that is reinforced by the presence of a dip in the northwest - southeast direction on the regional anomaly map and a low anomaly in the middle of a high anomaly that indicates a graben structure on the residual anomaly map. The results of 3D inversion modelling show the presence of Cap Rock in the form of volcanic and pyroclastic layer rocks rich in clay minerals with a depth range of 100 - 1400 meters in the eastern manifestation and 50 - 450 meters in the western manifestation with a density value range of 2.843 – 2.893 g/cm3. There are also reservoirs in the form of slate rocks and granite intrusive with a depth of 800 - 1800 meters in the eastern manifestation and 450 - 700 meters in the western manifestation and a density value range of 2.843 – 2.793 g/cm3.

1. INTRODUCTION

Indonesia is located at the confluence of three tectonic plates and is in the Ring of Fire. This makes the geological conditions through which Indonesia passes have many volcanoes as many as 117 spread throughout Indonesia and produce geothermal energy potential in Indonesia is quite large. Indonesia alone has 299 geothermal prospects scattered along volcanic lines, which have a potential of 29 GWe (about 40% of all world reserves). However, only about 7.2% of the potential is utilized as electrical energy in the country. Indonesia has the largest geothermal energy potential in the world, accounting for about 40% of the world's potential. The Indonesian government continues to increase the mix of geothermal power generation with a target of 7.2 GW by 2025, and 17.6 GW by 2050 (Gunawan et al., 2021). To deal with the energy crisis that will occur in the future, solutions are needed to overcome

dependence on fossil fuels, one of the solutions is by exploring geothermal energy again in unreached or remote areas. One area that shows indications of a potential geothermal energy source is the Cubadak and Panti area, West Sumatra. Based on 2017 data, the Cubadak and Panti geothermal areas have a total geothermal potential of 95 Mwe (Kementrian ESDM, 2017).

The Cubadak - Panti geothermal potential research area is located in Pasaman Regency, West Sumatra with different sub-districts. Cubadak geothermal potential is located in Duo Koto sub-district which is in the west of the research area and have 2 geothermal manifestations. Panti geothermal potential is located in panti sub-district which is in the east of the research area and have 2 geothermal manifestations. Because of this difference in distance between the two geothermal potentials. The team used satellite gravity data, land surface temperature, and Landsat 9 methods to identify geothermal systems in the cubadak - panti area, Pasaman, West Sumatra. Gravity method was conducted to determine the geological structure and density of the subsurface. Meanwhile, land surface temperature and Landsat 9 were conducted to describe the average temperature and minerals suspected as potential geothermal sources in the Cubadak - Panti area.

The results of this research can delineate geothermal sources in the cubadak and panti areas and are then expected to create a new geothermal power plant that can have a major social and economic impact on the people of Pasaman Regency. Based on the latest data from the Pasaman Central Bureau of Statistics, the unemployment rate is still at 5.38% and the poor population still amounts to 19.94 thousand people (Badan Pusat Statistik Kabupaten Pasaman, 2023). Based on an article from the 2016 Indonesian Monetary and Banking Economic Bulletin, the presence of geothermal power plants can increase the value of gross domestic product by 3.7 billion rupiah and have a major effect on reducing carbon emissions by 3% - 5% (Nayasari and Djoni, 2016). Other data from the US-based Geothermal Energy Association (GEA) states that geothermal power plants can employ 1.17 - 2.13 people per Mwe generated by the plant. Geothermal also contributes high taxes, where the average 20 Mwe plant generates 6.3 - 11 million dollars in taxes per 30 - 50 years (Ritcher, 2023).

Figure 1: Research Location of Cubadak – Panti Geothermal Area (https://earth.google.com/web/).

Regional Geology

The geological research area is located on the lubuksikaping geological sheet. According to Rock (2011) on cubadak panti area there are various rock formations starting from the youngest formations, namely alluvium and piedmont fans (Qh and Qf) which are Holocene in age and consist of sandstone, silt, gravel and conglomerate. The next formation is a volcanic layer rock of Miocene age (Tmv) but this formation does not show a volcanic center. Still at the age of the Miocene formation there is a parlampungan intrusion (TMiu) consisting of granodiorite and diorite intrusion rocks. At the bottom there are 2 formations of permo-Triassic age, namely the Silungkang formation (Ppsi) and the Panti volcano formation (Ppvp). The Silungkang formation consists of limestone and meta limestone. While the Panti volcano formation consists of metagunungapi, and greenstone. In the basement of this area is the Kuantan (Puku) formation which consists of slate, quartzite, and metacrystic arenite (Rock et al., 2021).

the fault structure in the cubadak – panti study area is northwest - southeast oriented with cubadak geothermal heatsource is thought to have originated from residual heat (magma kitchen) associated with volcanic activity in the form of fissure eruptions. And panti geothermal heat source is thought to originated from graben structure based on northwest – southeast fault (Kementrian ESDM, 2017).

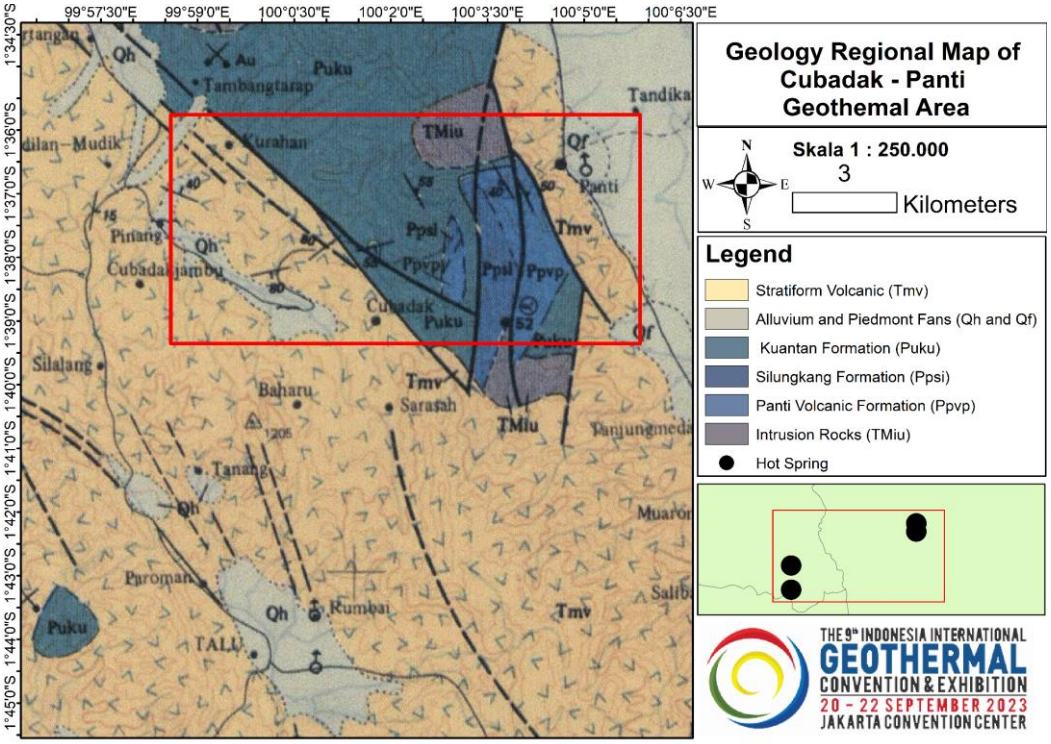


Figure 2: Regional Geological Map of Cubadak – Panti Area (Rock, 2011).

2. BASIC THEORY

2.1 Gravity

The gravity method is one of the geophysical exploration methods. This method is based on Newton's law, which states that there is an attractive force (F) between two objects with certain masses (m1 and m2) separated by a certain distance (r) (Telford et al, 1990). The equation for Newton's law is as follows:

$$F = G \frac{m_1 m_2}{r^2} \quad (1)$$

Where F represents the magnitude of the gravitational force measured in Newtons (N), G is the gravitational constant with a value of approximately 6,67 Kg^2/m^2, m_1 is the mass of the first object

measured in kilograms (kg), and m_2 is the mass of the second object measured in kilograms (kg) (Telford et al, 1990).

2.2. Landsat 9

Altered rocks are one of the manifestations of geothermal activity. There are three types of alterations: mineral replacement, filling of space, and rock dissolution (Utami et al., 2015). The presence of altered rocks is caused by the interaction between geothermal fluids and the rocks they pass through. The presence of altered rocks can be an indication for mapping geothermal potential, especially in areas surrounding manifestations that indicate the presence of an active geothermal system (Browne, 1970).

One way to obtain information about the Earth's surface and subsurface conditions is by using data obtained from satellites orbiting in space. An example of a satellite used in geophysical exploration is Landsat 9, which is a continuation of NASA's Landsat program, previously represented by Landsat 8. Landsat 9 will continue the data processing system based on established data collection and distribution strategies by the USGS (Masek, 2020).

Landsat 9 can assist in identifying altered rocks because different objects on the Earth's surface have varying reflectance characteristics, including the minerals resulting from hydrothermal alteration, which also exhibit different reflectance characteristics. Therefore, the distribution of alteration minerals in an area can be detected using Landsat 9 imagery. This can help determine regions with high potential for geothermal activity. Through initial surveys using remote sensing applications, the distribution of hydrothermal alteration minerals, which are often associated with the presence of geothermal manifestations, can be observed (Pratama et al., 2020).

2.3. Inversion Method

In geophysical exploration, the inversion method is a mathematical or statistical approach. This method takes observed data and directly generates a model or reconstruction based on that data. The main objective of the inversion method is to obtain physical information that was previously unknown or not directly visible through the available observation data (Melani et al., 2021).

2.4. Geothermal

In general, geothermal energy, also known as heat from the Earth, originates from the Latin root’s 'geo' meaning earth and 'thermal' meaning heat. Geothermal energy can be defined as the natural heat generated beneath the Earth's surface. Geothermal energy can be understood as the amount of heat stored within the Earth, forming the geothermal system that has existed since the formation of the Earth. The geothermal system includes the water system, hydrothermal system, heating processes, and the conditions where hot water accumulates, thus encompassing the availability of water, heating of rocks, rock reservoirs, shallow soil layers, and other requirements.

Geothermal resources are generally associated with mechanisms of magma formation and volcanic activity. High-temperature geothermal systems are typically found along volcanic belts, continental ridges, and in subduction zones and intraplate melting anomalies, such as in Indonesia. Moving plate boundaries are central sites for the formation of hydrothermal magmatic systems. The conductive transfer of heat energy in the tectonic plate environment is enhanced by the movement of magma and hydrothermal circulation. The main requirements for the formation of a geothermal system consist of a large heat source, heat reservoirs, and heat-bearing rocks. In this hydrothermal system, heat is transferred through conduction and convection. Conduction occurs through rocks, while convective heat transfer occurs at the contact between water and the heat source. Convection heat transfer is inherently driven by buoyancy. Water always tends to move downward due to gravity, but when water touches the heat source, heat transfer occurs, raising the water temperature and making it lighter. This condition causes hot water to flow upward and cooler water to flow downward, creating a circulation or convection of water (Al Anshory, 2010).

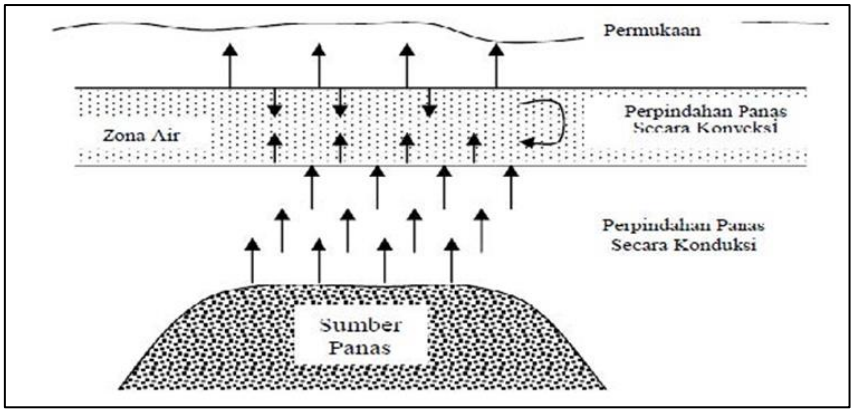


Figure 3: Geothermal System (Saptadji, 2002).

3. METHODOLOGY

This study utilizes satellite imagery data. The 6 Landsat-9 data was obtained from the USGS website, recorded on April, 2023, consisting of bands 2, 4, 5, 6, and 7. Band ratio processes were conducted on bands 4/2 and 6/7, followed by band compositing (4/2, 6/7, and 5/6) to identify the distribution of rock alterations and raster calculator to identify the land surface temperature in the research area.

Next, gravity data was collected from the GGMPlus website, consisting of 13
Elevation Model (DEM), Gravity Disturbance, and Geoid. Bouguer correcti
processes were applied to obtain the Complete Bouguer Anomaly (CBA).
was performed using a bandpass filter to obtain the residual anomaly. Inversion modeling was carried out in 3D to assess the depth, density values, and shape of geothermal system of Cubadak – Panti area.

4. RESULT

4.1. Rock Alteration Map

Alteration rocks are rocks that are present as a reaction between geothermal fluid and the rocks it passes through, where there are three types of alteration, namely 1) Mineral alteration, 2) Space filling, and 3) Rock dissolution (Utami et al., 2015). The presence of altered rocks can be an important clue in mapping geothermal potential, especially those around manifestations that indicate that there is an active geothermal system.

In this case the author uses Landsat 9 image analysis obtained from the USGS website. Landsat image analysis is commonly used in knowing the conditions on the earth's surface by looking at the reflectance and absorption characteristics of electromagnetic waves from objects on the earth's surface. Previous research shows that minerals resulting from hydrothermal alteration products have different reflectance characters and will show certain colors through RGB constructive color composite images.

Therefore, by linking the presence of alteration minerals in an area with the detection that can be done by Landsat 9 imagery, it will be possible to determine the location of the distribution of hydrothermal alteration minerals in an area. This will be very helpful especially for preliminary studies in determining high-potential areas that have high geothermal activity, considering that geothermal exploration is carried out generally in areas that are often still untouched, so the initial survey through remote sensing is very helpful to see the distribution of hydrothermal alteration minerals which are often associated with the presence of geothermal manifestations.

In determining alteration minerals, the author uses the density slicing method to take a number of pixel values that indicate the presence of minerals on the earth's surface based on their reflection. In this study, 4/2, 6/7, and 5/6 ratio images are used, each of which shows the presence of clay minerals, chlorite, and epidote minerals.

In the band composite (4/2, 6/7 & 5/6) of Landsat 9, a rock alteration map was generated for the research area. In the map below, the red colors indicated the high value of clay, chlorite and epidote minerals. The epidote and chlorite minerals are one of the important indicators of the reservoir or high temperature alteration rocks. Meanwhile high value of clay minerals shows theirs is a geothermal manifestation on Cubadak – Panti Area. The clay mineral distribution at manifestation shows high value in all manifestation. chlorite and epidote distribution show high value in all manifestation but there's less red color at second manifestation at cubadak which directed to northwest (Figure 5).

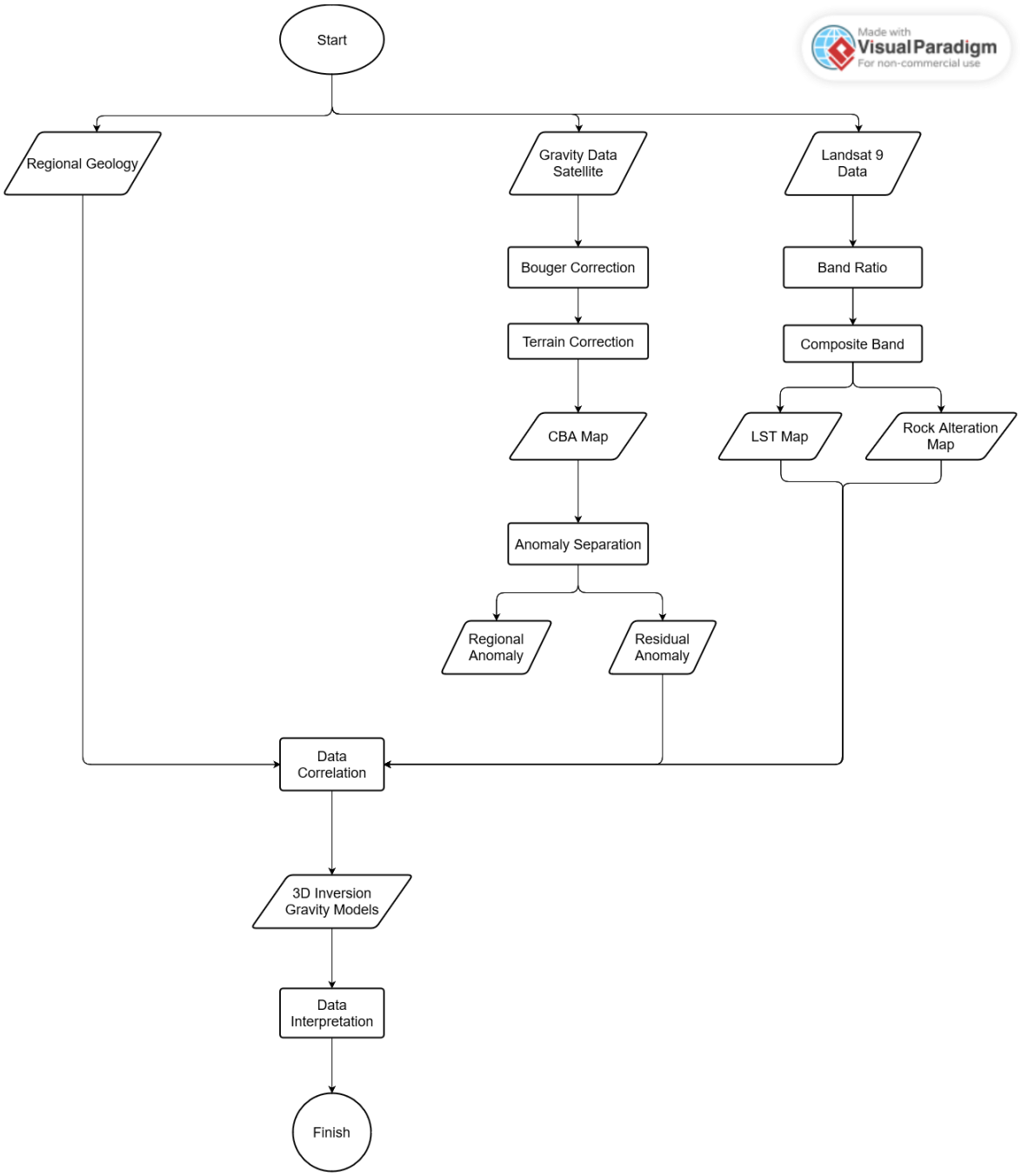


Figure 4: Research Flowchart.

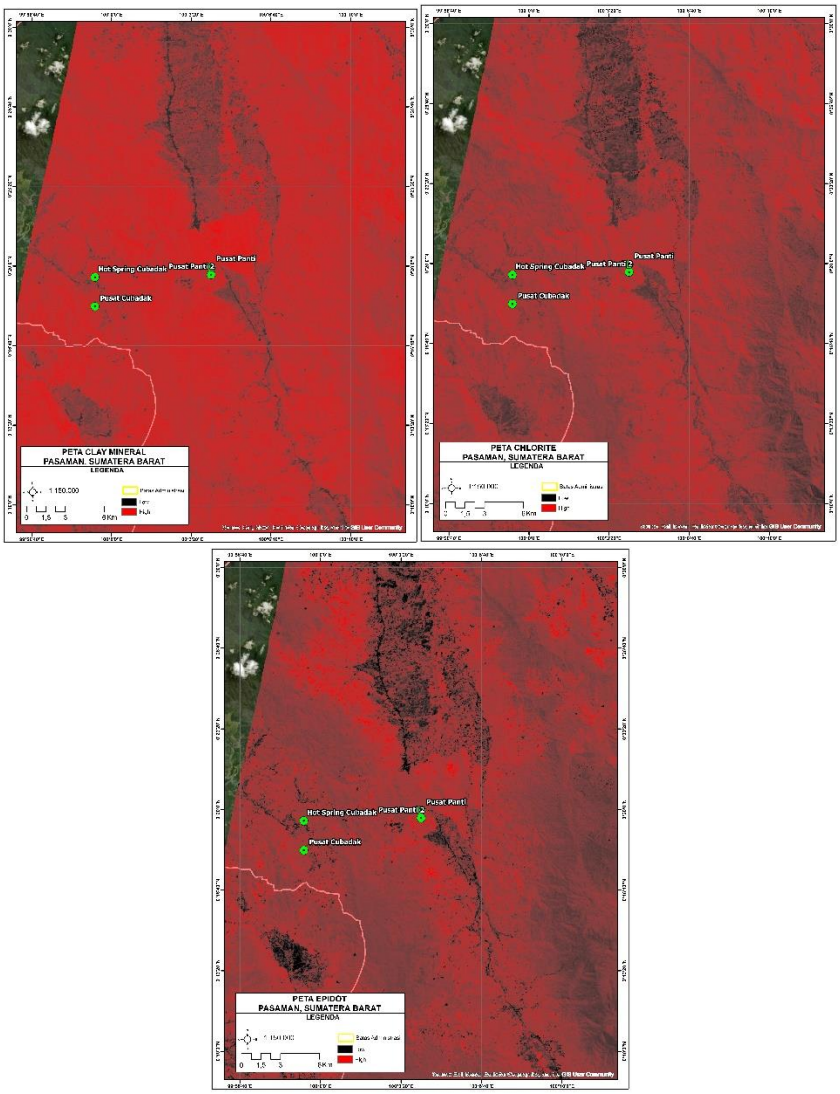


Figure 5: Rock Alteration Map (a) Clay Mineral, (b) Chlorite, (c) Epidote of Cubadak Panti Geothermal Area.

4.2. Land Surface Temperature (LST) Map

In the Land Surface Temperature (LST) Map below, it can be seen that the red box shows the main research location in the Cubadak - Panti area, Pasaman, in the western part there is 1 manifestation point and the eastern part has 2 geothermal manifestations. The manifestation area in the western part shows a surface temperature with a range of 26.29 - 28.7℃1. Meanwhile, the manifestation in the eastern part shows a large temperature with a range of 24.21 - 26.29 ℃. Both manifestations and temperatures show moderate to high temperatures indicating that there are true manifestations in the area.

4.3. Digital Elevation Map

The map of the study area below shows that the elevation in the Cubadak – Panti ranges from 221.7 – 1197.5 meters. The lowland area is blue ranging from 221.7 - 433.1 meters, the medium plain area is green to orange ranging from 466.1 - 885.2 meters, and the highland area is red to purple ranging from 905.7 - 1197.5 meters. in the western manifestation areas, it can be seen that the manifestation point borders between high and low elevations so that it can be estimated that the manifestation area is in the fault area. Meanwhile on the eastern areas there's lower area which thought to be a graben that controlled the manifestation and geothermal system.

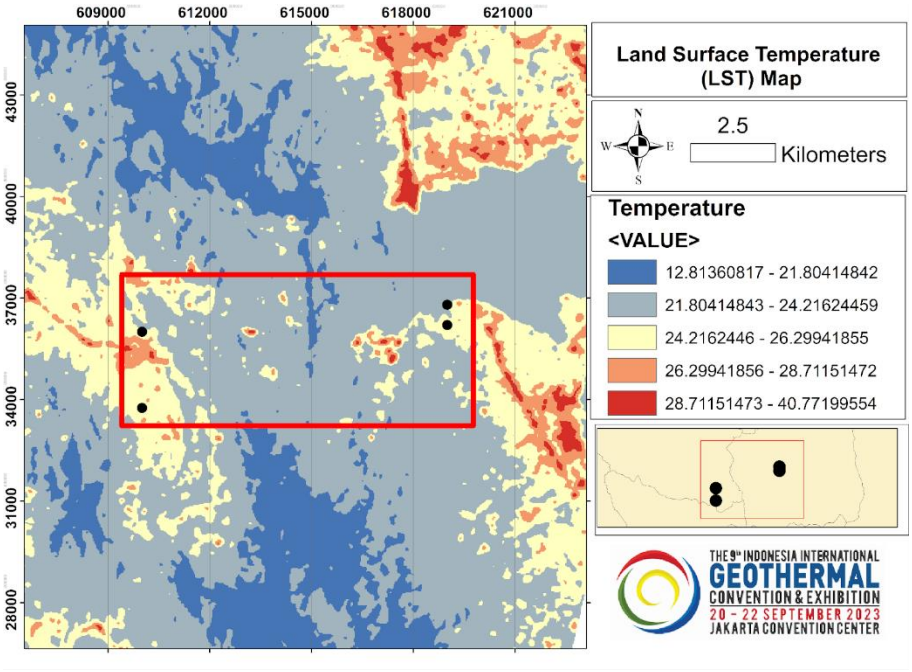


Figure 6: Land Surface Temperature (LST) Map.

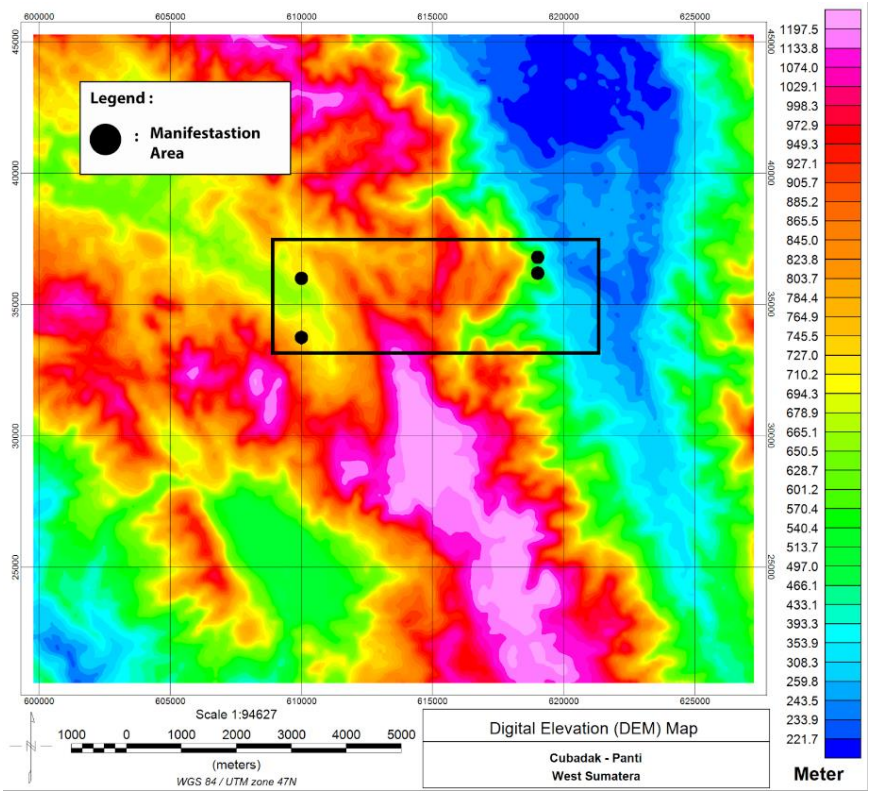


Figure 7: Digital Elevation Model (DEM) Map.

4.4. Gravity Anomaly Map

4.4.1 Complete Bouguer Anomaly (CBA) Map

In the study area of Complete Bouguer Anomaly (CBA) map below, low blue anomalies ranging from -38.0 - (-35.1) are identified in the rock formations that occupy the western, northwestern and central parts of the investigation area. This anomaly is thought to be related to alluvium deposits and lake deposits (loose sand, clay and waste rock). Meanwhile, the green to orange medium anomaly ranges from -34.8 (-31.0) starting from the northwest, east to southeast ends. This medium anomaly is thought to be occupied by volcanic rock units (andesite, basaltic andesite, basaltic rocks). Then high anomalies ranging from - 30.7 - (-24.1) generally occupy the hills to the north and northeast, namely around Kuraba village. This high anomaly is occupied by volcanic and metamorphic rock units (andesite, andesite-basaltic, obsidian and slate).

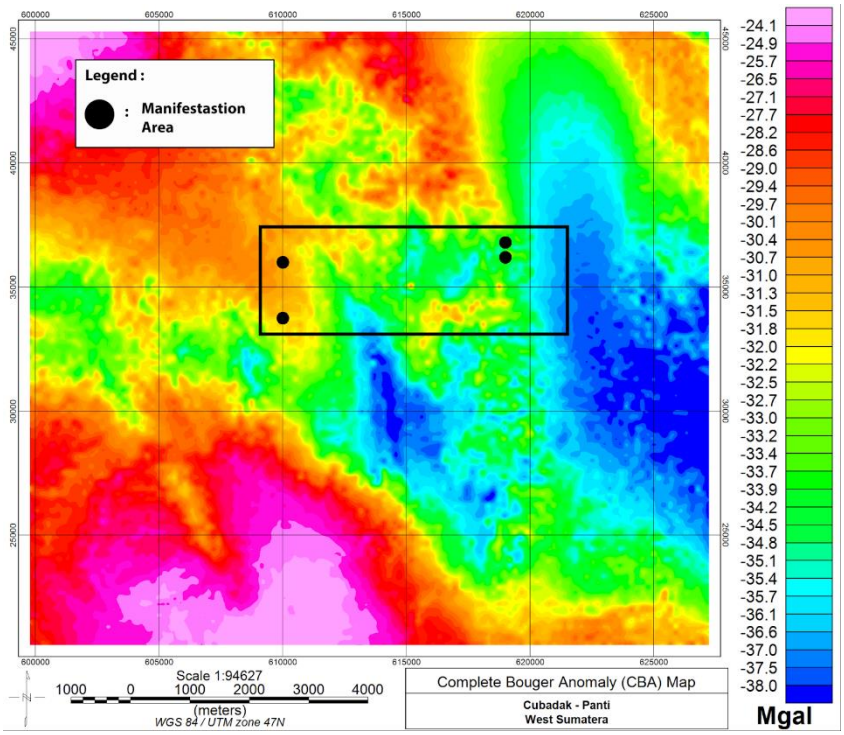


Figure 8: Complete Bouguer Anomaly (CBA) Map.

4.4.2 Regional Anomaly Map

Based on regional gravity resulted that conducted using satellite data. It shows the gravity anomaly ranges from -38 - (-24) mGal. The research area marked with a black line shows that the manifestation area is at a medium gravity anomaly value ranging from -34.7 - (-31.1) mGal which is thought to be volcanic rock or volcanic rock such as andesite, andesite-basaltic, and slate. on the regional map also in the northwest - southeast direction there is a straight line indicating that there is a fault that controls the manifestation in the west.

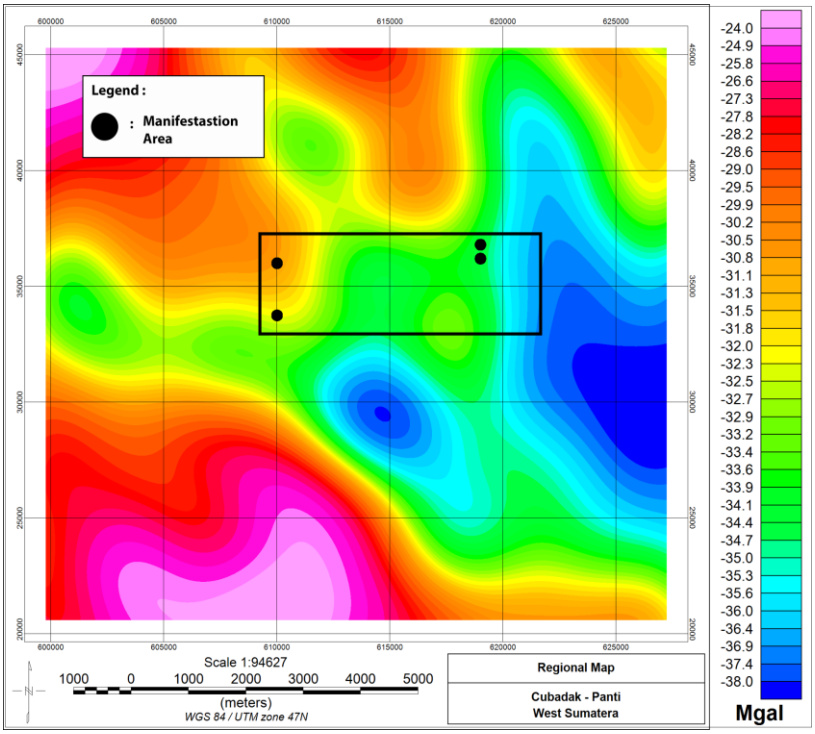


Figure 9: Regional Anomaly Map.

4.4.3 Residual Anomaly Map

the residual gravity anomaly shows the manifestations in the west and east have a moderate gravity anomaly range between 0.0367 - 1.0868 mGal. These anomalies show similarities in the residual and CBA maps which are thought to be volcanic rocks such as limestone, andesite and slate. but the volcanic rocks in this area have undergone alteration and enrichment of mineral content such as clay. In the eastern manifestation there are high anomalies in the west and east while in the center the gravity anomaly has a low value. This indicates the presence of a graben structure and gives rise to manifestations in the eastern part of the study area.

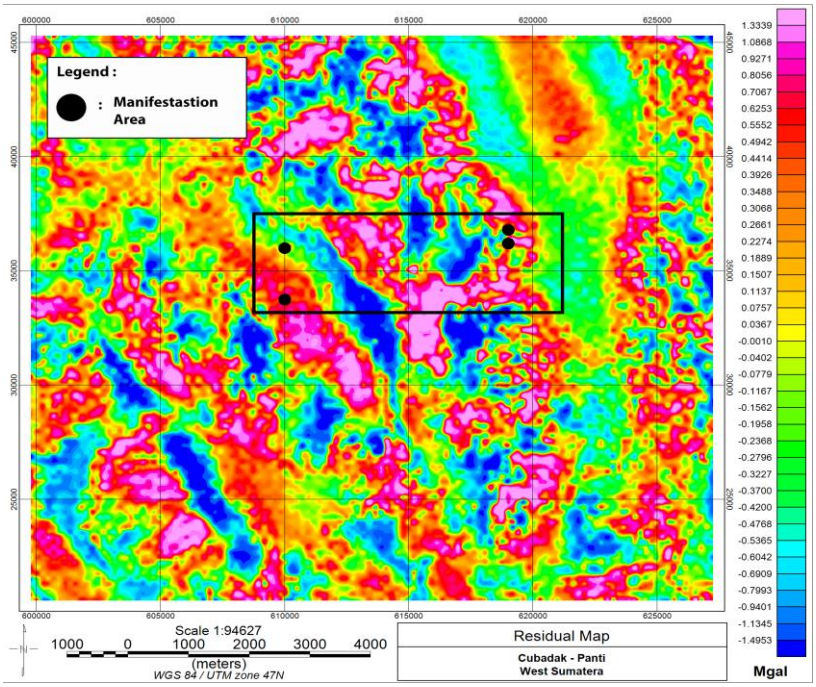


Figure 10: Residual Anomaly Map.

4.5. Correlation of Land Surface Temperature and Gravity Data

Based on the results of the overlay between the LST map and the Residual map, there are results/similarities that support each other. The Cubadak - Panti surface area has an average temperature of around 24.21 – 28.71 °C which is marked with the color Light Brown - Red. This area has 4 manifestations in the form of hot springs, therefore the temperature on the surface of this area is quite high. This is also validating the result of residual gravity.

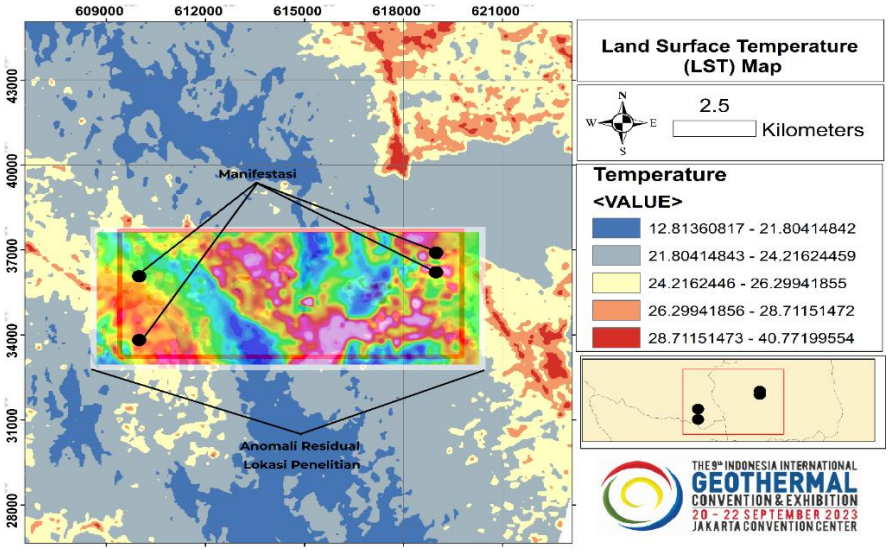


Figure 11: Correlation of LST and Gravity Data Results.

4.6. 3D Gravity Inversion Models

After correlating the results from the three methods, the next step involved conducting 3D inversion modelling on the residual gravity map to visualize the subsurface intrusive rocks based on density parameters as an indication of geothermal potential. 3D inversion modeling is divided into 4 models, namely A-A', B-B', C-C', and D-D'. A and B show modelling on the manifestation in the east, while C and D show subsurface modeling in the west. inversion 3D modelling is divided into 4 models namely A-A', B-B', C-C', and D-D'. A and B show modeling of the manifestation in the west, while C and D show subsurface modelling in the east.

4.6.1 A-A’ Models

Modeling A-A' is modeling on manifestations in the eastern part in the west - east direction. In the A-A' modeling, the red-yellow layer is suspected to be the Cap Rock layer with a depth of more than 100 - 1400 meters, in this area there are layers of alluvium, volcanic rocks, and pyroclastic rocks rich in clay minerals with a density of around 2.843 – 2.893 g/cm^3. The green-blue layer with a depth of 1400 - 1800 meters from the surface that inserts with the reservoir area contains sabak rock which is rich in fractures and is permeable which has a density of 2.843 – 2.793 g/cm^3.

4.6.2 B-B’ Models

Modeling B-B' is modeling on the manifestation in the eastern part with the direction of North - South. In the B-B' modeling, the red-yellow layer is thought to be the Cap Rock layer with a depth of more than 100 - 1100 meters, in this area there is a layer of alluvium, volcanic rocks, and pyroclastic rocks rich in clay minerals with a density of around 2.843 – 2.893 g/cm^3. The green-blue layer with a depth of 800 - 1800 meters from the surface that inserts with the reservoir area contains sabak rock which is rich in fractures and is permeable which has a density of 2.843 – 2.793 g/cm^3.

4.6.3 C–C’ Models

C-C' modeling is modeling on manifestations in the western part with a west-east direction. In the C-C' modeling, the red-yellow layer is thought to be the Cap Rock layer with a depth of more than 50 - 450 meters, in this area there is a layer of alluvium, volcanic rocks, and pyroclastic rocks rich in clay

minerals with a density of around 2.843 – 2.893 g/cm^3. The green-blue layer with a depth of 500 - 700 meters from the surface that inserts the reservoir area contains slate rocks and granite intrusive rocks that are rich in fractures and are permeable which has a density of 2.843 – 2.793 g/cm^3.

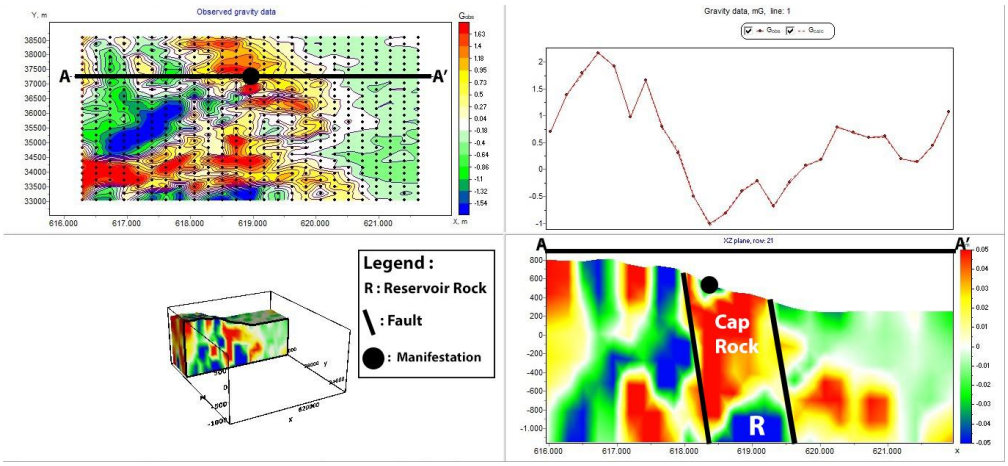


Figure 12: 3D Gravity Inversion A-A' Models.

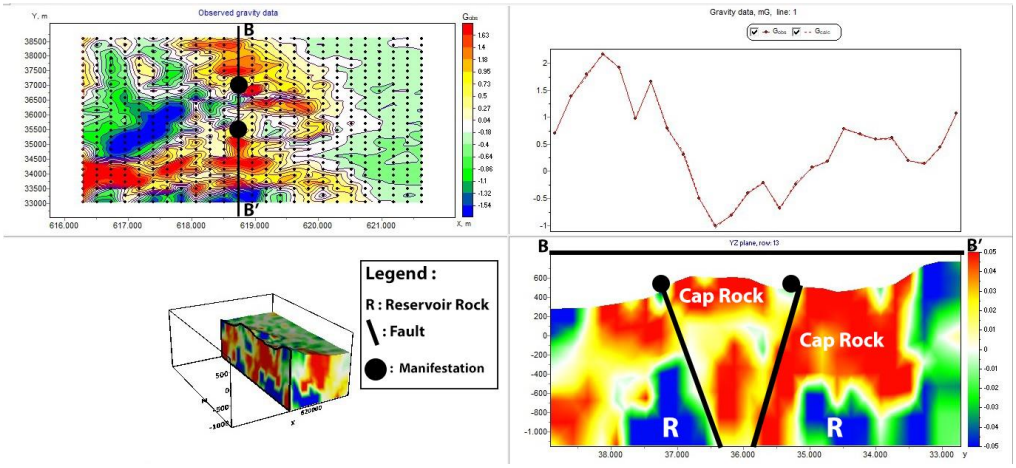


Figure 13: 3D Gravity Inversion B-B' Models.

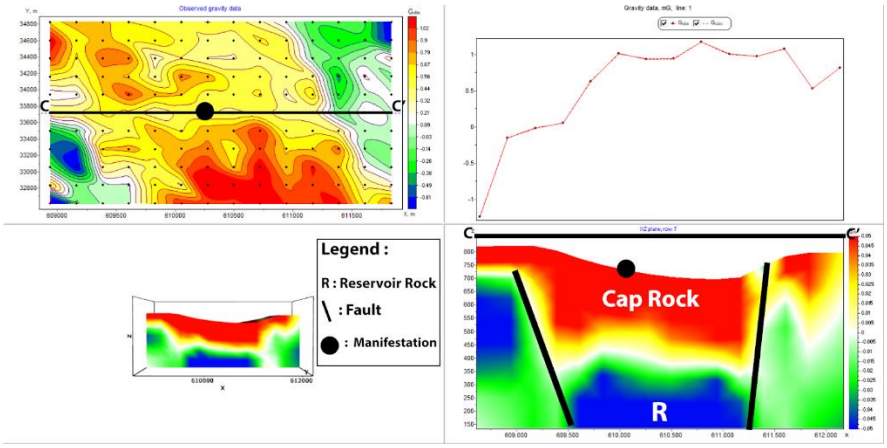


Figure 14: 3D Gravity Inversion C-C' Models.

4.6.4 D–D’ Models

Modeling D-D' is modeling on the manifestation in the western part with the direction of North - South. In the D-D' modeling, the red-yellow layer is thought to be the Cap Rock layer with a depth of more than 100 - 450 meters, in this area there are layers of alluvium, volcanic rocks, and pyroclastic rocks rich in clay minerals with a density of around 2.843 – 2.893 g/cm^3. The green-blue layer with a depth of 450 - 700 meters from the surface that inserts the reservoir area contains slate rocks and granite intrusive rocks that are rich in fractures and are permeable which has a density of 2.843 – 2.793 g/cm^3.

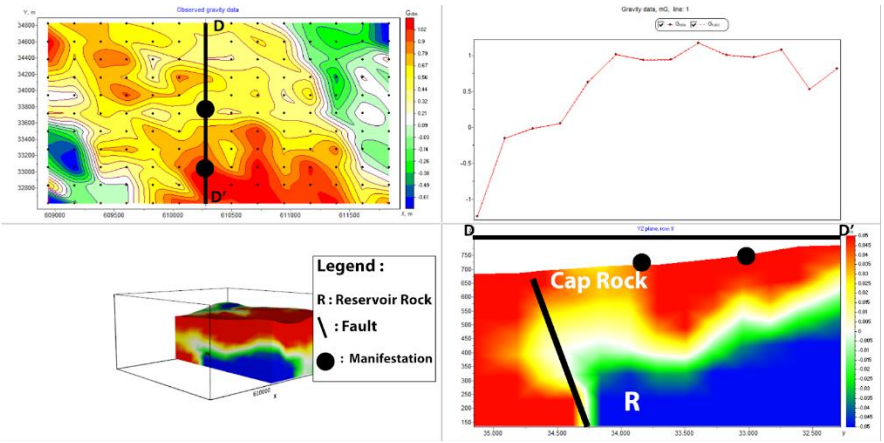


Figure 15: 3D Gravity Inversion D-D’ Models.

Based on A-A’ to D-D’ Models it can be seen in east part of research area the cap rock layer is range from 100 – 1400 m with density around 2.843 – 2.893 g/cm^3 and lithology of alluvium, volcanic rocks, and pyroclastic rocks rich in clay minerals. the reservoir is range from 800 – 1800 m with density around 2.843 – 2.793 g/cm^3 and lithology consist of sabak rock which is rich in fractures and is permeable. Meanwhile, on west part of research area the cap rock layer is lower than east part because it located at graben area with the range from 50 – 450 m with density around 2.843 – 2.893 g/cm^3 and lithology of alluvium, volcanic rocks, and pyroclastic rocks rich in clay minerals. The reservoir layer is range from 450 – 700 m with density around 2.843 - 2.793 g/cm^3 and lithology consist of slate rocks and granite intrusive rocks that are rich in fractures and are permeable.

5. CONCLUSION

Based on Result and Discussion we can get a conclusion as it follows:

1. Based on Rock Alteration Map it shows that the red color represents the high value of alteration minerals namely clay, chlorite and epidote. This clay mineral used to validate the thermal manifestation and chlorite and epidote indicate the high temperature geothermal area. The high value clay minerals distribute well around the manifestation area as well chlorite. Epidote however have a less distribution around second manifestation directed at northwest. The clay minerals result correlate with Land Surface temperature which indicate in manifestation area have a high value of land surface temperature range from 24.21 – 28.71 °C

2. The Digital Elevation Model (DEM) result shows that the elevation of research area ranges from 221.7 – 1197.5 meters. It can be seen that the manifestation point on the west is located at borders between high and low elevations so that it can be predicted that the manifestation area is in the fault area. Meanwhile on the eastern areas there’s lower area which thought to be a graben that controlled the manifestation and geothermal system. This prediction is reinforced with regional and residual map. in the regional map shows in the northwest - southeast direction there is a straight line with the value of -34.4 – (-32.0) mGal indicating that there is a fault that controls the manifestation in the west. meanwhile the residual shows a value range of 0.0367 - 1.0868 mGal In the eastern manifestation there are high anomalies in the west and east while in the center the gravity anomaly has a low value. This indicates the presence of a graben structure and gives rise to manifestations in the eastern part of the study area in the eastern

manifestation there are high anomalies in the west and east while in the center the gravity anomaly has a low value. This indicates the presence of a graben structure and gives rise to manifestations in the eastern part of the study area. The residual anomaly correlates with the Land Surface Temperature (LST) map and shows there's a high temperature at the east and west area.

3. The Complete Bouguer Anomaly (CBA) Map shows the value with range of -38 – (-24.1) mGal with low blue anomalies ranging from -38.0 - (-35.1) are identified in the rock formations that occupy the western, northwestern and central parts of the investigation area. This anomaly is thought to be related to alluvium deposits and lake deposits (loose sand, clay and waste rock). Meanwhile, the green to orange medium anomaly ranges from -34.8 (-31.0) starting from the northwest, east to southeast ends. This medium anomaly is thought to be occupied by volcanic rock units (andesite, basaltic andesite, basaltic rocks). Then high anomalies ranging from - 30.7 - (-24.1) generally occupy the hills to the north and northeast. And high anomaly is occupied by volcanic and metamorphic rock units (andesite, andesite-basaltic, obsidian and slate).

4. Based on A-A' to D-D' 3D Inversions Models it can be seen in east part of research area the cap rock layer is range from 100 – 1400 m with density around 2.843 - 2.893 g/cm^3 and lithology of alluvium, volcanic rocks, and pyroclastic rocks rich in clay minerals. the reservoir is range from 800 – 1800 m with density around 2.843 - 2.793 g/cm^3 and lithology consist of sabak rock which is rich in fractures and is permeable. Meanwhile, on west part of research area the cap rock layer is lower than east part because it located at graben area with the range from 50 – 450 m with density around 2.843 - 2.893 g/cm^3 and lithology of alluvium, volcanic rocks, and pyroclastic rocks rich in clay minerals. The reservoir layer is range from 450 – 700 m with density around 2.843 – 2.793 g/cm^3 and lithology consist of slate rocks and granite intrusive rocks that are rich in fractures and are permeable.

REFERENCES

Alexander Ritcher., https://www.thinkgeoenergy.com/economic-values-of-of-geothermal-power-development-and-operation-a-2015-brief-by-gea/. Access on 12 July 2023

Al Anshory, H., 2010. Pemodelan Sistem Geothermal Daerah X Menggunakan Metode Magnetotelluric. Pp. 1–71. 2010.

Badan Pusat Statistik Kabupaten Pasaman. 2023. Pasaman dalam angka 2023.

Browne, P. R. L., 1970, Hydrothermal Minerals as an Aid in Investigating Geothermal Field. Journal of Geothermics, 2 (1), pp 564 – 570. Browne, P. R. L., 1998, Hydrothermal Alteration, Geothermal Institute, The University of Auckland.

Gunawan, I., Windarta, J., dan Harmoko, U. 2021. Overview Potensi Panas Bumi Provinsi Jawa Barat. Jurnal Energi Baru dan Terbarukan, vol. 2., pp. 60-73.

Kementrian ESDM. 2017. Buku Potensi Panas Bumi Jilid 1

Masek. 2020. Landsat 9: Empowering Open Science and Applications Through Continuity. Jurnal E l Remote Sensing Environment.

Melani, Octavia., et al. 2021. Penerapan Metode Inversi Dalam Pendugaan Nilai Resistivitas. Jurnal Teknika Sains, Vol. 6 No. 2.

Nayasari,A., Djoni,H. 2016. The Impact of Geothermal Energy Sector Development on Electricity Sector in Indonesia Economy Buletin Ekonomi Moneter dan Perbankan, Volume 19, Nomor 2.

Rock., N.M.S., Aldiss.D.T., Aspden. J.A., Peta Geologi Lembar Lubuksikaping, Sumatera, 2011. Pusat Survey Geologi

Saptadji, N. M. 2002. Teknik Panas Bumi. Institut Teknologi Bandung. Bandung.

Telford, W. M., Geldart, L. P. & Sheriff, R. E. 1990. Applied geophysics. Cambridge, UK: Cambridge University Press

Utami P., et al., 2015. Hydrothermal Alteration and Evolution of the Lahendong Geothermal System, North Sulawesi Proceedings World Geothermal Congress 2015 Melbourne, Australia, 19-25 April 2015

Yusuf Arico Pratama, Rifaldy, Anggun Mutika. 2020. Identifikasi Alterasi Hidrotermal Menggunakan Citra Landsat 8 Oli/Tirs: Studi Kasus Gunung Patuha, Kabupaten Bandung, Jawa Barat. BULLETIN OF GEOLOGY, VOL. 5, NO. 1, 2021, DOI: 10.5614/bull.geol.2021.5.1.3.

Identification of low to moderate fault-controlled geothermal system using satellite gravity method – A comparative study

Fadhila Friany Putri[1,2], Yunus Daud[1,2,3], Surya Aji Pratama[3], Wambra Aswo Nuqramadha[3], and Fikri Fahmi[3]

[1]PT. NewQuest Geotechnology, Pesona Khayangan Estate DC12, Depok 16411, Indonesia
[2]Geothermal Exploration Magister Program, Graduate Program of Physical Sciences, Department of Physics, Faculty of Mathematics and Natural Sciences, Universitas Indonesia, Kampus, Depok 16424, Indonesia
[3]Geothermal Research Center (GRC), Institute for Sustainable Earth and Resources (I-SER), Faculty of Mathematics and Natural Sciences, Universitas Indonesia, Kampus, Depok 16424, Indonesia

fadhila.friany@newquest-geotechnology.com

Keywords: satellite gravity, geothermal, low-to-moderate temperature, fault-controlled system

ABSTRACT

Currently, most of the high-temperature geothermal system in Indonesia has been developed into power plants, leaving only low-to-moderate-temperature potential. Out of 349 geothermal locations in Indonesia, 46% of them (167 locations) have moderate temperature potential. Most of them are associated with fault-controlled geological settings. To carry out the exploration phase, a method to detect the characteristics of a fault-controlled system is needed. This method is expected to map effectively and efficiently considering the need for cost savings since the amount of electricity generated is smaller than the high-temperature system. One of the geophysical methods that is often used in geothermal exploration is the gravity method. With the availability of the satellite gravity method, geothermal system mapping is now more accessible and more efficient. This study aims to map and identify the characteristics of a fault-controlled geothermal system in several geothermal fields on Sulawesi Island, Indonesia. In several research areas, the results show some high-low-high anomaly patterns associated with fault structures on Sulawesi Island, one of which is the Palu-Koro fault. These results show appropriateness after being compared with the field gravity data. Therefore, the satellite gravity method is expected to be one of the "key" methods for identifying the distinctive patterns between fault-controlled and volcanic systems in delineating reservoirs, permeable zones, and structural patterns.

1. INTRODUCTION

Indonesia has a geothermal energy potential of 23.7 GW (EBTKE, 2020) spread across almost all provinces. Most of Indonesia's high-temperature geothermal potential has been developed into PLTP, leaving low to medium-temperature potential. Out of 349 geothermal locations in Indonesia, 46% of them (167 locations) have moderate temperature potential. Most are associated with fault-controlled geological settings, such as the Palu-Koro fault, located on Sulawesi Island. Therefore, delineating the main faults that control the formation of geothermal reservoirs is required in the exploration stage.

The Palu-Koro Fault is a sinistral shear fault that divides Central Sulawesi Province. This 460 km long fault stretches from the North Sulawesi trench (Minahasa Trench), to be precise on the border between the Makassar Strait and the Sulawesi Sea to Dondowa, North Luwu Regency bordering the Matano fault (Liu & Shi, 2021). This fault is even expected to continue until it ends in Bone Bay. The presence of surface manifestations that appear in several segments of this fault indicates the existence of a geothermal system controlled by the Palu-Koro fault.

This study compares the results of satellite gravity surveys and land gravity measurements from several low-medium geothermal

prospect areas along the Palu-Koro fault. The good similarity of the anomaly patterns between satellite gravity and land surveys is expected to be the primary consideration for satellite gravity as an initial reference before conducting field surveys. Thus, surveys can be carried out more effectively and

efficiently. With satellite gravity technology, graben patterns or possible structures that control the appearance of geothermal systems with low to moderate temperatures can also be identified.

2. METHODOLOGY

2.1 Data and Method

This research was conducted by utilizing the gravity disturbance data of Global Gravity Model Plus (GGMplus). GGMplus is a combined solution based on the three key constituents of GOCE/GRACE satellite gravity, EGM2008, and topographic gravity with a resolution of up to 200 m (Hirt et al., 2013). The gravity disturbance data is used because it is equivalent to the gravity anomaly resulting from the free air correction (Suprianto et al., 2021). The GGMplus result was then compared with the land gravity result as Complete Bouguer Anomaly (CBA) maps to test the effectiveness and efficiency of satellite gravity data. The CBA map of land gravity data was obtained from various open-source research, primarily from the Center for Mineral, Coal, and Geothermal Resources.

2.2 Study Area

In this research, case studies were conducted in three areas: the Bora Geothermal Field, Marana Geothermal Field, and Kadidia-South Kadidia Geothermal Prospect Area (Figure 1). The Bora and Marana geothermal fields are crossed directly by the Palu-Koro fault. While the Kadidia-Kuala Rawa Prospect Area is crossed by a branching segment trending NWW-SEE, which is still correlated with the Palu-Koro fault (Wibowo et al., 2015).

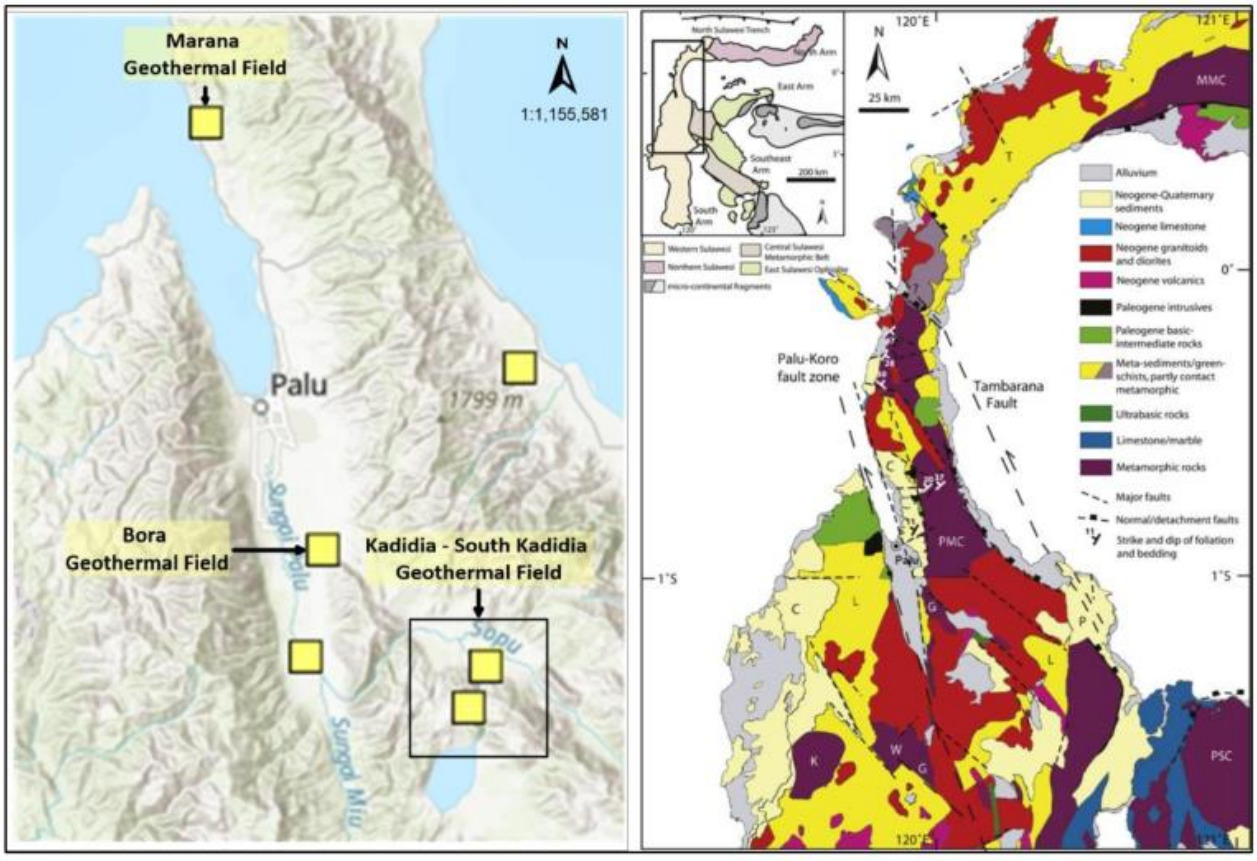


Figure 1: (Left) Study areas include Marana, Bora, and Kadidia - South Kadidia Geothermal Area. All in Central Sulawesi Province. (Right) Geological map of west Central Sulawesi from Hennig et al. (2017) include structures through the study area.

3. RESULT AND DISCUSSION

Below are the results of data processing in the Bora area, Marana area, and Kadidia-South Kadidia. Each area is presented with three maps: one Complete Bouguer Anomaly (CBA) map from land measurements and two CBA maps from GGMplus satellite data. The CBA map of land measurement results is obtained from published article sources with modifications to the map layout. Meanwhile, the GGMplus satellite CBA map is presented in two results: the CBA map with full grid points of GGMplus and the CBA map with selected grid points as land measurement stations. However, because the spacing of GGMplus grid points is constant ~200 m in latitude and longitude, not all GGMplus grid points have the same grid position coordinates as the field data. Therefore, to anticipate data gaps, field station points located on the GGMplus grid spacing are discovered by two to four GGMplus gravity points. In addition, to determine whether there is variation in the results due to the influence of the subsurface average density, GGMplus data with a full grid is processed using the same subsurface average density as field gravity. While the GGMplus data with a grid that has been adjusted to field gravity is processed using the subsurface average density obtained from calculations using the Parasnis curve plot.

In the Bora Geothermal Field (Figure 2), the GGMplus results have the same anomaly contour pattern as field measurement data that form a high-low-high pattern. There is a slight difference on the easternmost side of the area, where a low anomaly is formed in the land measurement CBA map while a high anomaly is formed in the satellite CBA map. In addition, land CBA anomaly values are in the range of -22 to 26 mgal, while the full grid GGMplus CBA ranges from 28 to 48 mgal, and the selected grid ranges from 28 to 5 mgal. Although there are slight differences in the anomaly values between the GGMplus data, they both show the same pattern. Even though the values of the anomaly ranges are very different, the high-low-high pattern that is formed is quite consistent with the field data and has been able to adequately describe the graben that is formed on the Palu-Koro fault path.

In the Marana Geothermal Field (Figure 3), the anomalous pattern formed by GGMplus is quite different from the field data anomaly. Only the northwest, north, northeast, and east areas have the same pattern. The existence of a local anomaly pattern in the middle of the field data area is not visible in GGMplus. This shows that even though it has a grid spacing of up to 200 m, most of the GGMplus data is still dominated by Earth Gravity Model data, so there are still only points of interpolation results. Even so, if viewed regionally, the anomalies shown by the GGMplus data correlate well with the indication of the Palu-Koro fault line that crosses the Marana area, as shown in Figure 1. Then, if the full grid and selected grid GGMplus data are compared, the anomalous contour pattern on the full grid follows the surface topography pattern. This also proves the statement of Hirt et al. (2013), namely GGMplus utilizes topographic gravity to increase the resolution of anomalies which makes it dependent on surface topography.

In the Kadidia - South Kadidia Geothermal Prospect Area (Figure 4), although on the south side, there is a difference where gravity field measurements tend to form low anomalies, and GGMplus shows an anomalous gradation, overall, the GGMplus CBA anomaly pattern has a good pattern in common with field gravity. These results also indicate an indication of a graben from the middle to the east and southeast of the study area, which is characterized by low anomalies. This low anomaly is likely to be closely correlated with the presence of the Palu-Koro fault segment that emerges towards the Kadidia area.

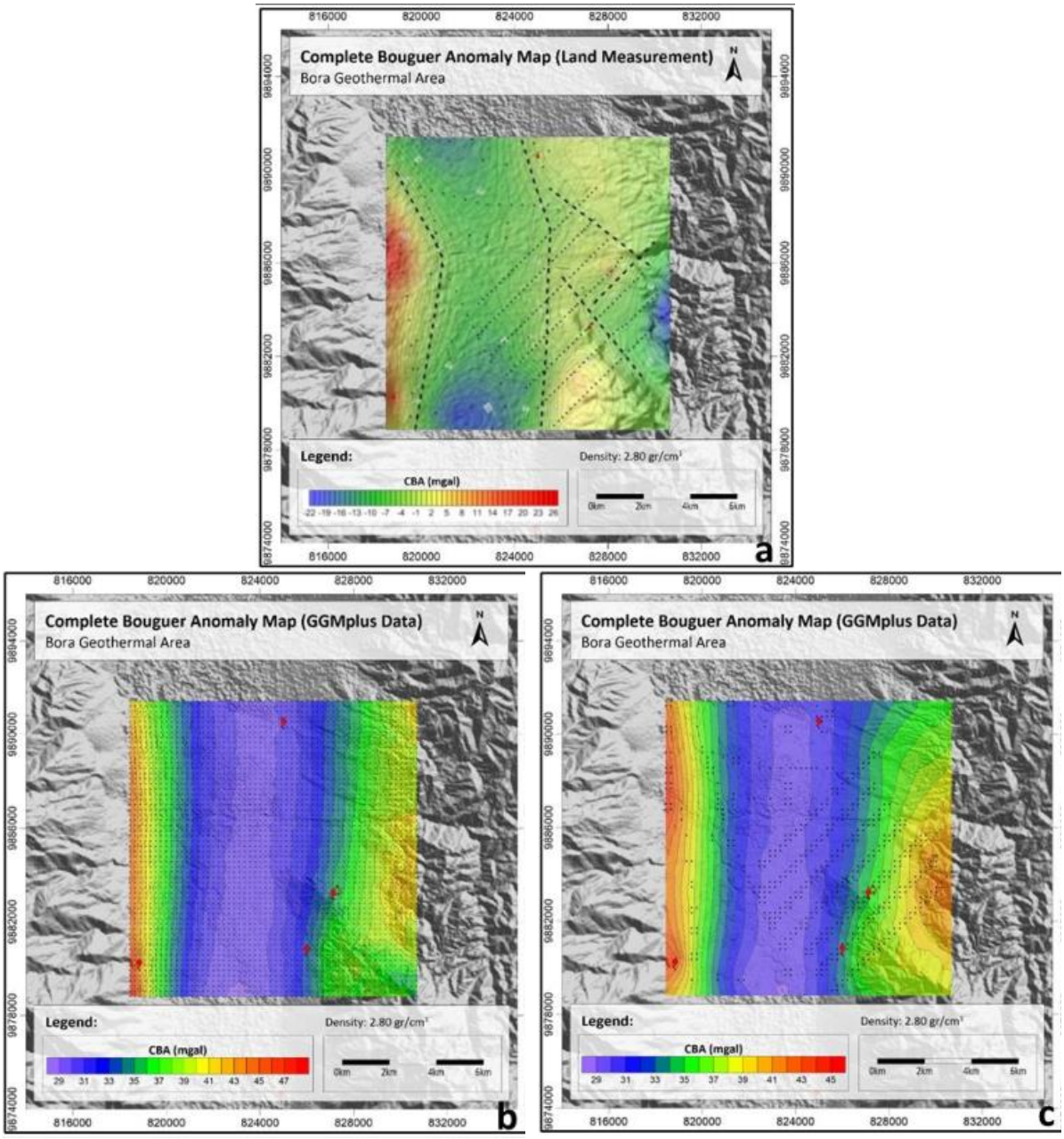


Figure 2: Bora gravity results: (a) CBA map from land measurement (modified from EBTKE, 2017), (b) CBA map from GGMplus data with density same as land measurement and grid using all GGMplus stations, (c) CBA map from GGMplus data with density obtained by Parasnis curve and grid stations selected similar to land measurements.

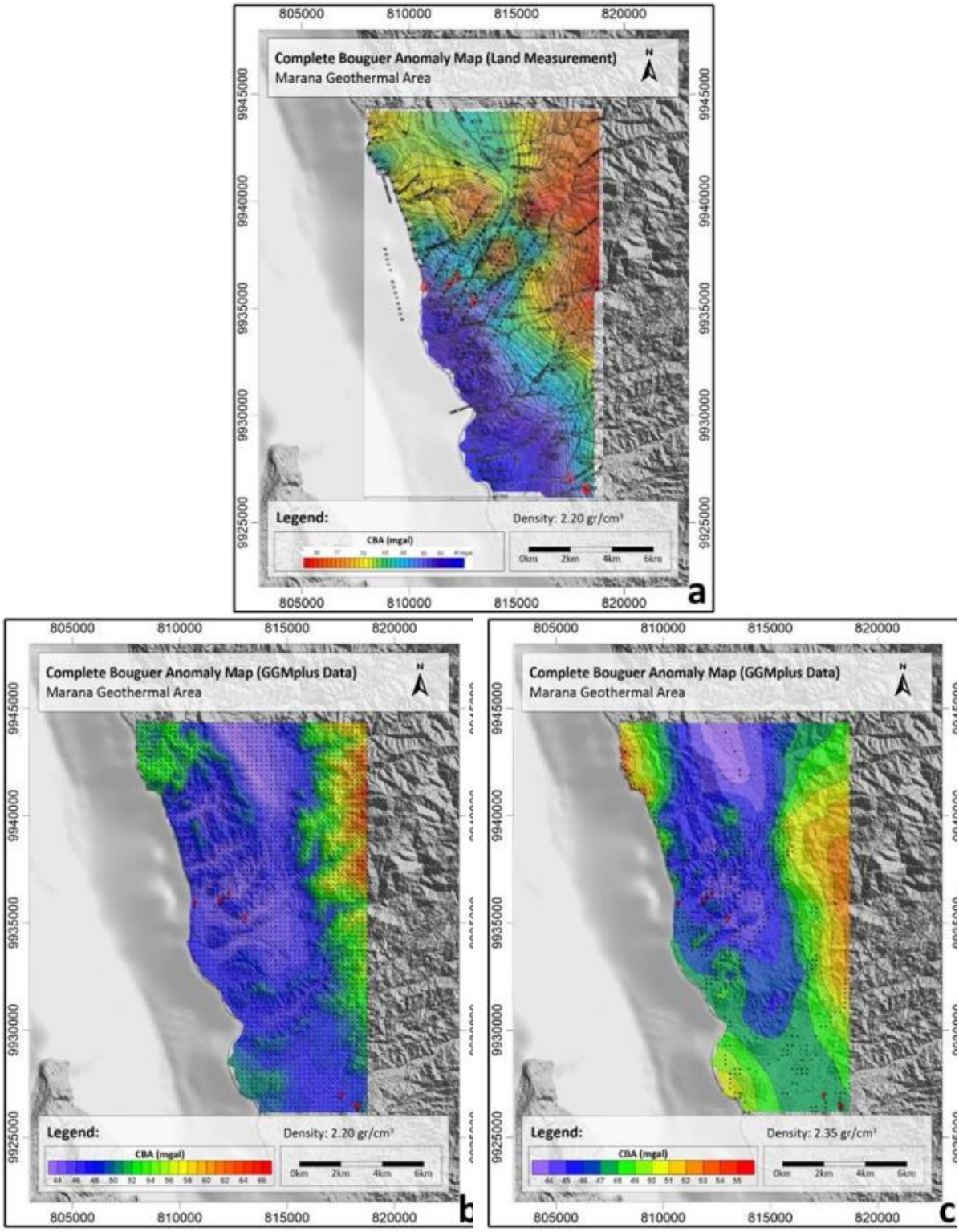


Figure 3: Marana gravity results: (a) CBA map from land measurement (modified from Putra, 2006), (b) CBA map from GGMplus data with density same as land measurement and grid using all GGMplus stations, (c) CBA map from GGMplus data with density obtained by Parasnis curve and grid stations selected similar to land measurements.

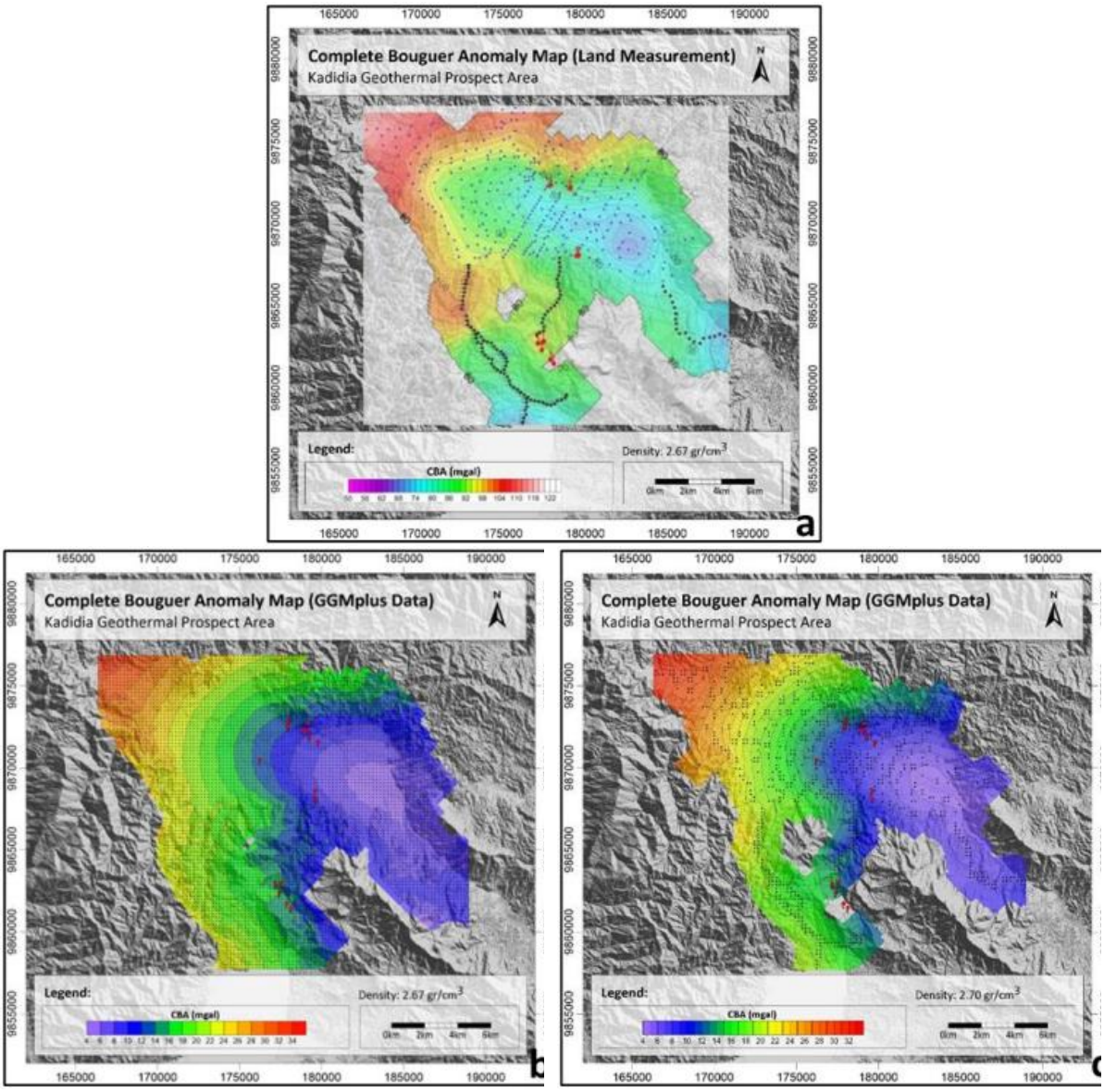


Figure 4: Kadidia-South Kadidia gravity results: (a) CBA map from land measurement (modified from Rahadinata & Nurdin, 2014), (b) CBA map from GGMplus data with density same as land measurement and grid using all GGMplus stations, (c) CBA map from GGMplus data with density obtained by Parasnis curve and grid stations selected similar to land measurements.

4. CONCLUSION

From some processing results, GGMplus data generally correlate well with field gravity data. In the Bora and Kadidia – South Kadidia areas, GGMplus has the same pattern as the field gravity data. Whereas in the Marana area, the GGMplus anomaly contour shows a more regional pattern and cannot detect local anomalies. Even so, GGMplus data is proven to detect high-low-high patterns that form grabens in the Palu-Koro fault zone. These results show that GGMplus satellite data can be useful for mapping faults that control low-to-moderate-temperature geothermal systems.

ACKNOWLEDGEMENT

The author thanks Hirt et al. for research conducted in developing high-resolution satellite gravity technology and Curtin University, Australia, for providing data in an open-source manner. The author also thanks the Center for Geological Resources, Directorate of Geothermal - Directorate General of New, Renewable Energy, and Energy Conservation, and Ministry of Energy and Mineral Resources for the availability of the Indonesian Geothermal Potential book and the website www.geoportal.esdm.go.id which can be accessed publicly to support any geothermal research development.

REFERENCES

Directorate of Geothermal, Directorate General of New, Renewable Energy, and Energy Conservation (EBTKE). (2017). Potensi Panas Bumi Indonesia Jilid 2. Jakarta: Ministry of Energy and Mineral Resources.

Directorate General of New, Renewable Energy and Energy Conservation (EBTKE). (2020). Strategic Plan (Renstra) for 2020-2024. Jakarta: Ministry of Energy and Mineral Resources.

Hennig, J., Hall, R., Forster, M. A., Kohn, B. P., Lister, G. S. (2017). Rapid cooling and exhumation as a consequence of extension and crustal thinning: Inferences from the Late Miocene to Pliocene Palu Metamorphic Complex, Sulawesi, Indonesia. Tectonophysics, 712–713, 600–622. http://doi.org/10.1016/j.tecto.2017.06.025

Hirt, C., Claessens, S.J., Fecher, T., Kuhn, M., Pail, R., Rexer, M. (2013), New ultra-high resolution picture of 2 Earth's gravity field, Geophysical Research Letters, Vol 40, https://doi.org/10.1002/grl.50838

Liu, C., & Shi, Y. (2021). Space-time stress variations on the Palu-Koro fault impacting the 2018 Mw 7.5 Palu earthquake and its seismic hazards. Geochemistry, Geophysics, Geosystems, 22, e2020GC009552. https://doi.org/10.1029/2020GC009552

Putra, R. A. (2006). Pemodelan Geofisika Terpadu Sistem Panasbumi Marana/Marawa Kab. Donggala, Sulteng Berdasarkan Data Gravitasi dan Geolistrik [Integrated Geophysics Modeling of the Marana/Marawa Geothermal System, Donggala District, Central Sulawesi Based on Gravity and Geoelectric Data]. Depok: Perpustakaan Universitas Indonesia.

Putriyana, L., Daud, Y., Saha, B., Nasruddin. (2022). A comprehensive data and information on low to medium temperature geothermal resources in Indonesia: a review. Geomechanics and Geophysics for Geo-Energy and Geo-Resources. 8. https://doi.org/10.1007/s40948-022-00375-5

Rahadinata, T., Nurdin, N. M. (2014). Survei Terpadu AMT dan Gaya Berat daerah panas bumi Kadidia Selatan, Kabupaten Sigi, Provinsi Sulawesi Tengah [Integrated Survey of AMT and Gravity of the South Kadidia geothermal area, Sigi Regency, Central Sulawesi Province]. Pusat Sumber Daya Geologi, Kementrian Energi dan Sumber Daya Mineral [Center for Geological Resources, Ministry of Energy and Mineral Resources].

Suprianto, A., Supriyadi, Priyantari, N., Cahyono, B. W. (2021). Journal of Physics: Conference Series, Volume 1825, 10th International Conference on Physics and Its Applications (ICOPIA 2020) 26 August 2020, Surakarta, Indonesia. https://doi.org/10.1088/1742-6596/1825/1/012023

Wibowo, A. E. A., Nurhadi, M., Rezky, Y., Hermawan, D., Setiawan, D. I. (2015). Determination of Reservoir Similarity of Kadidia and Kadidia Selatan Geothermal Systems based on Geochemical Method in Sigi Regency, Central Sulawesi Province. Buletin Sumber Daya Geologi Volume 10 Nomor 2 – 2015.

Identification of New Geothermal Manifestation Using Remote Sensing Method at Solok, West Sumatera

Ghaly Yana Putra, Maulana Mafazan Budiyanto, Safira Auriska Qurotta Aini, Kamila Azzahra Meinareza, Dani Mardiati, and Sutarto

Teknik Geology UPN "Veteran" Yogyakarta

yanaghaly60@gmail.com

Keywords: Geothermal, Lineament, LST, Remote Sensing, Solok

ABSTRACT

Geothermal is an eco-friendly energy sector with large reserves in Indonesia. Therefore, this energy can contribute to achieving Indonesia's NET Zero Emission target in 2060. Solok, West Sumatra, is one area with geothermal potential. However, it has yet to be extracted and is still in exploration. This research aims to identify the possibility of new geothermal manifestations in Solok Regency so that it can be used as a reference for further geothermal exploration. The research area is composed of quaternary volcanic rocks and Permian metasediment situated within the western part of the Sunda Island arc and influenced by the Great Sumatran Fault. Several analyses include the interpretation of geothermal systems from geology and geomorphology conditions, Land surface Temperature Day time and Night time analysis, Fault Fracture Density analysis, and Land Cover correction. The data used in this research are Landsat 8 OLI/TIRS for Geomorphology interpretation and creating Land Cover Map, DEM Image for Fault Fracture Density Analysis and geomorphology interpretation, and ASTER Image for Land Surface Temperature analysis during Day Time and Night Time. Geology and Geomorphology analysis are used to detect the possibility of geothermal systems, while the results of Land surface temperature and Fault Fracture Density are used to determine manifestation points which are then corrected by land cover. Daytime LST analysis results have a temperature range of 10oC to 46oC with an average temperature of 26oC, while Nighttime LST analysis results have a temperature range of 12oC to 27oC with an average temperature of 20oC. Meanwhile, the Fault Fracture density analysis produces a high FFD value of 4-7.34 Km/Km2. This research identified manifestation sites that correspond to the distribution of existing hot spring points with 83.33% accuracy. Moreover, this research interpreted twenty (20) new geothermal manifestation sites distributed mostly in the X Koto Singkarak district, west of Solok City.

1. INTRODUCTION

Geothermal is one of the renewable energy sources that can be used as an alternative to the fulfillment of eco-friendly national energy. One area that has potential in Indonesia is in Solok, Solok, West Sumatra because there are geothermal manifestations in the form of five hot springs (Hermawan et al., 2011) and supported by the presence of Argillic and propylitic alteration in the area (Sukaesih et al., 2015). Putriyana & Soekarno (2016) have conducted research related to reservoir temperature, which is between 176°C to 199°C with a hot water system. In addition, according to Sasilani et al. (2019), Solok geothermal prospect area is located in the area around Lawi and Lakuak hot springs from Fault Fracture Density (FFD) method.

Solok in general formed in the Median Graben between Solok and Singkarak. The morphology of Solok consists of volcanic hills, morphology unit, non-volcanic morphology unit, and plain morphology unit. Solok consists of 4 rock units. These are Limestone (Kuantan Formation), Limestone (Suhur Formation), Unseparated Volcanic Material, and River Alluvium deposits. Physiographically, the study area is included in the Semangko zone and the Jajaran Barisan zone (Bemmelen, 1949) which is composed of 4 rock units, namely the Limestone member of Kuantan Formation (PCkl), the Limestone member of Suhur Formation (TRtl), the Unseparated Volcanic material unit (QTau), and River Alluvium deposits (Qal) (Silitonga, P.H. & Katsuwo, 1995).

In general, geothermal systems have manifestations on the earth's surface, in the form of hot springs, fumaroles, mud pools, geysers, and other types of manifestations (Saptadji, 2012). These manifestations are associated with the release of hydrothermal fluids to the surface due to fractures. As a result, the surface temperature rises and hydrothermal alteration occurs. Therefore, geothermal manifestations can be identified based on temperature anomalies higher than the surroundings and the number of structures in an area.

Based on the description above, there has been no research on the distribution of new geothermal potential points in this area. Therefore, this research aims to identify new manifestation points through remote sensing methods on the temperature anomalies, alignment density, and land cover which are expected to be a reference for further geothermal exploration. Please be very careful to use styles throughout the document, so that all the papers will have a similar appearance.

2. METHODS

The method used in this research is remote sensing. It is using three images, namely ASTER, Landsat-8 OLI/TIRS, and DEM to find geothermal potential based on geology and geomorphology, surface temperature anomalies at night and day, straightness density, and land cover evaluation. The geology and geomorphology of the study area are used as basic clues to the existence of geothermal systems. In addition, Fault Fracture Density (FFD), night LST, and day LST is used to find geothermal manifestation points such as hot spring and fumarole. Meanwhile, the land cover map is used to evaluate areas that are unlikely to be read as geothermal manifestation points, namely interference from residential land cover.

Table 1: Image Data Used.

Image Name	Band	Resolution	Acquisition time
ASTER Day time	VNIR (1-3) SWIR (4-9) TIR (10-14)	15 m 30 m 90 m	3 July 2007
ASTER Night Time	VNIR (1-3) SWIR (4-9) TIR (10-14)	15 m 30 m 90 m	25 May 2009
Landsat-8 OLI/TIRS	Band 1- 6 Band 8	30 m 15 m	17 July 2021
DEMNAS		0.27 Arc second	Accessed 24 May 2022

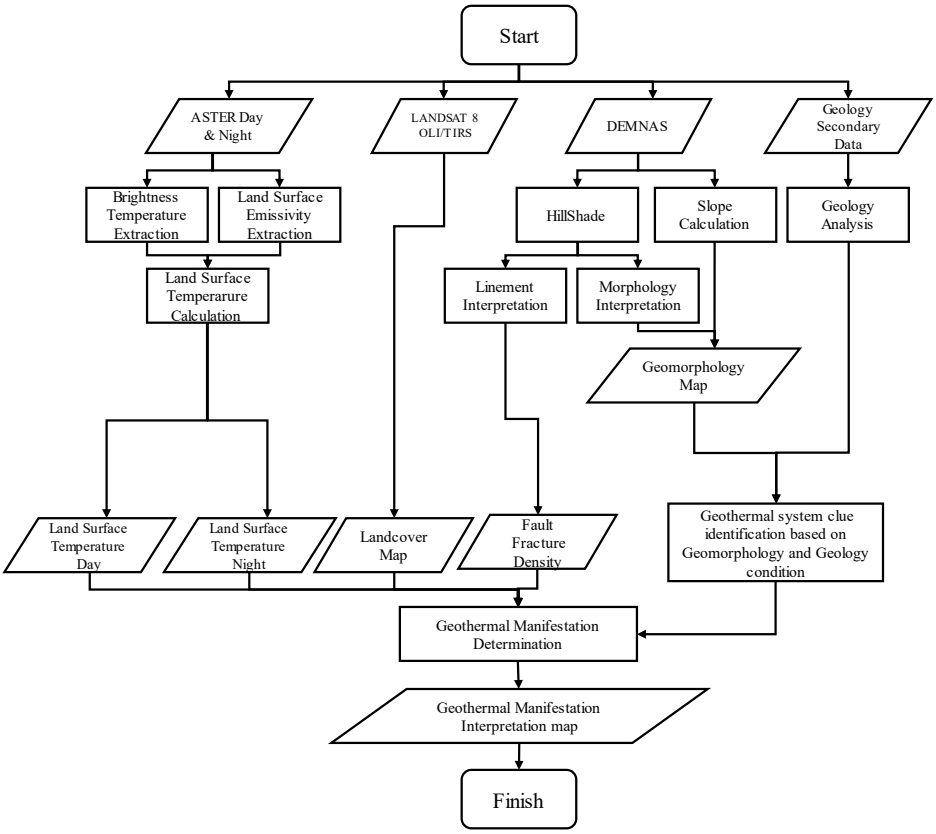


Figure 1: Research Flowchart.

2.1 Geomorphology Map Construction

Geomorphology maps were created based on DEM images through qualitative and quantitative analysis in ArcGIS 10.4.1. Qualitative analysis was conducted based on the shape of the earth's face from the hillshade tool. Meanwhile, quantitative analysis was conducted based on slope calculations.

2.2 Geological Map

The Geological map used is secondary data by Hermawan (2011).

2.3 Surface Temperature Calculation

The analysis was conducted with the software ENVI using ASTER day and night images. The analysis begins with Radiometric calibration correction and atmospheric correction to remove atmospheric scattered radiation errors. Followed by brightness temperature extraction with emissivity normalization tools performed on each ASTER night and day.

2.3.1 Land Surface Emissivity (LSE) Calculation

The LSE value is needed to generate the Land Surface Temperature value (formula 5) which is obtained from processing NDVI, the proportion of vegetation, and emissivity calculations on ASTER day Image (Ndossi & Avdan, 2016).

a. NDVI (Ndossi & Avdan, 2016)

$$\text{NDVI} = \frac{NIR - RED}{NIR + RED} \quad (1)$$

NIR represents the reflectance of the near-infrared band and RED represents the reflectance of the red channel on ASTER.

b. Proportion of Vegetation (Ndossi and Avdan, 2016)

$$Pv = \frac{NDVI - NDVI_S}{NDVI_v - NDVI_S} \quad (2)$$

Where NDVIv represents NDVI values on vegetated surfaces and NDVIs represent NDVI values on the surface without vegetation taken from sampling values on NDVI raster pixels.

c. Land Surface Emissivity (Ndossi and Avdan, 2016)

$$\varepsilon = \varepsilon_v \times Pv + \varepsilon_s(1 - Pv) \quad (3)$$

ε_v is the emissivity of the vegetated surface and ε_s is the emissivity of the bare soil surface. These two values are obtained from sampling the PV values and then calculated with the following formula:

$$\varepsilon = 0.941 + 0.04Pv \quad (4)$$

2.3.2 Land Surface Temperature (LST) Calculation

The LST calculation is performed using the Plank Function inversion method which is formulated as follows (Ndossi and Avdan, 2016):

$$LST = \frac{BT}{1 + \left[\frac{\lambda \times BT}{\rho}\right] \times \ln \varepsilon} \quad (5)$$

Where λ is the wavelength of the daisy channel and ρ is 1.438×10^{-2} m·K.

2.4 Land Cover Analysis

The land cover raster is obtained by the supervised method on Landsat-8 OLI/TIRS band 1-7 which has previously been pan-sharpened with band 8. The supervised method used is the maximum likelihood of the sample area that is manually delineated from the Landsat-8 OLI/TIRS band 1-7 image.

2.5 Fault Fracture Density (FFD) Map Construction

This analysis used the hillshade tools from the DEM processed with ArcGIS. Straightness was analyzed qualitatively on each hillside with the N045˚E, N135˚E, N225˚E, and N315˚E irradiation directions. The results of the qualitative analysis of the straightness of each irradiation direction were combined and used to obtain the Line Density value (quantitative).

2.6 Manifestation Point Determination

Determination of the manifestation point is done by selecting the surface temperature anomaly area that is equally high on LST day and LST night. Then, the land cover is corrected by removing the value of each settlement pixel. After that, points outside the medium-high FFD area were eliminated, so the geothermal manifestation distribution points were obtained.

3. RESULT AND DISCUSSION

3.1 Geomorphological Condition

Qualitative and quantitative analysis of the study showed several landforms of structural, volcanic, and fluvial origin.

a. Structural Landform

- Structural hills: Landforms arising from the presence of the Mundak water fault and Solok fault.
- Fault Scrap: In the caldera section, steep slopes are found, characterized by tight contours.

- Fault ridge: The result of the appearance of straightness formed by the influence of tectonic factors in the form of faults in the study area

b. Volcanic Landform
In qualitative and quantitative analysis, inward-oriented formations were found that characterized the presence of the calderas with the discovery of volcanic product materials in the form of pyroclastic flows, lava flows, volcanic lakes, and fluvial-volcanic deposits.

c. Fluvial Landform
Fluvial landforms are formed due to surface water transportation processes in the form of degradation and aggradation processes. This landform at the study site is a carrier of volcanic material to lower parts. There is also an alluvial fan that is visible after quantitative analysis based on the slope value.

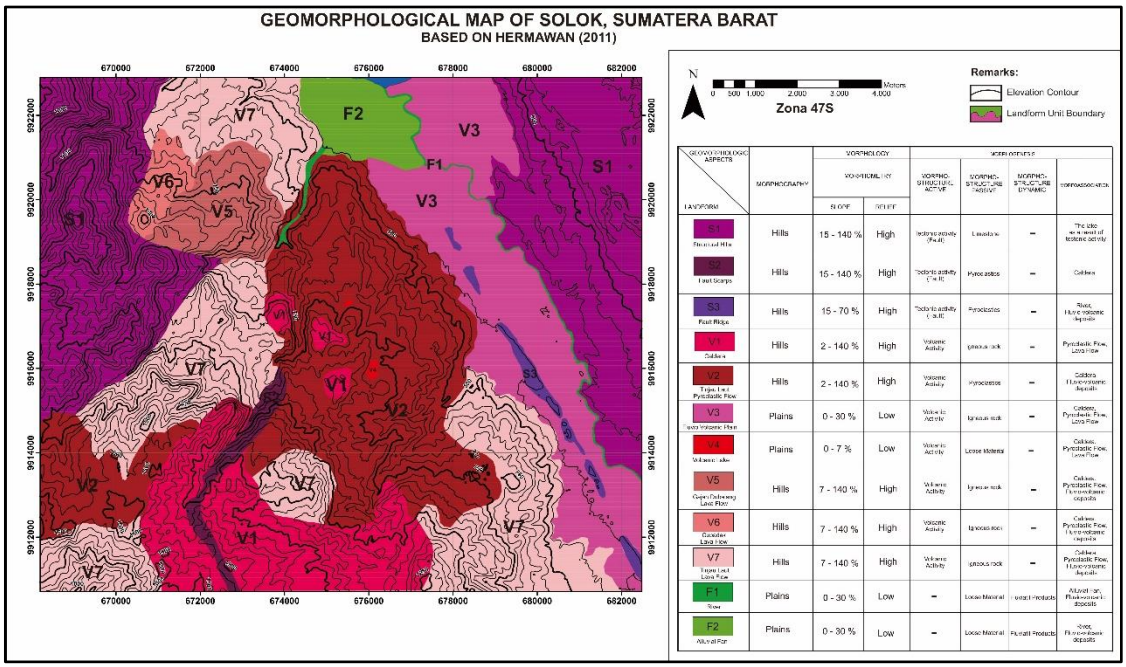


Figure 2: Geomorphological Map of Study Area.

Based on the results of geomorphological analysis, many landforms show mature - old stadia volcanic activity, such as calderas and ridges of a lava flow or pyroclastic flows that have begun to denudate. This indicates that the Solok area has old volcanism which can be a clue to the existence of a heat source from the volcanic system. In addition, the presence of structural morphology that indicates faults can indicate that the Solok area is tectonically active. This association of volcanic and structural landforms can indicate the possibility of a potential geothermal system, especially the presence of heat source components, reservoirs, and recharge areas.

3.2 Geological Condition

The Solok area is located in the Median Graben between Solok and Singkarak which is included in the great Sumatra fault that is still active today. This is evidenced by the presence of a northwest-southeast trending fault that indicates tectonic activity of the Solok-Singkarak segment during the Quaternary. The Quaternary tectonics is reflected by the eruptive activity of the fissures seen in the presence of white ignimbrite tuff in this graben which is closely related to tectonics and volcanoes. In addition, there are small fault lines (scraps). The morphology consists of a volcanic hills morphology unit, non-volcanic hills morphology unit, and a plain morphology unit.

- The Solok area consists of several rock units (Hermawan, 2011) which can be seen in Figure 3 namely:

- Permian aged matalimestone
- Tertiary volcanic rocks

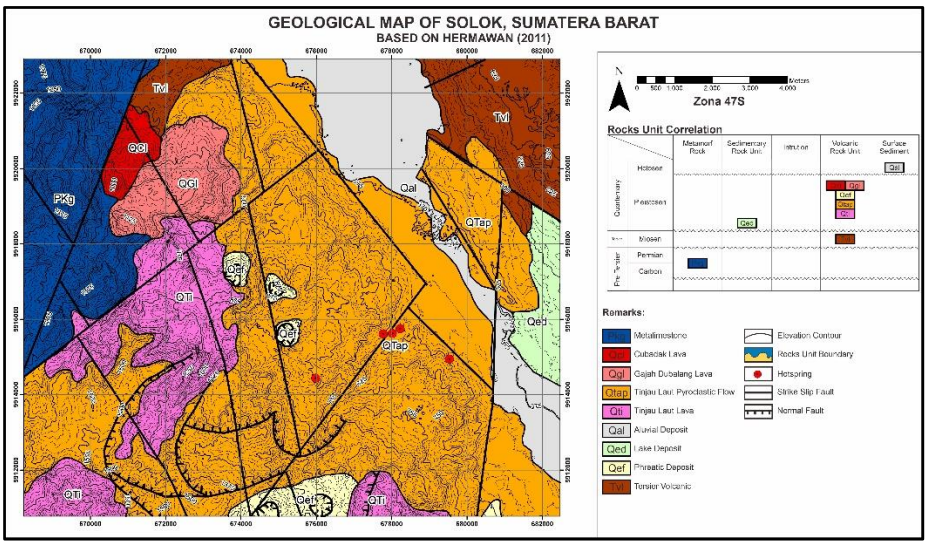


Figure 3: Geological Map of Study Area.

Pleistocene-aged rocks, including lava units and pyroclastic, flows of marine age, Gajah dubalang lava, phreatic deposits, and Pleistocene-aged Cubadak lava

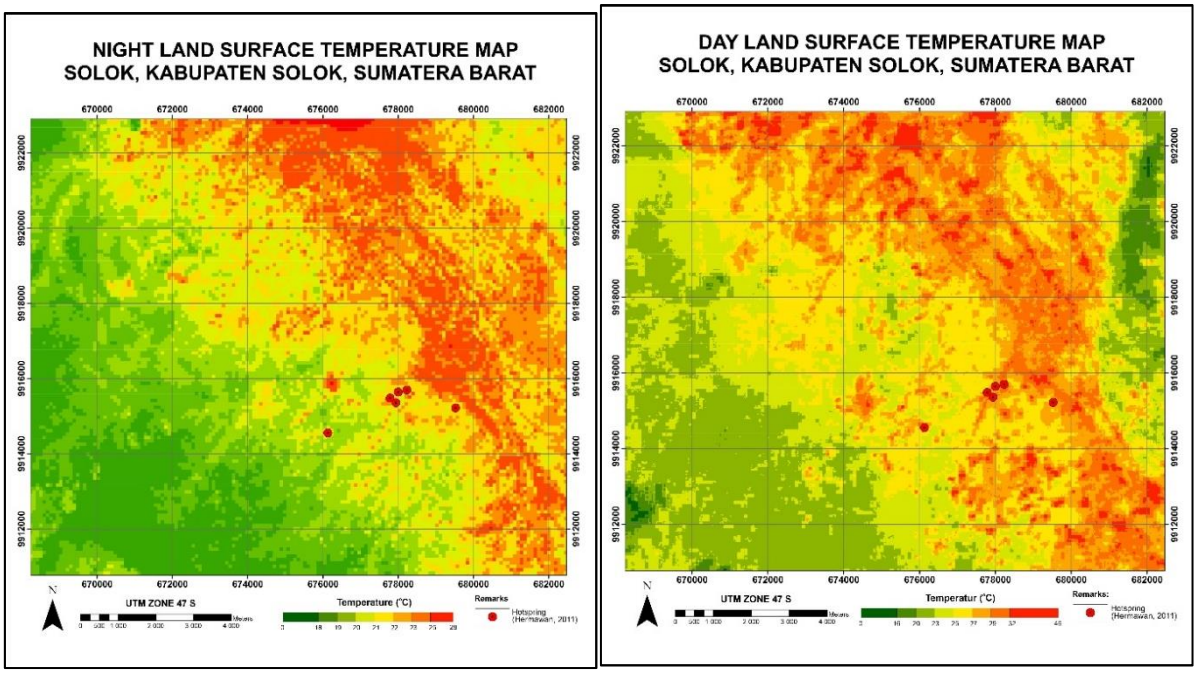
Furthermore, the geology of this region is controlled by a regional dextral fault that extends northwest-southeast, resulting in numerous fault structures. Additionally, significant volcanic activity occurred from the Mio-pliocene period, forming overlapping volcanic cones that resulted in interlocking calderas in the western region.

3.3 Land Surface Temperature

The results of the LST calculation on the day ASTER image showed a maximum temperature is 46.82°C, a minimum temperature of 15.33°C, and an average temperature is 26.61°C. The heat distribution is located in the central part and stretches from the northwest to the southeast, a low-temperature area with many settlements. Meanwhile, the southwestern to northern parts of the map are hilly areas covered with vegetation and dominated by moderate to low temperatures.

Similarly, the results of LST calculation on the night ASTER image showed a maximum temperature is 28.78°C, a minimum temperature is 15.87°C, and an average temperature is 21.06°C. The heat distribution is almost similar to the LST on the day ASTER image, but the southwestern part is much cooler on the night ASTER image, and the distribution of low temperatures in the northwest is narrower than in the day ASTER image.

In Figure 4, it can be seen that the temperature of the body of water at night will be higher than the surrounding land at the same altitude. Conversely, during the day, the temperature of the water is lower or almost the same as the surrounding land at the same altitude. However, if the water is a manifestation of geothermal its temperature will always be warmer than its surroundings both at night and during the day due to the steady heat source (Wang et al., 2019). This is one of the criteria for determining geothermal manifestation points in this study, where manifestations are characterized by temperature anomalies hotter than the surroundings during the day or night.



(a) (b)

Figure 4: (a) Night and (b) Day Land Surface Temperature of Study Area.

3.4 Fault Fracture Density (FFD)

This analysis yielded three density-orientation classes marked by the colors red, green, and yellow. The green color represents the smallest density range values of 0-230 Dam/Km2, occupying 30% of the map. The yellow color has a medium density level and ranges from 230-391 Dam/Km2, occupying 50% of the map. The red color has the highest density range values of 391-734 Dam/Km2, occupying 20% of the map.

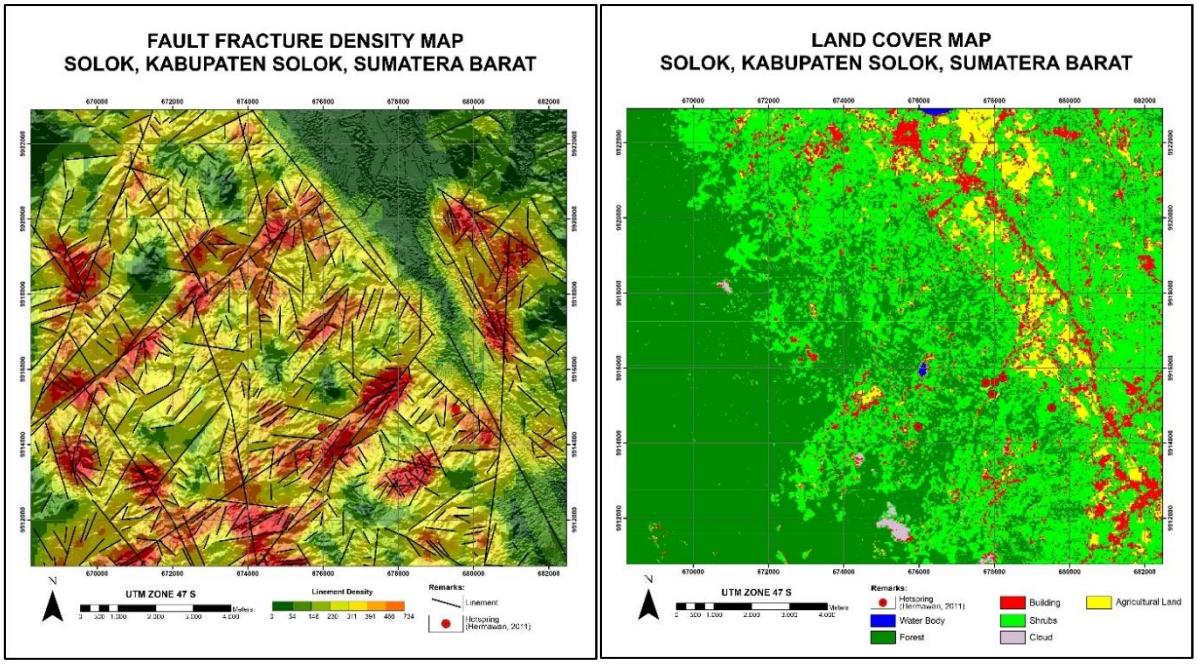
The hot springs in the study area are located in areas with high density. This is consistent with Soengkono's opinion that areas with high-density values can indicate the outflow or upflow zones of hydrothermal fluids as a manifestation of geothermal energy. Therefore, pixels with high-density orientation in this study can be used to determine geothermal manifestation points. In addition to functioning as a pathway for fluid ascent, structures can also act as a recharge area. Therefore, the high FFD values around the manifestation can be interpreted as a recharge area depending on the lithological conditions and the relationships between the structures.

3.5 Land Cover Map

The land cover in the study area is classified into several objects, including water bodies (blue), dense vegetation or forests (dark green), shrubs (light green), agricultural land (yellow), settlements (red), and clouds (grey) (Figure 5b). The interpretation results from the land cover map are used to correct the Land Surface Temperature (LST) map as there is a possibility of temperature anomalies being influenced by settlements. In addition, clouds are also used to correct the results of hot spring manifestation distribution as they have non-representative reflectance data.

3.6 Determination of Hot Spring Manifestation Points

Based on LST night and day, FFD, and Landcover, the Determination results of hot spring manifestation points are obtained as shown in Figure 6. Two classes of hot spring manifestation determination results are obtained, namely high-confidence hot spring manifestation points (red) and medium-confidence hot spring manifestation points (orange). The red pixels are obtained from hot spring manifestation points based on LST day and night corrected by land cover in areas with high FFD, while the orange pixels are in areas with medium FFD values. Additionally, the predicted determination results of hot spring manifestation points are spread in areas of volcanic lithology affected by faults.



(a) (b)

Figure 5: (a) Fault Fracture Density Map and (b) Land Cover Map of Study Area.

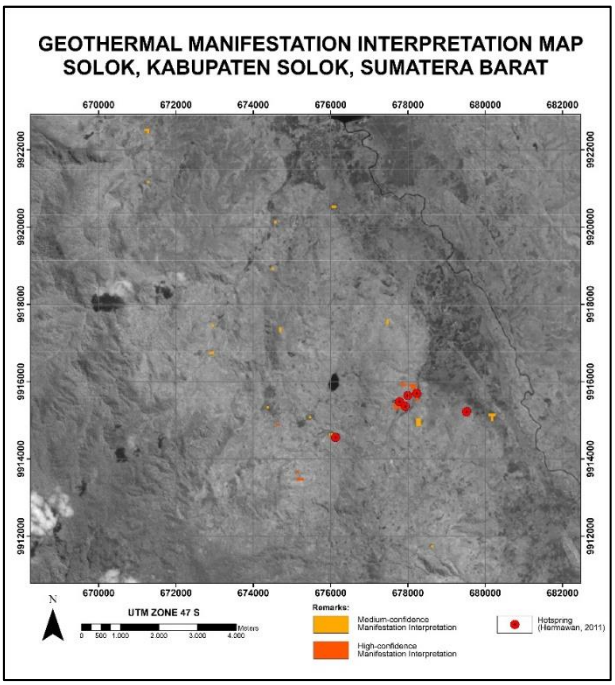


Figure 6: Geothermal manifestation interpretation map.

The results show that 5 out of 6 hot spring manifestation points by Hermawan (2011) have a positive correlation with the determination results of hot spring manifestation points in this study. Therefore, the other determination results have an 83.33% chance of containing hot spring manifestation points. Manifestations that can be identified using this method are those with higher temperatures than their surroundings, such as hot springs, solfatara, and mud pools since the reference used is the surface temperature anomaly.

4. CONCLUSION

The Sumani area has the potential to have a geothermal system based on its geological and geomorphological conditions, as well as the presence of geothermal manifestations around the lava unit.

The predicted geothermal manifestations determined from this study are visible in Figure 6 and have an accuracy of 83.33%. Therefore, other points may contain geothermal manifestations. However, this study still has limitations since it did not consider subsurface conditions using gravity methods and alteration of mineral distribution on the surface.

REFERENCES

Bemmelen, R. W. Van. (1949). *The Geology of Indonesia*. The Haque.

Hermawan, D., Widodo, S., S, R., K, D., Kholid, M., Zarkasyi, A., & J, W. (2011). Geologi, Geokimia, dan Geofisika Daerah Panas Bumi Sumani, Provinsi Sumatera Barat. *Buku 1: Bidang Energi*.

Ndossi, M. I., & Avdan, U. (2016). Inversion of land surface temperature (LST) using terra aster data: A comparison of three algorithms. *Remote Sensing*, 8 (12), 1–19. https://doi.org/10.3390/rs8120993

Putriyana, L., & Soekarno, H. (2016). Simulasi Pegembangan Lapangan Panas Bumi Di Sumatera Barat. *Ketenagalistrikan Dan Energi Terbarukan*, 15 (1), 33–44.

Saptadji, N. M. (2012). *Teknik panasbumi*. Dapartemen Perminyakan ITB.

Sasilani, R., Didit Haryanto, A., Hutabarat, J., Hermawan, D., & Widodo, S. (2019). Zone of Geothermal Prospects Based on Fault Fracture Density (Ffd) Method in Sumani Region, West Sumatera. *Journal of Geological Sciences and Applied Geology*, 3(2), 22–35.

Silitonga, P.H., A., & Katsuwo. (1995*). Peta Geologi Lembar Solok, Sumatera*. Pusat Penelitian dan Pengembangan Geologi.

Soengkono, S. (1999). Analysis of digital topographical data for exploration and assessment of geothermal systems. *21st New Zealand Geothermal Workshop*, 163–167.

Sukaesih, S., Rezky, Y., Rosana, M. F., & Mardiana, U. (2015). Alterasi Di Sumur Pengeboran Smn-1 Dan Smn-2 Di Daerah Panas Bumi Sumani, Kabupaten Solok, Propinsi Sumatera Barat. *Buletin Sumber Daya Geologi*, 10(3), 20–33. https://doi.org/10.47599/bsdg.v10i3.145

Wang, K., Jiang, Q. gang, Yu, D. hao, Yang, Q. lei, Wang, L., Han, T. cheng, & Xu, X. yu. (2019). Detecting daytime and nighttime land surface temperature anomalies using thermal infrared remote sensing in Dandong geothermal prospect. *International Journal of Applied Earth Observation and Geoinformation, 80* (May), 196–205. https://doi.org/10.1016/j.jag.2019.03.016

Waesano Geothermal Prospect Assessment

Luthfi Rahmawati, Airlangga Sani Cahya Margaliu, and Ambrosius Hernawan Wibisono

Universitas Lampung, Lampung, Indonesia

luthfirhmwti25@gmail.com

Keywords: Geothermal, Magnetotelluric, Caprock, Gravity, Geology Structure

ABSTRACT

Indonesia as a ring of fire area has a large potential for Geothermal energy resources. One of the largest potentials was found on Mount Waesano's slope in East Nusa Tenggara. Characterized by manifestations in the form of the Sanonggoang caldera and several hot springs. In 2017, the Directorate General of EBTKE estimates that the potential for speculative geothermal reserves in the area is 121 MWe. Geology and Geophysical is a suitable blend of earth sciences to determine the subsurface. Geology helps to identification the regional setting and Geophysics identifies the presence and thickness of the Caprock layer by magnetotelluric method (MT) and also identifies the presence of geological structure by gravity method. Magnetotelluric shows 1D inversion modeling consisting of 10 MT stations. 1D inversion model has validated by Second Vertical Derivative (SVD) of gravity method to analyze geology structure. The result shows the top layer of Caprock at a depth of 150 masl and the lowest layer at a depth of 2000 masl, an average thickness of 736 m was obtained. MT Station of MTWS-93 shows differences in resistivity values that were quite contrasting and were identified as fault structure and validation by SVD approve the station is in the zero contour zone, which represents the presence of geological structure. In addition, the MTWS-93 station is close to the manifestation which further strengthens the suspicion that there is a geological structure as a way for heat to escape from the earth's interior to the surface.

1. INTRODUCTION

Based on the Directorate General of EBTKE and the Geological Agency of the Ministry of Energy and Mineral Resources in 2017, geothermal resources in the Waesano area are estimated at 121 MWe. The existence of geothermal potential in Waesano is characterized by surface manifestations including Lake Waesano which is a caldera and a number of hot springs scattered around the Waesano volcano. Previously, in 2015 a research was conducted by the PSDMBP investigation group to determine geological and geochemical conditions. In the same year, some field surveys were conducted using geophysics' MT method, to determine the boundaries of the Waesano geothermal prospect area. However, no research has been conducted to determine the geothermal system using combined MT and gravity analysis.

The MT method can determine the distribution of rocks and layers in the subsurface by looking at the value of its specific resistivity, for caprock layer identification in a geothermal system. To get the subsurface structures of a geothermal area, a gravity anomaly analysis can be carried out by applying several analytical techniques. One of the methods is SVD (second vertical derivative) analysis (Sarkowi, 2010). So, in this study, the caprock layer and geological structures in the Waesano geothermal prospect area were analyzed using a combined MT 1D model and Gravity Second Vertical Derivative (SVD) method.

2. RESEARCH METHODOLOGY

2.1 Research Location

Administratively, the location of the research area is in Wae Sano Village, Sano Nggoang District, West Manggarai Regency, East Nusa Tenggara Province. Geographically, it is located at 8°42'54.9 "S 120°00'37.5 "E. The research was conducted around the area of surface manifestations such as calderas and hot springs by taking MT measurements as many as one track.

2.2 Regional Geology

The research site consists of volcanic structures including the Mbeliling caldera, Golo Leleng Depression, Waemunting Depression, Sano Nggoang Crater. Northwest-southeast oriented structures include Poco Dedeng Fault, Tantong Fault, Watuwangka Fault, Ndaring Fault, Werang Fault. Southwest-Northeast trending structures: Taal Fault, Lempe Fault, Nampar Fault. The main structures that control the Waesano area are the Namparpacing normal fault, the Wae Racang (Bobo) normal fault and the Waesano caldera.

The study area is dominated by the Old Volcano unit (QTv) which consists of a mixture of breccia, lava, and tuff composed of andesite and basalt. Wae Sano Young Volcano Unit (QVws) which is the result of the eruption of Mount Wae Sano consisting of tuff, passive tuff, and pumice tuff. The layered limestone unit (Tml) is characterized by having a gray color, solid in shape, containing inserts of tuffaceous limestone, quartz limestone, tuff, and conglomerate. This unit is covered harmoniously by tuffaceous limestone (Tmpl), and unconformably covered by volcanic rocks (Tlmv) (Ratman and Yasin, 1978). Then there is the Bari formation unit (Tmb) composed of limestone interspersed with passive limestone. The Nangapanda formation (Tmn) is composed of sandstone and limestone. Tanahau formation (Tmt) composed of lava, breccia, and tuff, greenish gray in color with dacite and pillow structure. The Kiro formation (Tmk) is composed of breccia, lava, and tuff with tuffaceous sandstone inserts (Koesoemadinata et al., 1994).

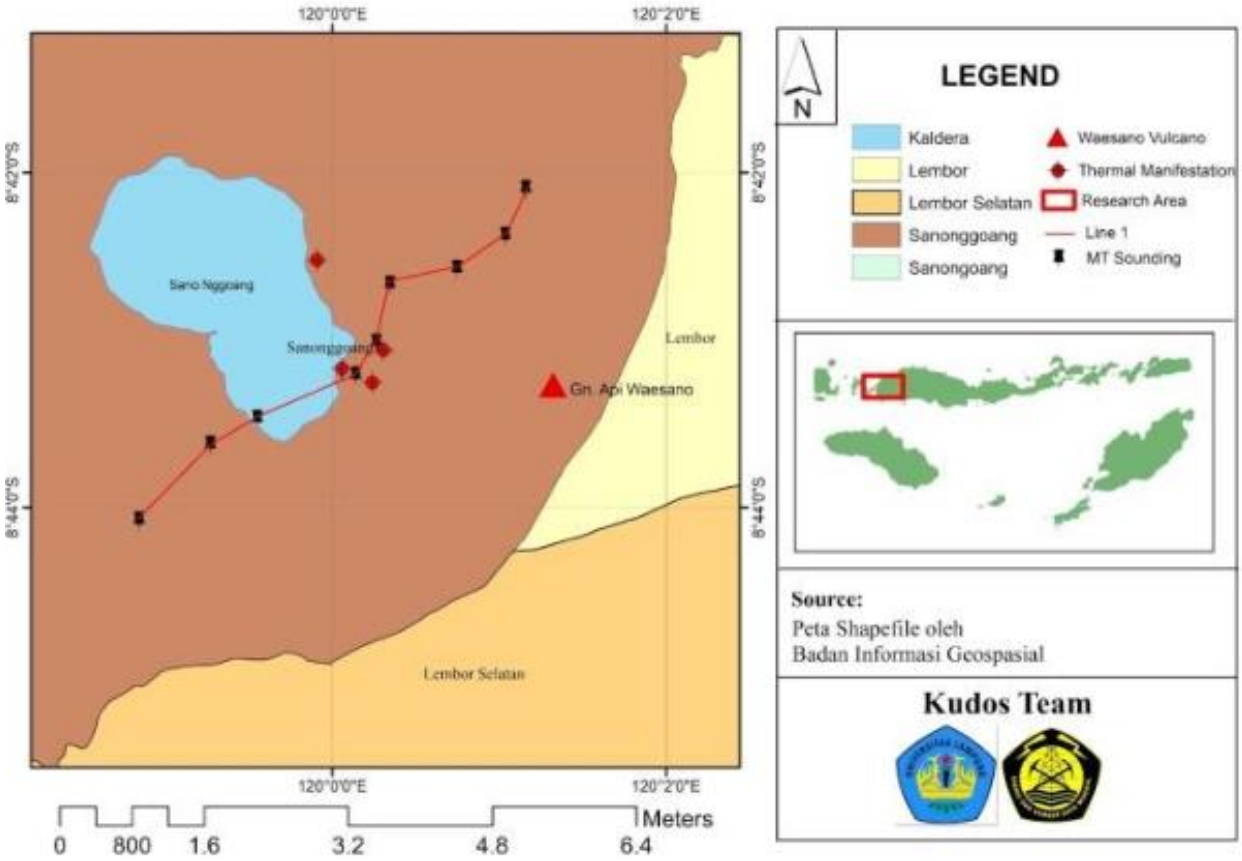


Figure 1: Research area location at Waesano, NTT.

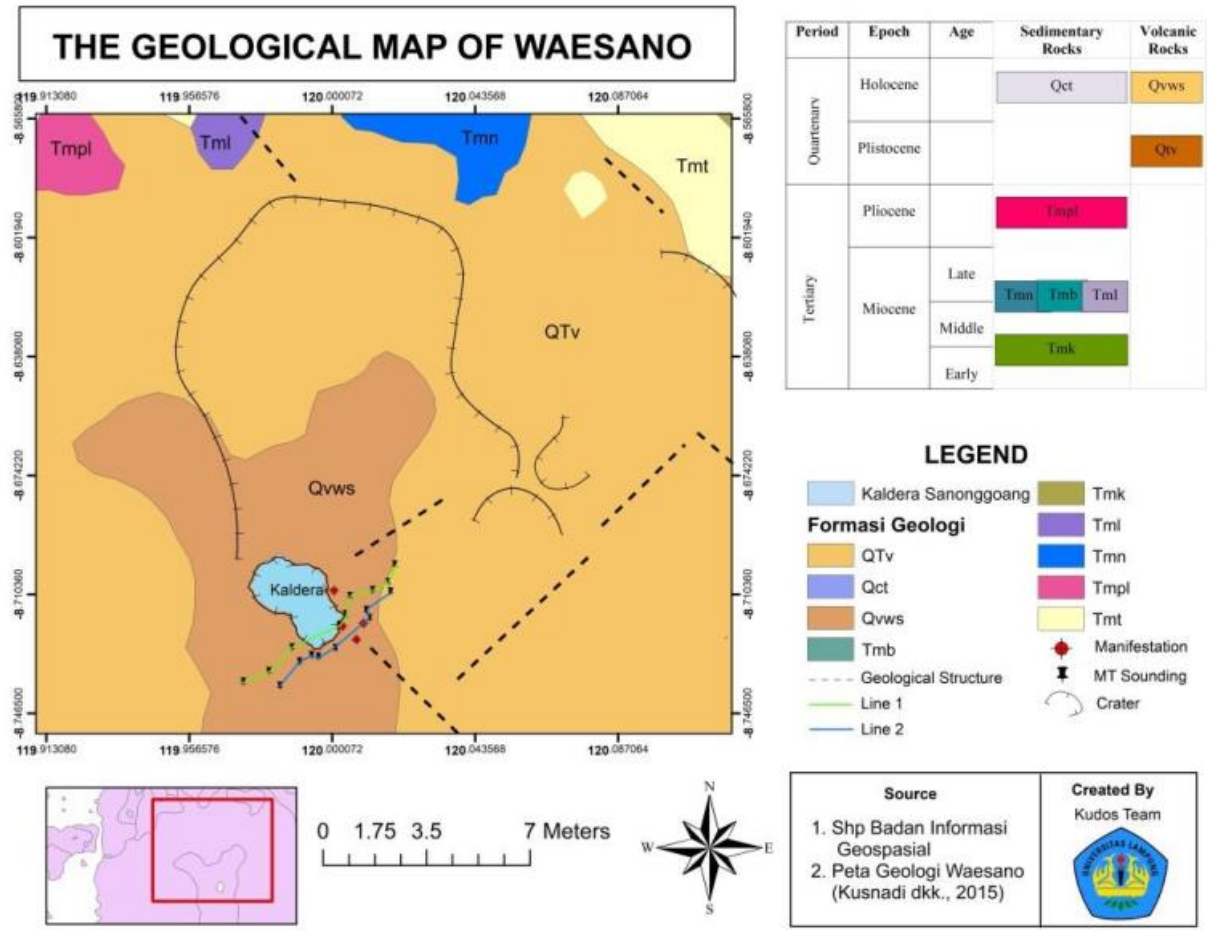


Figure 2: Geological map.

Based on Figure 2, it can be seen the sequence of rock units from the oldest to the youngest. The research area is composed of volcanic rocks and sedimentary rocks in the Quaternary and Tertiary periods. The measurement target area consists of old volcanic rocks aged around 0.0117-0 m.y and young volcanic rocks aged around 1.806-0.0117 m.y. Therefore, the Waesano area has geothermal prospects. Therefore, the Waesano area has good geothermal prospects due to its association with Quaternary volcanoes. According to Soeharno (2013), this category of prospect usually has a wide expanse of prospects. The permeability of the reservoir system is quite good due to the long development process of the geological structure.

2.3 Geochemistry Analysis

In 2015, PSDMBP conducted geochemical research on manifestations found in Waesano. The condition of the manifestation can be seen in Table 1.

Table 1: Surface manifestation of Waesano geothermal (PSDMBP, 2015).

Manifestasi	BT	LS	Elevasi	T_{AP} (°C)	T_{UD} (°C)	Debit (l/s)	pH	k (µS/cm)
APWS1	120° 00' 11"	8° 43' 02"	647	81,57	24,91	0,1	5,79	53.200
APWS2	120° 00' 04	8° 43' 07"	646	71,13	24,91	0,1	6,21	36.000
APWS3	120° 00' 15"	8° 43' 09"	680	36,8	24,30	0,5	3,67	627
Air Danau Sanonggoang1	120° 00' 09"	8° 43' 00"	646	30,27	24,91		2,52	3.930

In this study, geothermal fluid analysis was carried out using the Cl-SO4-HCO3 (Figure 3), Na-K-Mg (Figure 4), and Cl-Li-B (Figure 5) trilinear diagrams on surface manifestations around the measurement area.

Based on the plotting results on the Cl-SO4-HCO3 (Figure 3) diagram, it can be seen that APWS1 and APWS2 hot springs belong to the chloride water type with mature waters conditions and contain high chloride ions (Cl) with little sulfate and bicarbonate elements. Hot springs ADS1 and ADS2 belong to the same type of water, except that the chloride ion (Cl) content tends to be lower and under volcanic waters conditions. The low Cl concentration in these hot springs is likely due to the mixing of reservoir water with surface water on the way to the surface. The APWS3 and ADS3 hot springs can be seen to belong to the sulphate water type with volcanic waters.

The plotting results on the Na-K-Mg (Figure 4) diagram show that of all the hot spring samples, 4 of them are included in the immature waters type, namely APWS3, ADS1, ADS2, and ADS3. This means that the fluid in the hot springs has not been heated for a long time. In addition, this type of water contains a dominant concentration of Mg, suggesting that rock dissolution by Mg-rich meteoric water or rock dissolution near the surface has occurred. Hot springs that are in partial equilibrium include APWS1 hot spring with a temperature of 2200C, and APWS2 hot spring with a temperature of 2400C. According to Giggenbach (1988), geothermal fluids formed in this condition are good for estimating subsurface temperatures, especially in reservoirs.

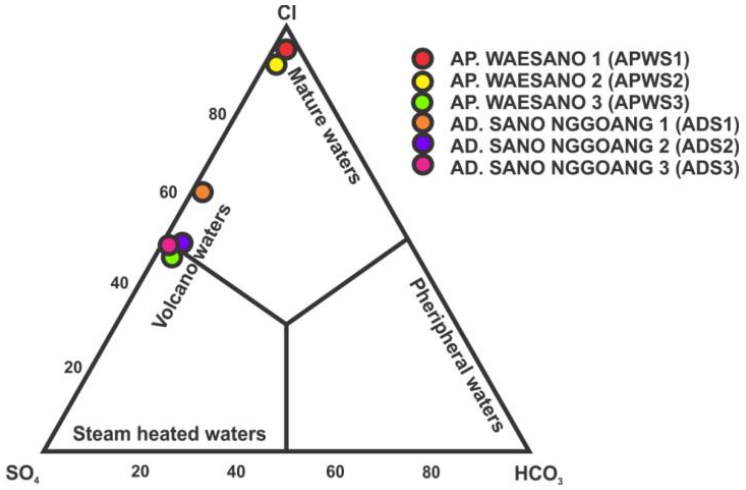


Figure 3: Diagram Triangle Cl-SO4-HCO3 (Modification of Kusani et al, 2015).

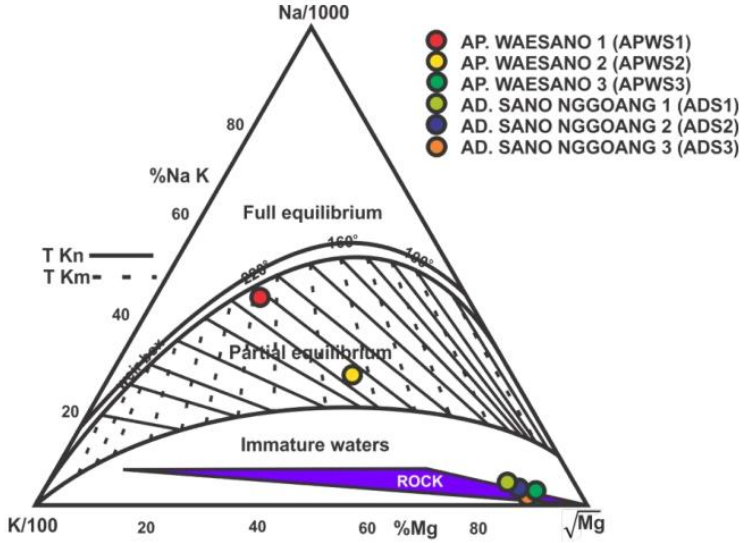


Figure 4: Diagram Triangle Na-K-Mg (Modification of Kusani et al, 2015).

The Cl-Li-B (Figure 5) triangle diagram can be used in determining the origin of hot water. It can be seen in Figure 5 that the plotted diagrams show that the positions of all hot springs tend to be in the Cl and B directions, indicating that the hot water interacts with the volcanic system. The content of Li concentration is low. Nicholson (1993) suggests that the low content of Lithium is because this ion is more easily absorbed by secondary minerals (e.g. quartz, clays, and chlorite). This is due to the reaction with rocks (in this case sediments) when heading to the surface, if the distance of fluid transfer to the surface is getting farther, the lithium concentration decreases. So, it can be concluded that the geothermal fluid is related to the geothermal system, but at a fairly deep layer and during migration to the surface a lot happens with other rocks.

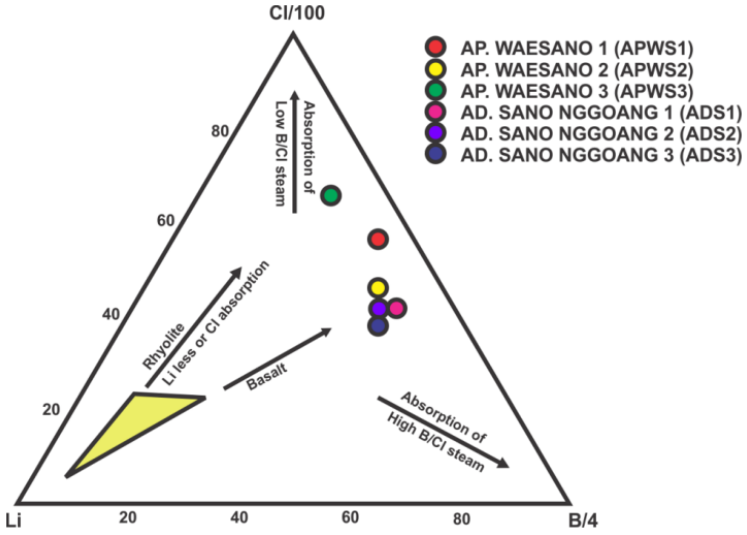


Figure 5: Diagram Triangle Cl-Li-B (Modification of Kusani et al, 2015).

The characteristics of Waesano geothermal fluid based on geochemical analysis using a triangular diagram are summarized in Table 2.

Table 2: Summary of geochemical analysis.

No.	Geothermal Fluids	Fluid Type	Fluid State	Fluid Origin
1.	Air Panas Waesano1 (APWS1)	Chloride Water (high Cl concentration)	*Partial Equilibrium*	Reservoir
2.	Air Panas Waesano2 (APWS2)	Chloride Water (high Cl concentration)	*Partial Equilibrium*	Reservoir
3.	Air Panas Waesano3 (APWS3)	Sulfate Water	*Immature Waters*	Reservoir
4.	Air Danau Sanonggoang 1 (ADS1)	Chloride Water (low Cl concentration)	*Immature Waters*	Reservoir
5.	Air Danau Sanonggoang 2 (ADS2)	Chloride Water (low Cl concentration)	*Immature Waters*	Reservoir
6.	Air Danau Sanonggoang 3 (ADS3)	Sulfate Water	*Immature Waters*	Reservoir

2.4 Research Methods

2.4.1 Magnetotelluric (MT) Method

The MT method is an electromagnetic (EM) sounding method to determine the subsurface type resistance structure by passively measuring the components of the electric field (E) and the natural magnetic field (H) that change with time using EM wave frequencies with a frequency spectrum of 10-5 Hz -104 Hz. At a low enough frequency (less than 1 Hz), the solar wind containing electrically charged particles will interact with the earth's main magnetic field, causing variations in the electromagnetic field (Grandis, 2010).

Maxwell's equation is a synthesis of experimental results on electrical and magnetic phenomena obtained by Faraday, Ampere, Gauss, Coulomb in addition to Maxwell himself (Grandis, 2010). In differential form, Maxwell's equations in the frequency domain can be written as follows:

$$\nabla \times E = -\frac{\partial \mathrm{B}}{\partial \tau} \quad (1)$$

$$\nabla \times H = J + \frac{\partial \mathrm{B}}{\partial \tau} \quad (2)$$

$$\nabla . D = q \quad (3)$$

$$\nabla . B = 0 \quad (4)$$

Description:

E = Electric Field (Volt/m)

B = Flux or Magnetic Induction (Weber/m^2 Atau Tesla)

H = Magnetic Field (Ampere/m)

J = Current Density (Ampere/m^2)

D = Perpindahan Listrik (Coulumb/m^2)

Maxwell's equations used in the MT method apply the assumption that traveling electromagnetic waves are plane waves. The earth does not generate electromagnetic waves but only absorbs or dissipates some electromagnetic waves. There is no accumulation of free charge in the layered earth and the earth is conductive (Simpson and Bahr, 2005).

2.4.2 Gravity Method

The heavy force method is an investigation method in geophysics that is based on the variation of acceleration or heavy force field on the earth's surface (Sulistianingsih, 2009). This method is very appropriate for estimating subsurface structures because it is able to detect density contrasts of rock bodies.

Newton's law of gravity states that the force of attraction between two objects is proportional to the mass of the two objects and inversely proportional to the square of the distance between the centers of mass of the two objects (Nurcahyati, 2016). The application of this law for two objects m and M separated at a distance of R as in the picture will obtain the gravitational force as shown in the following equation.

$$F = G\frac{mM}{R^2} \quad (5)$$

Description:

F = Force (Newton)

m = Mass 1

M = Mass 2

R = Distance

G = Gravity constant $(6.67 \times 10^{-11})\ m^3 kg s^2$ (Blakely, 1996)

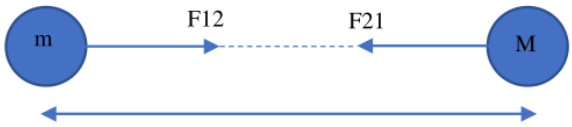


Figure 6: Force of attraction between two objects.

3. RESULTS AND DISCUSSION

3.1 MT Data Processing

MT data obtained from acquisitions in the field cannot be separated from noise disturbances so that data processing needs to be done (Simpson & Bahr, 2005). The stages carried out during magnetotelluric data processing are as follows.

3.1.1 Fourier Transformation

At this stage, data conversion is carried out. Basically, the data obtained during acquisition in the field is primary data in the form of time domain, data that is still in the form of time series cannot be used to remove noise. This process is carried out using SSMT 2000 software.

3.1.2 Robust Processing

The parameter components that need to be set include the frequency range to be used, cross power parameters, reference type (local data or remote data), robust parameters consisting of coherence settings and variations in resistivity values.

3.1.3 Crosspower Selection

At this stage, the correction process begins to reduce noise in the data using the MT Editor software. The MT data to be corrected is all resistivity and phase shown in the form of a curve. It is at this stage that the corrected data can be turned on or off to get the desired curve shape and the smaller error value.

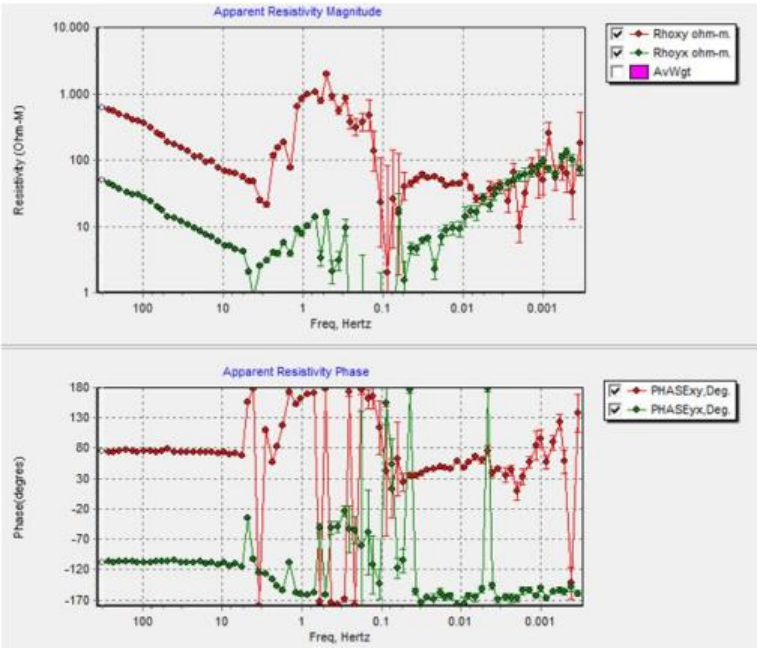


Figure 7: Apparent resistivity and phase curves before picking.

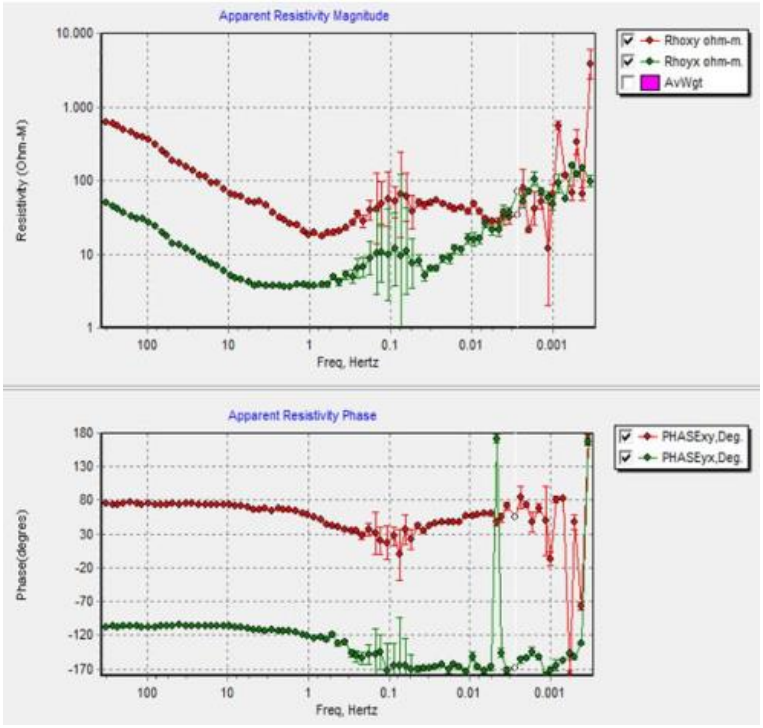


Figure 8: Apparent resistivity and phase curves after picking.

3.2 Identification of 2D MT Cross Section

MT data collection was carried out in the Waesano area, East Nusa Tenggara in 2016 by the Center for Mineral, Coal and Geothermal Resources (PSDMBP). In this study, MT data was used in a number of 2 tracks from the southwest to the northeast, which for line-1 consisted of 9 measurement points namely MTWS-46, MTWS-90, MTWS-91, MTWS-92, MTWS-93, MTWS-94, MTWS-95B, MTWS-96 and MTWS105. Below is the 2-dimensional inversion model of the MT data.

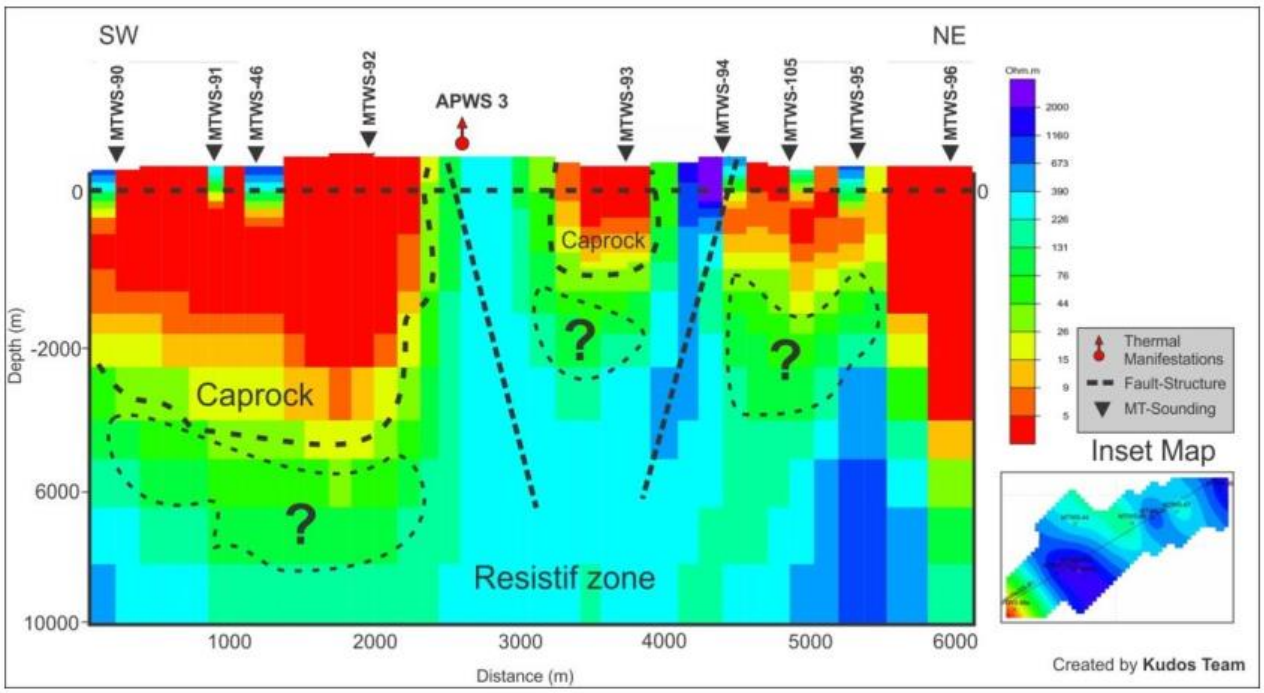


Figure 9: Model inverse 2 dimension magnetotelluric.

Based on the 2-dimensional modeling in the figure above, it can be seen that the distribution of resistivity values shown by the cross section is divided into two resistivity distribution patterns: low resistivity, medium resistivity, and high resistivity. Areas with low resistivity (1-26 ohm.m) are shown in red and yellow. This layer is identified as the caprock layer, which serves to retain the heat accumulated in the reservoir. Therefore, the caprock layer is composed of impermeable rocks that have relatively low resistivity values.

Furthermore, areas with medium resistivity (26-131 ohm.m) are shown in green. The layer with medium resistivity value is identified as a permeable layer that is capable of being flowed by fluid, but this layer is suspected not to be a reservoir. This is because the geochemical analysis shows that the water coming out through the surface manifestation (APWS3) is reservoir water with a low lithium content, indicating that the reservoir is located far from the surface manifestation. Consider Figure 9, between points MTWS-92 and MTWS-93, there is a contrast in resistivity values where the medium resistivity pattern is disconnected. In the same area, it is known that there are manifestations in the form of hot springs, so it is suspected that there is a geological structure that is a way for heat to escape from the reservoir to the earth's surface.

3.3 Gravity Data Identification

The gravity data used is the complete Bouguer anomaly data for the Wae Sano area, East Nusa Tenggara, which is obtained from the GGMplus satellite gravity data. GGMplus data is satellite gravity data with the highest resolution among other satellite gravity data, namely with a space between points of approximately 220m (Hirt et al., 2013). Raw data obtained from GGMplus data is in the form of gravity acceleration data which is then carried out various corrections to get a complete Bouguer anomaly.

3.3.1 Complete Bouguer Anomaly

Complete Bouguer Anomaly is a gravity anomaly that is dense in the subsurface mass of a research area. The complete bouguer anomaly value of the research area ranges from 94 to 128 mGal. Areas with high bouguer anomaly values are in the north area, heading northwest - southeast with values of 114 to 128 mGal. While low anomalies are in the east and southwest of the area with values of 94 to 106 mGal. High Bouguer anomalies represent areas with relatively higher density compared to areas with low Bouguer anomaly values. Furthermore, anomaly separation is carried out to obtain the residual anomaly value.

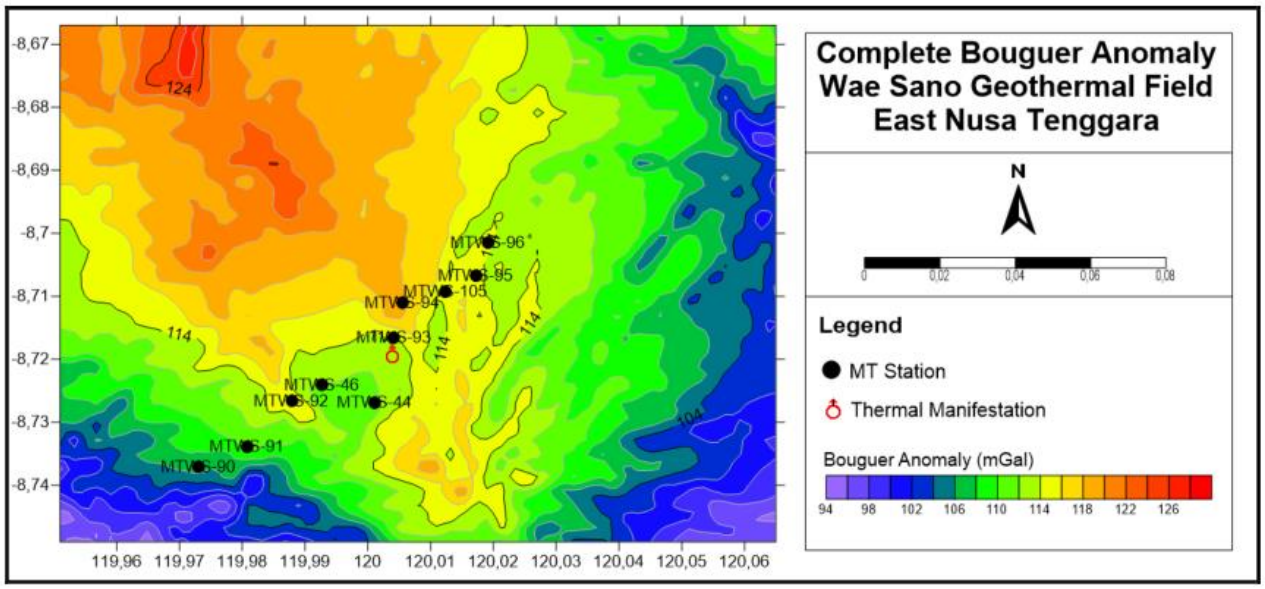


Figure 10: Complete Bouguer Anomaly Map of Study Area.

3.3.2 Residual Anomaly

The residual anomaly is obtained from the separation of anomalies using a moving average filter. Simply put, the residual anomaly is the result of subtracting the complete Bouguer anomaly from the regional anomaly. The residual anomaly shows a more complex pattern, which represents a shallower rock distribution. In the study area the residual anomaly ranges from -8 to 10 mGal. In the center of the study area there is a low anomaly ranging from -6 to -2mGal which is close to the APWS-3 manifestation and is also related to the presence of Sano Nggoang lake.

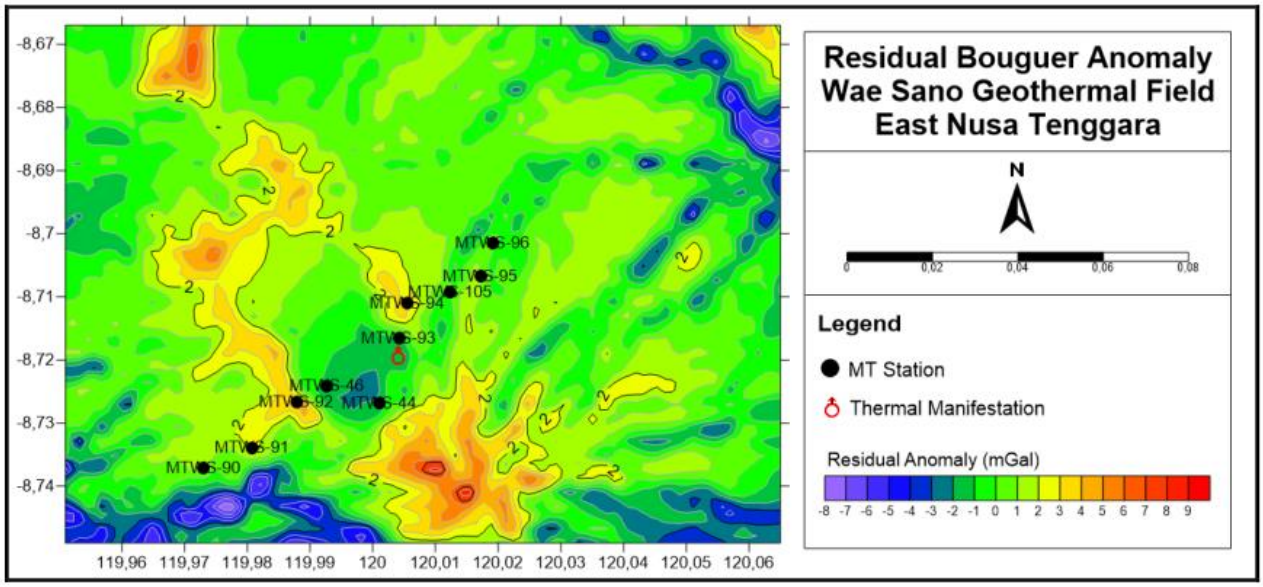


Figure 11: Residual Anomaly.

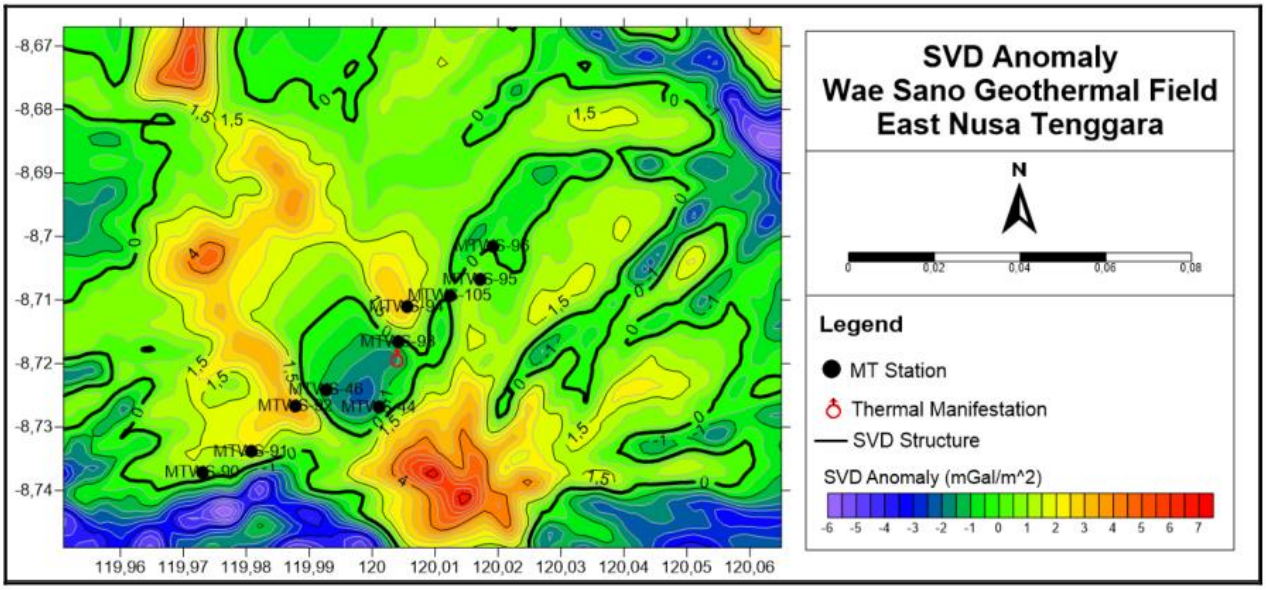


Figure 12: SVD Anomaly.

3.3.3 Second Vertical Derivative

Furthermore, from the residual anomalies, second vertical derivative analysis is carried out using the Elkins operator. The zero-valued black contour flanked by high and low anomalies represents the presence of structures in the study area. In principle, the zero contour in the second vertical derivative anomaly indicates the value of a boundary, so it can be assumed to be a structure in the form of a fault (Sarkowi, 2021). In the research area, the SVD Anomaly value ranges from -6 to 8 mGal/m2. The structure in the research area is predominantly northeast to southwest, and there is a zero contour with a circular pattern between MTWS-46 and MTWS-93 which is a caldera structure (Sano Nggoang Lake),

then there is a structure around the APWS-3 manifestation which may be associated with the existence of the APWS-3 manifestation.

3.3.4 3D Inversion Modelling of Gravity

3D modeling of Residual Anomaly Inversion is done using Grablox software. This inversion modeling uses residual anomaly data as input data. The results of 3D inversion modeling are shown Figure 13. The results of this inversion modeling provide an overview of the density distribution beneath the surface of the research area in 3 dimensions. The range of density values is from 2 to 2.9 g/cm3 with depths up to 3000 meters.

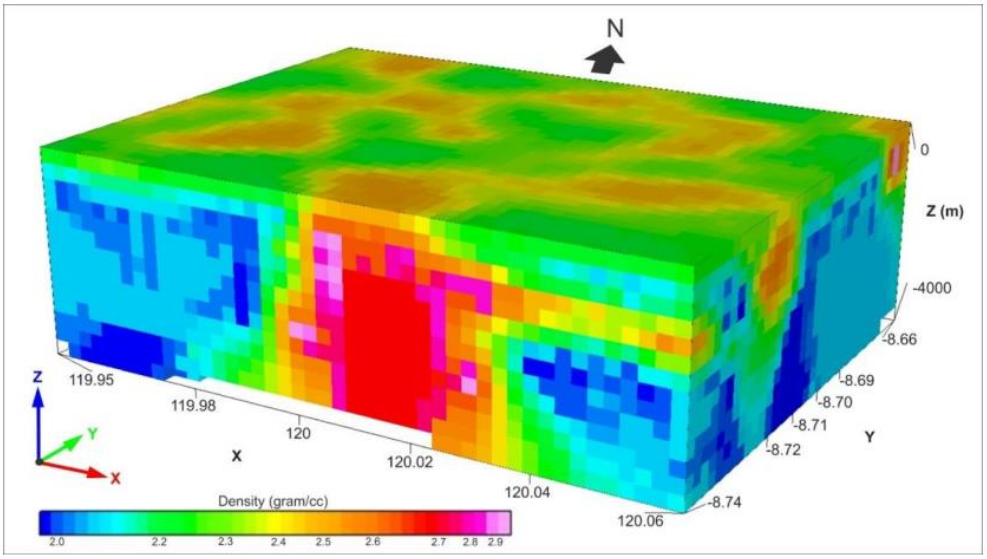


Figure 13: 3D inversion modelling of gravity.

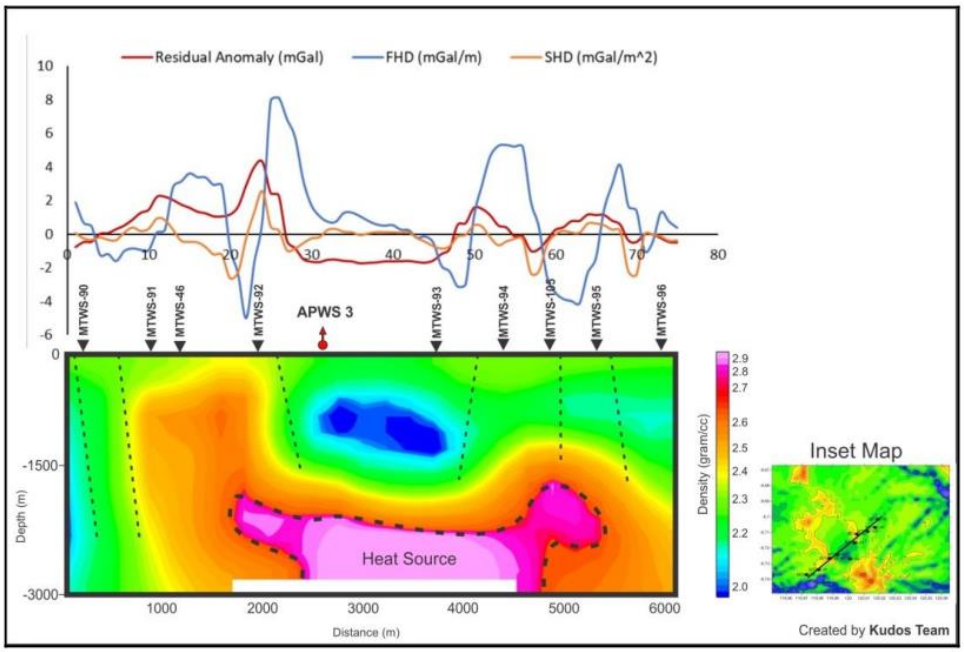


Figure 14: Density distribution cross-sectional model.

The subsurface density distribution model in the figure is then sliced to obtain a 2D depth cross section. Slicing is done according to the trajectory of the MT measurement station. The figure shows the 2D gravity cross section of the MT station trajectory. Fault structure analysis is also carried out using the first and second derivatives of the residual anomaly or first horizontal derivative (FHD) and second horizontal derivative (SHD) to reveal the presence of subsurface structures. The maximum or minimum

value of FHD m and zero value in SHD will indicate the presence of subsurface structures (Sarkowi, 2021). The figure shows the correlation between the FHD and SHD graphs and the 2D cross-section of gravity for identifying subsurface structures.

The correlation of the graph of FHD and SHD values with the 2D cross section of gravity gives the result that there are several subsurface structures that control the geothermal system of the study area, especially in the MT station track. The existence of the APWS-3 surface manifestation is also assumed to be associated with a fault structure. The 2D gravity cross section shows the presence of a reservoir represented by a low anomaly and the presence of a heat source represented by a very high anomaly.

3.4 Waesano Geothermal System

Based on the results of 2D inversion modeling on MT data (Figure 6), a subsurface cross-section model is obtained based on the distribution of resistivity values. Then the identification results on the MT cross-section model are validated with the gravity data (Figure 11) so as to obtain the Waesano geothermal system model illustrated as in the Figure 15. It can be seen that the Waesano geothermal system component consists of a Heat Source or heat source that functions to heat the geothermal fluid. The Heat Source is composed of volcanic rocks resulting from the freezing of molten magma which is still hot and able to flow heat, this is indicated by the high density value shown by gravity data (figure 14) and also resistivity data (figure 9) on the rock. There is a caprock layer located in the uppermost layer, composed of impermeable rocks so that it can accommodate and store heat in the reservoir. Based on geological information, the layer of caprock owned by the Waesano geothermal system is in the form of alteration sedimentary rocks formed due to the process of change from what was previously bedrock. The minerals found to compose these alteration rocks include haloysite, montmorillonite, illite, alunite and kaolinite which are characteristic of the advanced argillic alteration zone. This zone itself is a layer with alteration rocks resulting from hydrothermal processes dominated by clay minerals (Kusnadi et al., 2015).

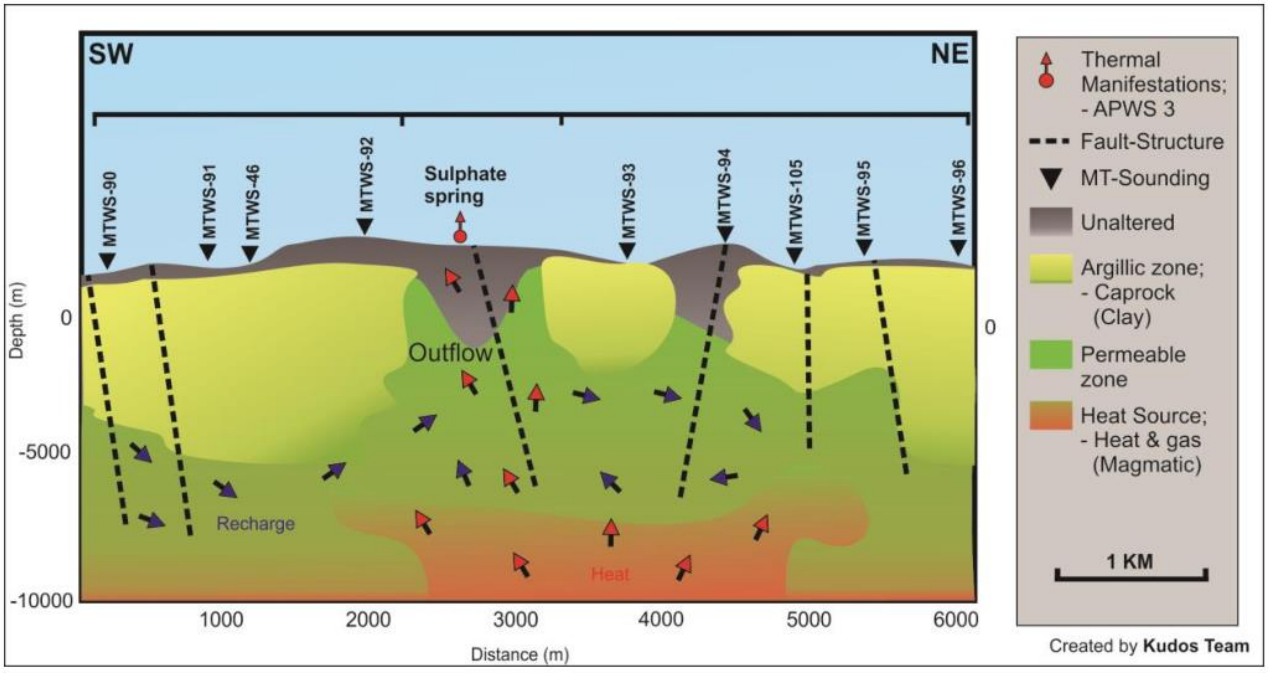


Figure 15: Illustration of Waesano geothermal system.

The layer between the caprock and the heat source is a layer of rock with good porosity and permeable, but in this area it is suspected that it is not a reservoir layer even though it is able to accommodate fluid and become a place for convection currents due to fluid heating flowing by the heat source. This assumption is based on geochemical analysis which shows that the area where the surface manifestation appears is an outflow zone, this can be proven by the low lithium ion content due to the distance of the

reservoir to the location of the surface manifestation so that lithium ions are absorbed by the rocks it passes through.

To indicate the presence of geothermal prospects in an area, it can be seen from the appearance of surface manifestations. Around the study area there are manifestations in the form of hot springs located close to the MTWS-92 point. It is identified that there is a geological structure in the form of a fault that facilitates the emergence of heat on the surface, the fault is indicated by the difference in resistivity values in the magnetotelluric model and validated by the gravity model using the second vertical derivative method and according to geological information there is a Poco Dedeng fault that facilitates the formation of Sanonggoang lake and hot springs in the vicinity

4. CONCLUSION

Based on the regional geology, the study area is composed of young volcanic rocks and old volcanic rocks of Tertiary to Quaternary age. Geochemical analysis shows that the surface manifestation closest to the measurement area is characterized as sulfate water from the reservoir and is also identified as an outflow zone. Based on geological, geochemical and geophysical analysis, it is known that the Waesano geothermal system is composed of caprock, hearsource, fault, surface manifestation and outflow zone. There is a permeable layer between the caprock and heat source, but it is suspected that it is not a reservoir layer, so it is necessary to conduct a further study to identify the reservoir layer by drilling.

REFERENCES

Ditjen EBTKE and Badan Geologi.: Potensi Panasbumi Indonesia Jilid 2, Direktorat Panas Bumi Direktorat Jenderal Energi Baru, Terbarukan dan Konservasi Energi Kementerian Energi dan Sumber Daya Mineral, Jakarta, (2017).

Giggenbach, W., F. : Geothermal Solute Equilibria, Geochimica et Cosmochimica Acta, 52 (12), (1988), 2749-2765.

Grandis, H.: Study Efek Statik pada Data Magnetotellurik dengan Menggunakan Pemodelan 2D, Institut Teknologi Bandung, Bandung, (2010).

Hirt, C., Claessens, S., Fecher, T., Kuhn, M., Pail, R., and Rexer, M.: New Ultrahigh-Resolution Picture of Earth's Gravity Field, Geophysical Research Letters, 40(16), (2013), 4279–4283.

Koesoemadinata, S., Noya, Y., and Kadarisman, D.: Peta Geologi Bersistem Indonesia, Lembar: Ruteng, 2107, (1:250.000), (1994).

Nurcahyati, E.: Analisis Spektrum Data Gravitasi pada Daerah Potensi Emas, Universitas Sunan Kalijaga, (2016).

Ratman, N., and Yasin, A.: Peta Geologi Bersistem, Nusa Tenggara, Lembar: Komodo 2007, (1:250.000), (1978)

Sarkowi, M.: Identifikasi Struktur Daerah Panas bumi Ulubelu Berdasarkan Analisa Data SVD Anomali Bouguer, Jurnal Sains MIPA, 16(2), (2010), 111–118.

Sarkowi, M., Sawitri, R. F., Mulyatno, B. S., and Wibowo, R. C.: Wai Selabung geothermal reservoir analysis based on gravity method, Jurnal Ilmiah Pendidikan Fisika Al-BIRuNI, 10(2), (2021), 211-229.

Simpson, F., and Bahr, K.: Practical Magnetotellurics, Cambridge University Press, United Kingdom, (2005).

Sulistianingsih, F.: Pemodelan Struktur Bawah Permukaan Daerah X untuk Menentukan Sumber Pasir Besi dengan Metode Gravity, (Skripsi), Universitas Indonesia, (2009).

LUSI FANDANGO - From A Natural Disaster to A Natural Geothermal Opportunity

Adriano Mazzini[1], Matteo Lupi[2], Anindita Samsu[3], and Soffian Hadi[4]

[1]Department of Earth Sciences, University of Oslo, Norway
[2]Department of Earth Sciences, University of Geneva, Switzerland
[3]Department of Earth Sciences, University of Lausanne, Switzerland
[4]Indonesian Geologist Association, Jakarta, Indonesia

adriano.mazzini@geo.uio.no, matteo.lupi@unige.ch, anindita.samsu@unil.ch, soffiangeologist@yahoo.co.id

Keywords: Lusi eruption, geothermal system, earthquake, volcanic complex, sedimentary-hosted, FANDANGO initiative

ABSTRACT

Lusi is identified as the largest clastic eruption on Earth, characterized by the release of boiling water, mud, rocks, oil, and gas. Research indicates that Lusi represents a sedimentary-hosted geothermal system, distinct from hydrocarbon provinces. Geological, geophysical, and geochemical studies reveal that a causative intrusion at depth induced fluid overpressure, leading to enhanced fluid release. Lusi's plumbing system is connected to the neighboring Arjuno-Welirang volcanic complex, and it is identified as the largest active methane vent globally. The FANDANGO initiative aims to transform Lusi's natural disaster into a geothermal opportunity. The proposal includes a holistic approach, combining geology, geochemistry, and geophysics. The plan involves high-resolution Nodal Ambient Noise Tomography (NANT) to locate and quantify subsurface geothermal and groundwater reservoirs. This geophysical survey is complemented by detailed geochemical monitoring of erupted fluids, providing insights into composition variations and crater activity. The integrated efforts aim to harness Lusi's energetic potential as a high enthalpy geothermal system.

1. INTRODUCTION

Lusi (East Java, Indonesia) is the largest and most spectacular clastic eruption currently active on Earth. Its inception occurred on the 29th of May 2006, almost two days after a 6.3 M earthquake struck the island (Mazzini et al., 2007). Within weeks several active aligned eruption sites developed along the Watukosek fault system and expanded in size (Mazzini et al., 2009a; Moscariello et al., 2018; Sciarra et al., 2018).. The largest vent (i.e., Lusi) was 100 m wide and released boiling water, mud, rock clasts, oil, and gas. Up to 180,000 m3 of mud were expelled per day, resulting in submerged villages and the displacement of more than 60,000 people birth. Lusi is still active today, with two major vents located in the crater zone. The regular activity of these vents is punctuated by powerful geysering events (Karyono et al., 2017; Lupi et al., 2018). Lusi is a rare newborn, tectonic-scale geothermal system that sources fluids from great depths, making it an interesting disaster-to-development opportunity for geothermal energy and lithium mining (Miller and Mazzini, 2018).

2. METHODOLOGY AND STUDIES

Multiple studies have shown that Lusi is the surface manifestation of a sedimentary-hosted geothermal system where high enthalpy hydrothermal fluids advect across permeable sedimentary units. Therefore, the mechanisms fueling the eruption are not solely related to processes observed in hydrocarbon provinces. Geological, geophysical, geochemical, and numerical studies (Mazzini, 2018 and refs. therein) reveal that a causative intrusion at depth promoted the development of fluid overpressure within the sedimentary sequence and enhanced the release of fluids from the heated organic-rich formations (Mazzini et al., 2012; Zaputlyaeva et al., 2020; Zaputlyaeva et al., 2019). Gas and water data (supported by passive seismic tomography) show that Lusi's plumbing system is connected to the neighboring Arjuno-Welirang volcanic complex (Fallahi et al., 2017; Inguaggiato et al., 2018; Malvoisin et al., 2018; Mauri et al., 2018; Mazzini et al., 2021; Mazzini et al., 2012; Mazzini et al., 2018; Panzera et al., 2018; Sohrabi et al., 2018; Sohrabi et al., 2021). In addition, CH4 emissions are estimated to be around 0.1 Tg year-1, making Lusi the largest methane vent currently active on Earth (Mazzini et al., 2021c).

Merging the flow rate data with our 3D ERT geoelectrical data, we estimate a total budget of ~0.5 km3 of erupted mud breccia during the first 13 years of activity (Mazzini et al., 2021b). Numerical models further highlight the extremely high geothermal potential of Lusi. All these evidence indicate that Lusi has the energetic potential of a high enthalpy geothermal system that reaches the surface and could be harnessed.

Figure 1: Drone view of the Lusi eruption plume during its regular geysering activity. The second vent is behind the main one and the Arjuno-Welirang volcanic complex in the background. The inaccessible 650 m in diameter pond surrounding the crater zone is filled by hot mud and laterally extensive oil slicks.

The goal of FANDANGO is to transform the Lusi natural disaster into a natural geothermal opportunity. We propose continuing using a holistic and interdisciplinary approach – combining geology, geochemistry, and geophysics – to investigate Lusi's potential for geothermal energy development. Proposed activities include a high resolution Nodal Ambient Noise Tomography (NANT) conducted using hundreds of wireless geophones (Smart Solo IGU-16HR 3C) deployed during the experiment to investigate the first 5 km of the upper crust. NANT may be directly used to locate, and quantify subsurface geothermal and groundwater reservoirs. Geophysical surveys will be coupled with detailed geochemical monitoring of erupted fluids in order to survey the variations in fluid's composition integrated with the monitoring of craters' activity.

Compared to traditional reflection seismic that target geological structures such as fault, and lithological units, Nodal Ambient Noise Tomography (NANT) is conceived to look directly to the reservoir. NANT uses surface waves (and possibly body waves) to invert for the shear wave velocity structure of the upper crust. Shear waves are strongly affected by the occurrence of fluids. This allows NANT to localize and quantify the resource at depth and to provide indications about the sweet point. An additional advantage is that the source of energy is ambient noise. Yet, compared to traditional ambient noise tomographies, NANT has a much higher degree of resolution thanks to the hundreds of nodes deployed during the experiment across a flexible grid. Additionally, NANT has a high social acceptance because all the captors are fully wireless and there is no need for vibro-trucks, explosions or airguns (whose operations are logistically and administratively complex to handle). NANT is very much relevant for Indonesian geothermal systems for both magmatic and sedimentary-hosted settings even in urbanized areas where the energy demand will soon be at its peak

REFERENCES

Fallahi, M. J., Obermann, A., Lupi, M., Karyono, K., and Mazzini, A., 2017, The Plumbing System Feeding the Lusi Eruption Revealed by Ambient Noise Tomography: Journal of Geophysical Research: Solid Earth, v. 122, no. 10, p. 8200-8213.

Inguaggiato, S., Mazzini, A., Vita, F., and Sciarra, A., 2018, The Arjuno-Welirang volcanic complex and the connected Lusi system: Geochemical evidences: Marine and Petroleum Geology, v. 90, p. 67-76.

Malvoisin, B., Mazzini, A., and Miller, S. A., 2018, Deep hydrothermal activity driving the Lusi mud eruption: Earth and Planetary Science Letters, v. 497, p. 42-49.

Mauri, G., Husein, A., Mazzini, A., Karyono, K., Obermann, A., Bertrand, G., Lupi, M., Prasetyo, H., Hadi, S., and Miller, S. A., 2018, Constraints on density changes in the funnel-shaped caldera inferred from gravity monitoring of the Lusi mud eruption: Marine and Petroleum Geology, v. 90, p. 91-103.

Mazzini, A., 2018, 10 years of Lusi eruption: Lessons learned from multidisciplinary studies (LUSI LAB): Marine and Petroleum Geology, v. 90, p. 1-9.

Mazzini, A., Carrier, A., Sciarra, A., Fischanger, F., Winarto-Putro, A., and Lupi, M., 2021, 3D Deep Electrical Resistivity Tomography of the Lusi Eruption Site in East Java: Geophysical Research Letters, v. 48, no. 18, p. e2021GL092632.

Mazzini, A., Etiope, G., and Svensen, H., 2012, A new hydrothermal scenario for the 2006 Lusi eruption, Indonesia. Insights from gas geochemistry: Earth and Planetary Science Letters, v. 317, p. 305-318.

Mazzini, A., Scholz, F., Svensen, H. H., Hensen, C., and Hadi, S., 2018, The geochemistry and origin of the hydrothermal water erupted at Lusi, Indonesia: Marine and Petroleum Geology, v. 90, p. 52-66.

Miller, S. A., and Mazzini, A., 2018, More than ten years of Lusi: A review of facts, coincidences, and past and future studies: Marine and Petroleum Geology, v. 90, p. 10-25.

Panzera, F., D'Amico, S., Lupi, M., Mauri, G., Karyono, K., and Mazzini, A., 2018, Lusi hydrothermal structure inferred through ambient vibration measurements: Marine and Petroleum Geology, v. 90, p. 116-124.

Sohrabi, R., Jansen, G., Malvoisin, B., Mazzini, A., and Miller, S. A., 2018, Numerical modeling of the Lusi hydrothermal system: Initial results and future challenges: Marine and Petroleum Geology, v. 90, p. 191-200.

Sohrabi, R., Malvoisin, B., Mazzini, A., and Miller, S. A., 2021, Multi-GPU based 3D numerical modeling of fluid migration and clay dehydration influence on Lusi hydrothermal activity (Java, Indonesia): Journal of Volcanology and Geothermal Research, v. 419, p. 107377.

Zaputlyaeva, A., Mazzini, A., Blumenberg, M., Scheeder, G., Kürschner, W. M., Kus, J., Jones, M. T., and Frieling, J., 2020, Recent magmatism drives hydrocarbon generation in north-east Java, Indonesia: Scientific Reports, v. 10, no. 1, p. 1786.

Zaputlyaeva, A., Mazzini, A., Caracausi, A., and Sciarra, A., 2019, Mantle-Derived Fluids in the East Java Sedimentary Basin, Indonesia: Journal of Geophysical Research: Solid Earth, v. 124, no. 8, p. 7962-7977.

Magnetotelluric Signature over the Low to Moderate Temperature Geothermal System

Wambra Aswo Nuqramadha, Fikri Fahmi, Donny Isa MSP, Surya Aji Pratama, and Yunus Daud

PT. NewQuest Geotechnology

wambra.aswo@newquest-geotechnology.com

Keywords: geothermal, low-to-medium temperature, magnetotelluric, resistivity

ABSTRACT

Of all the geothermal potentials in Indonesia, almost 41.3% are categorized as low-to-medium geothermal systems. The potential of these low-to-moderate geothermal systems has not been massively developed or even studied. The potential can occur in several geological play types, one of which is a typical fault-controlled geothermal system. The distinctive feature of this system is the occurrence of manifestations that are limited to the vicinity of the fault. The pattern of MT curves as well as the subsurface resistivity model in such a system are quite different from those of a volcanic-hosted geothermal system. The distribution and value of the resistivity anomaly may reflect the occurrence of the geothermal reservoir. This paper discusses the distinctive resistivity characteristics observed in low-to-moderate temperature fault-controlled geothermal systems.

1. INTRODUCTION

Indonesia has a number of low-to-medium temperature geothermal systems which are widely spread over 254 of the total 357 geothermal potencies. Currently, this potency has not been massively developed or even studied. Insufficient data and information regarding the potential of low-and-medium temperature resources lead to under-utilization (Putriyana et al, 2022). It is important to deeply recognize the characteristics of a low-to-medium temperature system to exploit the potential benefit of these potencies.

The Magnetotelluric (MT) method is the most frequently used geophysical method to reconstruct a geothermal system model. The MT method is sensitive to the electrical resistivity signatures of the main components of the geothermal system, such as heat source, cap rock, and geological structures that control the fluid flow (Rodriguez et al, 2021). A conceptual model of a geothermal system is produced by integrating the MT model with surface geology, geochemistry, and other geophysical data. This conceptual model is subsequently used to target deep drilling and numerical resource estimation as well as a selection of the appropriate energy conversion technology and projection of project economics.

The low resistivity anomaly mostly observed over geothermal system is one of the most important exploration targets. Conductive clay produced by hydrothermal alteration is the most common cause of low resistivity in a zone above the reservoir. (Ussher et al, 2000). The formation of these hydrothermal alteration minerals is usually dependent on the temperature, permeability, pressure, fluid composition, the initial composition of the rock, and the duration of the hydrothermal activity. These factors are largely independent, but the effects of one or more of the factors can exert a dominant influence on the location and extent of hydrothermal alteration (Lagat, 2010). This paper describes the characteristic of subsurface resistivity pattern observed from several unimpressive hydrothermal activity over low-to-medium temperature geothermal systems.

2. LOW-TO-MEDIUM GEOTHERMAL SYSTEM

There are various classifications of geothermal systems derived from many references. Reservoir temperature becomes the simplest parameter to classify the geothermal system. The selection of low-to-medium geothermal fields described in this paper is referred to the classification from Hochstein, 1990 which divides geothermal system into three classifications based on their reservoir temperature as follows.

1. Low temperature geothermal system : < 125°C
2. Intermediate temperature geothermal system : 125-225°C
3. High temperature geothermal system : > 225°C

Geologically, the existence of low-to-medium geothermal systems can occur in many different geological settings which mostly can be grouped as follows referred to Hochstein & Brown, 2000:

1. System overactive and inactive volcanic arcs, i.e., hosted by volcanic rocks.
2. "Heat-sweep" systems in active rifts and at plate collision boundaries.
3. Fracture zone systems hosted by sedimentary or metamorphic rocks.

3. ALTERATION AND RESISTIVITY OF ROCKS

As a result of hydrothermal activity occurrence, the rocks in a geothermal area can be altered and turned into new hydrothermal minerals. Within the temperature range 100–150°C, rock minerals are most susceptible to hydrothermal alteration and formation of high surface conductivity smectite. From 150 to 200°C, the clay changes to a less conductive mixed phase of illite and smectite (Komori et al. 2013). Smectite is not observed in rocks > 200°C, as it transitions to less conductive illite and chlorite (Essene and Peacor, 1995).

The interpretation of conductive anomaly at low-to-medium temperature geothermal systems must be made with caution. A fractured reservoir with hot fluid could have the same resistivity signature as clay-bearing rock, especially in the presence of the smectite clays common in hydrothermal alteration zones (Revil et al. 2015; Komori et al. 2013). Another challenge in evaluating conductive anomaly at the low-to-medium geothermal systems is the occurrence of sediment infill which also represented by a low resistivity value.

4. MAGNETOTELLURIC METHODS

MT method is a passive geophysical electromagnetic (EM) method that measured naturally Earth time-varying electromagnetic fields. Natural EM variation is recorded for several hours (about 12-16 hours) on the surface with a specific layout and producing MT time series data in each MT station. By applying Fast Fourier Transform (FFT) and Robust calculation to the MT time-series data, the impedance tensor as a function of frequency can be obtained. The MT Data is usually represented as an MT curve which consists of apparent resistivity and phase versus frequency as shown in Figure 1. For a homogeneous Earth, the apparent resistivity represents the actual resistivity, whereas for a multi-dimensional Earth, the apparent resistivity is the average resistivity represented by an equivalent uniform half-space. (Simpson & Bahr, 2005). Equations 1, 2, and 3 show the correlation of the impedance, apparent resistivity, and phase.

$$Z_{xy} = \frac{\boldsymbol{E_x}}{H_y} \tag{1}$$

$$\rho_{xy} = \frac{1}{\omega\mu}\left|\frac{E_x}{H_y}\right| \tag{2}$$

$$\emptyset_{xy} = tan^{-1}\,(Z_{xy}) \tag{3}$$

Where ω is angular frequency (ω=2πf) and μ is magnetic permeability. In the studies of the Earth, μ is usually assigned the free-space value (μ_0=4π x 10^(-7) H m^(-1)).

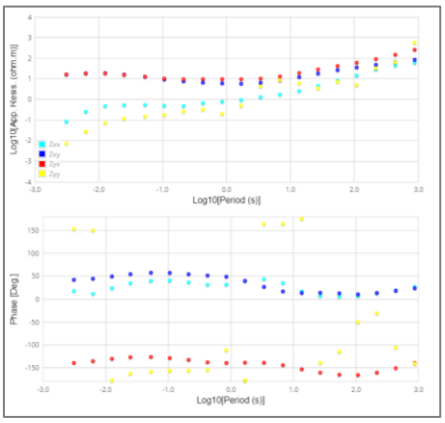


Figure 1: Apparent resistivity and phase in frequency domain.

Furthermore, to obtain a subsurface resistivity model, the inversion modeling is applied to the MT data. Before that, the static shift correction is performed to correct the MT data from the static shift effect. This process is important to be conducted to avoid misleading in the inversion model.

In this research, the 3-D inversion process has been carried out for several MT data sets from three geothermal Fields which are categorized as low-to-medium temperature geothermal systems. Several resistivity sections were then produced to analyze the subsurface resistivity pattern in each selected geothermal field.

5. RESULTS

5.1 Geothermal Field 1

Geologically, Geothermal Field 1 is situated in a depression zone. Thermal surface manifestations occur in this area consisting of three hot springs with a temperature of 68.4-74.8^{o}C and one warm spring with a temperature of 37.1^{o}C. Each manifestation is controlled by geological faults as shown in Figure 1. The estimated reservoir temperature calculated using a SiO2 geothermometer is around 148-161^{o}C which is categorized as a medium temperature geothermal system. Meanwhile, using a Na-K geothermometer, the temperature of the reservoir is estimated to be around 210^{o}C which is situated at the boundary from medium to high temperature geothermal system.

There are 19 existing MT stations which are distributed around the manifestations. To delineate the subsurface resistivity a 3-D inversion process was applied. The resistivity sections for the three lines are provided in Figure 2.

5.2 Geothermal Field 2

Geothermal Field 2 is a typical non-volcanic geothermal system. The area is dominantly covered by metamorphic and sedimentary rock products. Several major geological structures exist in this area and separate the two products as well as control the appearance of thermal manifestation. Several surface thermal manifestations are found in this area, including a hot ground with a temperature of about 100.6°C, and two hot springs with a temperature of 58.1^{o}C and 90.1^{o}C. Besides that, there are also three warm springs with a temperature range of 37.8-44.3^{o}C. The estimated reservoir temperature based on the Na-K geothermometer is around 219°C which is classified as a medium temperature geothermal system.

Two resistivity sections were extracted from the 3-D MT inversion result as shown in Figure 3. A total of 39 MT stations were included for the 3-D inversion process in this area.

5.3 Geothermal Field 3

Geothermal Field 3 is categorized as a medium temperature geothermal system. The estimated reservoir temperature of the geothermal system in this area is about 200°C, which is derived from Na-K geothermometer. Manifestations occurred in this area consists of several hot springs and warm springs with temperatures of 58-81°C and 37-39°C respectively. Geologically, Geothermal Field 3 is hosted by volcanic rocks.

A 3-D inversion process was carried out for 42 MT stations. The results were then provided in two resistivity sections as shown in Figure 4.

5.4 The Signature of the Subsurface Resistivity Model

As mentioned in the previous chapter, the subsurface resistivity model can be used to represent the geothermal system model. The resistivity anomaly values, and its distribution can describe the parts of the geothermal system. For example, in a high-temperature geothermal system, the presence of a clay cap is represented by a conductive anomaly that has a resistivity value of <10 Ωm and it is massively distributed over the area. Likewise, the presence of a heat source can be represented by a resistive or conductive anomaly depending on the type (Magmatic/Plutonic body). Furthermore, the thinning and thickening of the conductive layer is usually used to define the upflow and outflow zones of a geothermal system. In addition, the upflow zone in high temperature systems can be identified by observing the dome-shaped resistivity pattern which is generally formed in the hottest part of the reservoir. These are patterns that are commonly found in the resistivity model of high temperature geothermal systems.

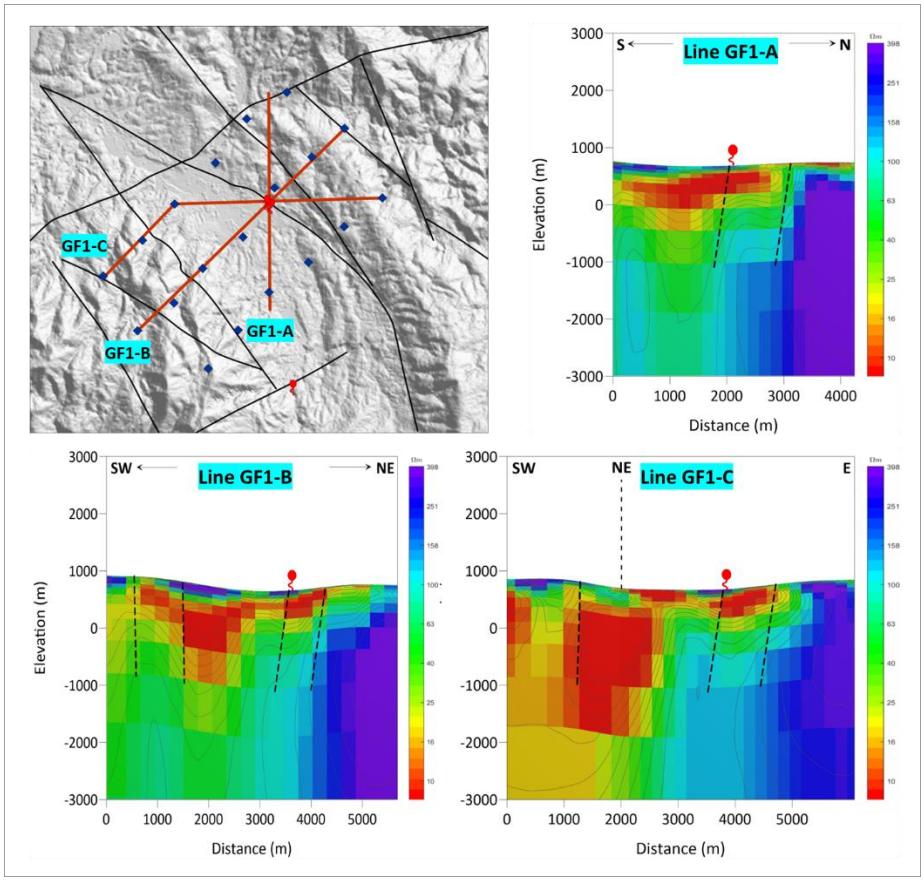


Figure 2: Subsurface resistivity model of geothermal field 1 derived from 3-D inversion.

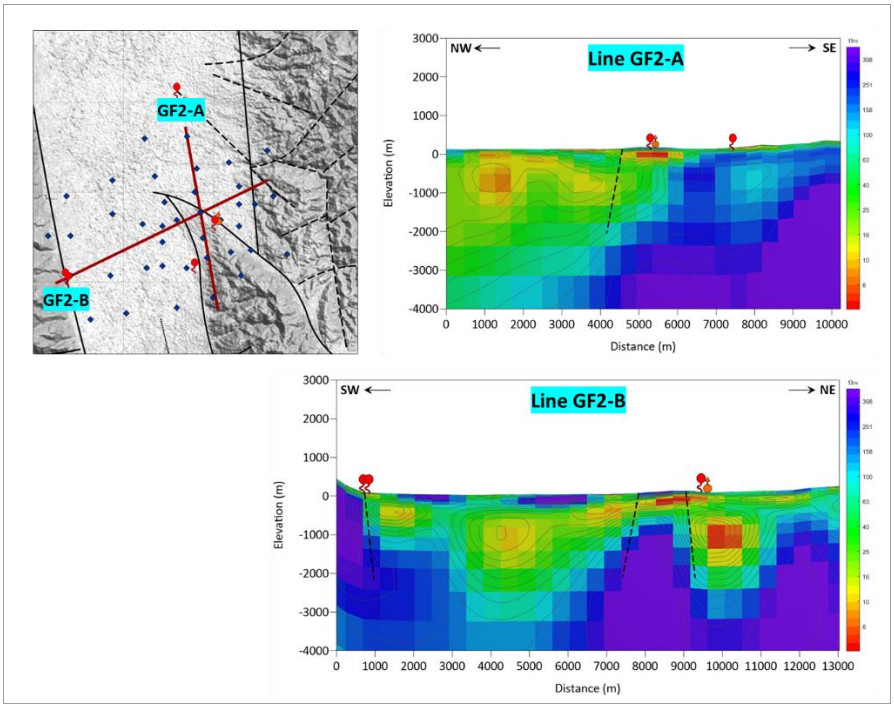


Figure 3: Subsurface resistivity model of geothermal field 2 derived from 3-D inversion.

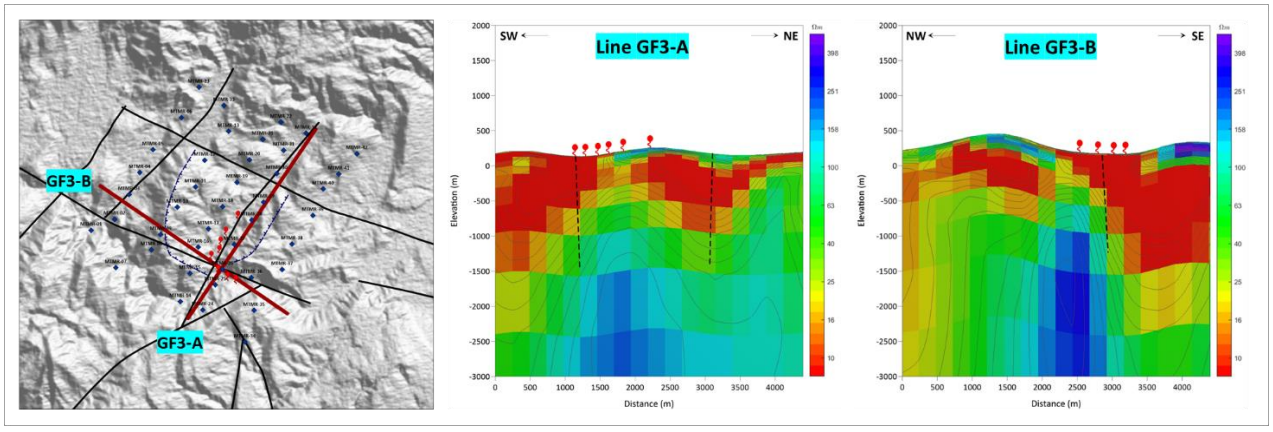


Figure 4: Subsurface resistivity model of geothermal field 3 derived from 3-D inversion.

The resistivity model from the three selected samples of low-to-medium temperature geothermal system shows a slightly different pattern. Geothermal Field 1 and Geothermal Field 2 have similar geological characteristics, which are situated at the graben structural complex. The high resistivity part is related to the horst, while the conductive part is the graben. The geothermal system is most probably controlled by fault, which is clearly observed by the resistivity contact between high and low anomalies. Instead of looking for updome resistivity patterns as is often found in volcanic systems with high temperatures, the presence of faults represented by resistivity contacts is the main target. In addition, caution is needed in interpreting the existence of a base of conductor which usually correlates with temperatures of 180 - 200°C in high temperature geothermal systems. Because altered rock is not the only cause of the conductive layer, the presence of layers of sedimentary rock that fills the graben structure also shows a low resistivity response.

Geothermal Field 3 has slightly different geological conditions from the two previous fields. Even though its manifestations appear to be controlled by faults, the volcanic products present in this field

may also have an important role in the formation of the current geothermal system. Thus, the resistivity pattern in the form of an updome, as is often found in high-temperature volcanic-hosted geothermal systems, is the main target of exploration in this field.

6. CONCLUSION

Since many high temperature fields are owned and utilized, the development of low-medium temperature geothermal fields is one of the current challenges in Indonesia. Fields with low-medium temperatures also have a variety of geological settings, some are associated with inactive volcanic products, some are where the presence of reservoirs is controlled by faults. Both types have different resistivity patterns. For systems associated with volcanic products, updome shape resistivity patterns are still found. However, for fault controlled systems such as in Geothermal Fields 1 and 2, the contact resistivity between high and low anomalies is a major concern.

REFERENCES

Essene EJ, Peacor DR.: Clay mineral thermometry–A critical perspective. Clays Clay Miner. (1995). 43(5):540–53.

Hochstein, M.P.: Classification and assessment of geothermal resources.

Hochstein, M.P., Browne, P.R.L.: Encyclopedia of Volcanoes: Surface Manifestations of Geothermal System with Volcanic Heat Source. (2000). Academic Press.

Rodriguez. J.A.: Magnetotellurics in Exploration for Geothermal Targets.

Komori S, Kagiyama T, Takakura S, Ohsawa S, Mimura M, Mogi T.: Effect of the hydrothermal alteration on the surface conductivity of rock matrix: comparative study between relatively high and low temperature hydrothermal systems. J Volcanol Geoth Res. (2013). 264:164–71.

Lagat. J., Hydrothermal alteration mineralogy in Geothermal fields with case examples from Olkaria domes geothermal field, Kenya. Presented at Short Course V on Exploration for Geothermal Resources, organized by UNU-GTP, GDC and KenGen, at Lake Bogoria and Lake Naivasha, Kenya, Oct. 29 – Nov. 19, 2010.

Putriyana, L., Daud, Y., Saha. B.B., Nasruddin. N.: Comprehensive data, and information on low to medium temperature geothermal resources in Indonesia: A review. Geomech. Geophys. Geo-energ. Geo-resour. (2022) 8:58, doi.org/10.1007/s40948-022-00375-5.

Revil A, Cuttler S, Karaoulis M, Zhoa J, Raynolds B, Batzle M.: The plumbing system of the Pagosa thermal springs, Colorado: application of geologically constrained geophysical inversion and data fusion. (2015). J Volcanol Geotherm Res. 2015;299:1–18.

Simpson, F., Bahr, K.: Practical magnetotellurics. (2005). Cambridge University Press.

Ussher, G., Harvey, C., Johnstone, R., dan Anderson, E.: “Understanding the resistivities observed in geothermal system”. (2000). Proceedings World Geothermal Congress 2000, 1915-1920.

Potential of Hot Sedimentary Aquifer Calculation with Heat in Place Equation and Determination of Prospect Area Using Ordinary Kriging Method in South Sumatra Basin, Indonesia

Chotimah. N, Kenny. L, Solomon. M, Fauzan. M, and Suryantini

Teknik Geologi ITB

12020032@students.itb.ac.id, 12020039@students.itb.ac.id, 12020024@students.itb.ac.id, 12020022@students.itb.ac.id, suryantini@itb.ac.id

Keywords: Hot Sedimentary Aquifer, South Sumatra Basin, ordinary kriging

ABSTRACT

Hot Sedimentary Aquifer is a geothermal system with conductive heat transfer in a sedimentary basin. With the existence of many sedimentary basins in Indonesia, the hot sedimentary aquifer geothermal system deserves further research. In addition, many sedimentary basins have been exploited for the oil and gas industry to assist in the exploration process. The South Sumatra Basin as one of the exploited basins has four sub-basins namely Jambi Sub-basin, North Palembang Sub-basin, Central Palembang Sub-basin, and South Palembang Sub-basin. This study aims to calculate heat in place in each sub-basin using the equations from previous studies. Parameters such as reservoir porosity, sediment thickness, production temperature, injection temperature, and aquifer heat bulk capacity are defined. Available well temperature data from the previously study is used to calculate heat in place in the Central Palembang Sub-basin, Jambi Sub-basin, South Palembang Sub-basin, and North Palembang Sub-basin, with the respective calculation results being 4.5 x 108; 4.3 x 108; 3.8 x 108; and 2.7 x 108 PJ/km2. Based on geostatistical analysis results using the ordinary kriging method, the prospect area is in the northeastern Jambi sub-basin and the Southeastern Central Palembang sub-basin. Thus, the South Sumatra Basin can become one of the potential sites for developing hot sedimentary aquifers.

1. INTRODUCTION

Population growth or population increase worldwide will result in increased demand, including energy demand. The most common energy is from burning fossil fuels. Along with the high use of fossil fuels will result in the production of greenhouse gases, such as CO2 which will result in drastic climate change. This requires a substitute resource, namely geothermal sources. This is also supported by the fact that Indonesia is a country that has a large potential for geothermal energy by saving 40% of its resources. Evidenced by the ministry of energy and mineral resources, in 2020 Indonesia's geothermal energy potential is estimated at 23.7 GW. (Kementerian Energi Dan Sumber Daya Mineral, 2020)

Geothermal systems that have been developed in Indonesia are still in conventional form, while non-conventional geothermal systems still do not exist. Judging from the tectonic setting, Indonesia can develop unconventional geothermal systems. Unconventional geothermal systems are defined as geothermal systems that require unconventional extraction methods to extract natural heat from beneath the surface. One of the non-conventional geothermal systems that can be developed in Indonesia is the Hot Sedimentary Aquifer (HSA). Hot Sedimentary Aquifer is a geothermal system with conductive heat transfer in sedimentary basins. The term HAS is defined as a system that refers to the existence of extensive aquifer systems filled with hot fluids and high permeability, in relatively deep conductive formations (Mijnlieff, 2020).

Indonesia is the 3rd largest oil and gas producing country in Asia, this is supported by the number of potential basins reaching 128 basins (Kementrian Energi dan Sumber Daya Mineral, 2020). South Sumatra is a province that produces the 3rd largest oil in Indonesia, so it is used as a research area in this work. Sedimentary basins will not last long in producing petroleum, so sedimentary basins no longer used in oil and gas production can be processed in the Hot Sedimentary Aquifer geothermal system. This is supported by temperature data obtained from petroleum exploration. This temperature data will be used in calculating the value of heat in place according to Limberger (2018).

The purpose of this study is to calculate heat in place from several parameters, namely aquifer thickness, rock thermal conductivity, subsurface temperature, porosity, and rock density. From the heat in place calculation, it can be used to determine areas that have potential in HSA system geothermal resources.

2. GEOLOGICAL SETTING

Geologically, The South Sumatra Basin is included in the back-arc basin which lies behind the Barisan Mountains as a magmatic arc (Salim et al., 1995). The South Sumatra Basin is a Tertiary back-arc basin as a result of subduction between Sunda Shelf as part of the Eurasian Plate and the Indo-Australian Plate (Pulunggono et al., 1992; Bishop, 2001). South Sumatera Basin was formed by three major tectonic phases: 1) extension during late Paleocene to early Miocene forming north-trending grabens that were filled with Eocene to early Miocene deposits; 2) relative quiescence with late normal faulting from early Miocene to early Pliocene; and 3) basement-involved compression, basin inversion, and reversal of normal faults in the Pliocene to Recent.

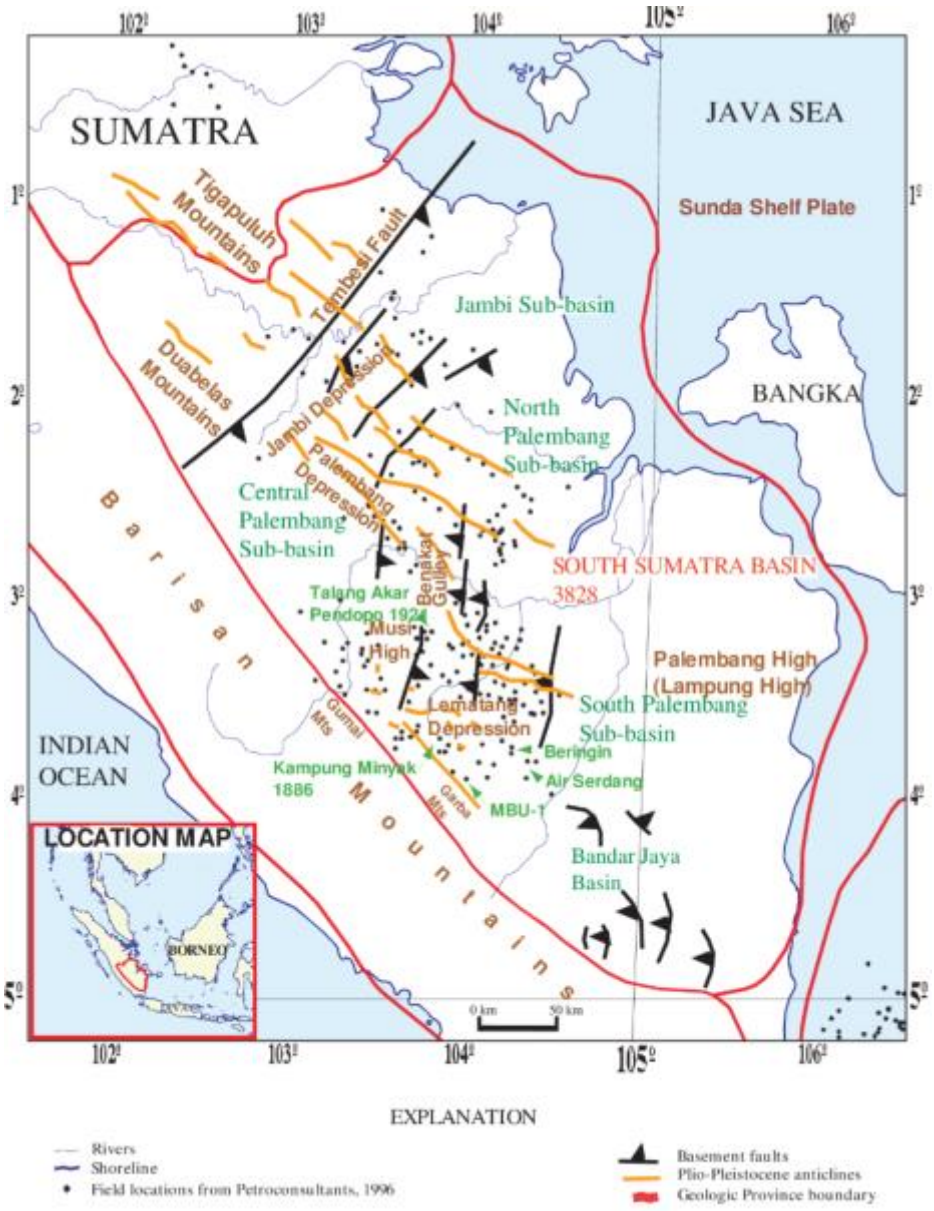


Figure 1: Location of South Sumatera Basin (Bishop, 2001).

2.1 Stratigraphic Overview

The regional stratigraphy of the North Sumatra Basin from oldest to youngest can be seen in Figure 2. The stratigraphy of South Sumatra basin area is known as one megacycle, consisting of a transgression followed by regression. The formations formed during the transgression phase are grouped into the Telisa Group (Talang Akar Formation, Baturaja Formation, and Gumai Formation). During the regression phase the Palembang group (Air Benakat Formation, Muara Enim Formation, and Kasai Formation) was deposited, while the Lemat and older Lemat Formation were deposited before the main transgression phase (Ginger & Fielding, 2005 in Khatimah et al., 2022).

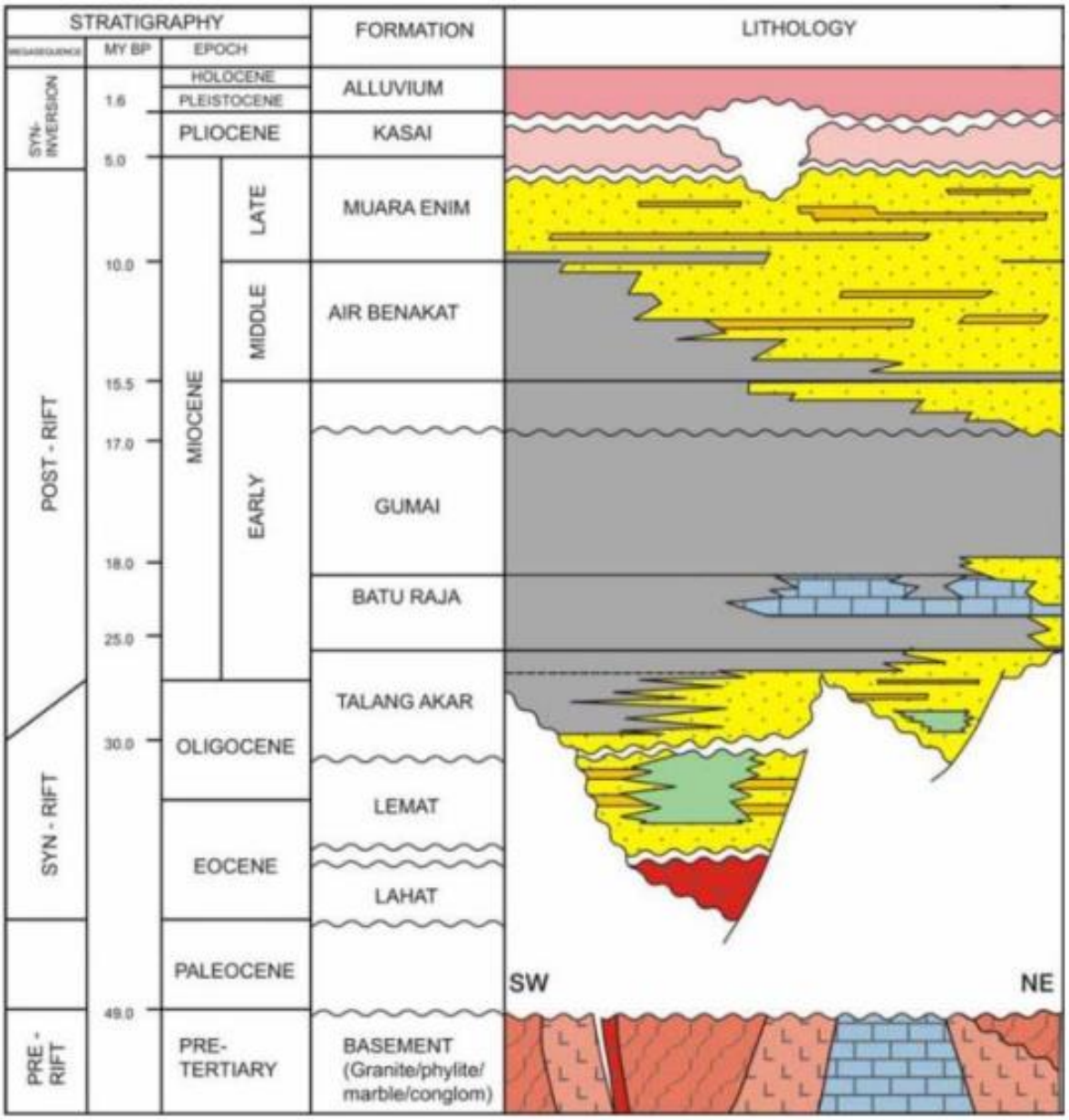


Figure 2: Lithostratigraphy of South Sumatera Basin from Ginger & Fielding (2005).

2.2 Tectonic and Structural History

The structural development that occurred in the South Sumatra Basin is the result of the interaction of the three main structural patterns, namely the Jambi Pattern which is trending NE-SW, the Sumatra Pattern which is trending NW-SE, and the Sunda Pattern which is trending N-S (Suta & Xiaoguang, 2005). This causes the South Sumatra Basin structures to be more complex than other basins along the island of Sumatra. Many of the normal faults that formed the depositional basins in South Sumatra have been reactivated and some have been reversed during Miocene to Plio-Pleistocene compression and basin inversion (Zeliff et al., 1985; Moulds, 1989; Sudarmono et al., 1997 in Bishop, 2001). The history of the South Sumatra basin can be divided into three tectonic phases as can be seen in Longley (1997).

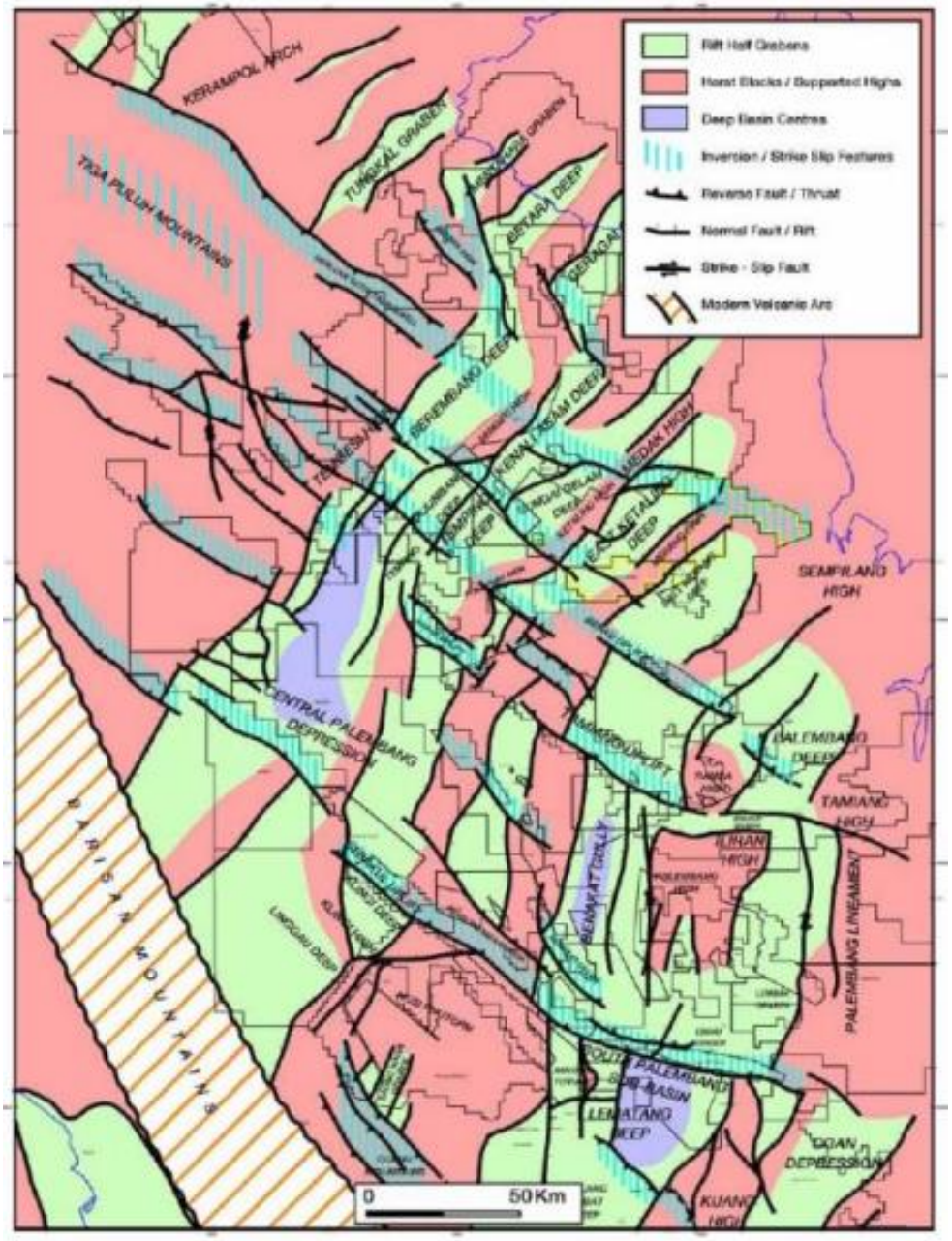


Figure 3: Structural elements trending northeast-southwest of the Eocene-Oligocene age which control the South Sumatra Basin (Ginger & Fielding, 2005).

3. DATA AND METHODS

3.1 Sample Data

This study used secondary data from Hall (2002). The number of samples used in this study was 20 wells data of Jambi Sub-basin, 18 wells data of Middle Palembang Sub-basin, and 18 wells data of South Palembang Sub-basin.

3.2 Resource Estimation

The calculation of estimated geothermal reserves is especially important. However, one of the main challenges for all resource assessment is uncertainty quantification when dealing with geological data (Limberger et al., 2018). So, it is necessary to determine the right method and good assumptions in the analysis. In this study the reserve estimation method is used in calculating heat in place. Heat in place (H) analysis is used to calculate the heat stored in a rock. This method has been used in other studies (Muffler & Caltadi, 1978; Williams, 2007; Limberger et al., 2018).

$$H = h.(Tprod - Tinj).\gamma \quad (1)$$

$$\gamma = \emptyset.Cw.\rho w + (1 - \emptyset).Cr.\rho r \quad (2)$$

Equation 1 shows the effective total aquifer volume can be translated into the theoretical capacity (heat in place H) with the use of a bulk heat capacity parameter γ (eq. 2). The bulk heat capacity is defined by the density (ρr and ρw) and heat capacity of rocks and fluids (Cr and Cw). The aquifer porosity (ϕ) is the ratio between fluids and rocks. Tprod is the aquifer temperature, Tinj is the reinjection temperature, h is the aquifer thickness.

3.3 Geostatistics

The geostatistical method was carried out to show the location spatially with heatflow and hot temperatures in the South Sumatra Basin. Heatflow and temperature become parameters in determining the prospect area and both parameters can be used to validate each other. This analysis can be used to determine prospect locations for hot sedimentary aquifer development. The geostatistical method used in this research is ordinary kriging. In this study the ILWIS 3.3 application was used.

The geostatistical method begins with determining the normal kriging parameters by modeling a semivariogram. Making the semivariogram model is done by trial and error, meaning that obtaining an accurate semivariogram model is done manually by changing the lag distance to get the semivariogram parameter values, namely, nugget effect, sill, and a reasonable and appropriate range (Guskarnali, 2016). Parameters from the best semivariogram used in ordinary kriging to make interpolations in the form of maps.

4. RESULT AND DISCUSSION

4.1 Resources Estimation

All parameters that used in this study is in the table 1 and table 2. Reservoir thickness for each sub-basin ranges from 2100–3500 m (Panggabean & Santy, 2012). Hence, reservoir thickness that used in this study is the average value between those range: 2800 m. Tprod value (table 2) in this study come from average value of bottom hole temperature (BHT) for each sub-basin from Hall, 2002. Tinj value can be generalised as +10℃ of surface temperature (Limberger et.al, 2018). Due to annual average surface temperature of South Sumatra is 27℃ (BMKG, 2013), Tinj value is 37℃. The lithology of the study area can be generalized first before determining the porosity value, rock heat capacity, and rock density. The lithology of the study area is generalized as sandstone due to domination of sandstone and limestone in Talang Akar Fm and Baturaja Fm. The sandstone has average porosity value of 15% (Tamtomo and others, 1997; Petroconsultants, 1996; In Bishop, 2001), rock heat capacity of 915 J/kgK (Jian et al., 2020), and rock density of 2420 kg/m3 (Mexant, 1980).

Table 1: Hot Sedimentary Aquifer calculation parameters.

Parameter	Value	Reference
h (m)	2800	Panggabean & Santy (2012)
T_{inj} (°C)	37	Limberger et al. (2018); BMKG (2023)
ϕ (%)	15	Petroconsultants (1996); Tamtomo et al. (1997) in Bishop (2001)
C_w (J/kg K)	1000	
ρ_w (kg/m3)	1042	
C_r (J/kg K)	915	Jian et al. (2020)
ρ_r (kg/m^3)	2420	Maxant (1980)

Table 2: T_{prod} in several South Sumatra sub-basins.

South Sumatera Sub-basin	T_{prod} (°C)
Jambi	112.9
Central Palembang	116.1
North Palembang	84.4
South Palembang	95.4

Calculation using equation 1 resulting heat in place value (table 3). Area that has highest heat in place value is central of South Sumatra Basin with 4.5 × 108 PJ/km2 and area with lowest heat in place value is northern of South Sumatra Basin with 2.7 × 108 PJ/km2.

Table 3: Heat in place values in several South Sumatra sub-basins.

South Sumatera Sub-basin	H (PJ km^{-2})
Jambi	433307584.5
Central Palembang	451296514.3
North Palembang	270797422
South Palembang	387593343.7

4.2 Geostatistics

4.2.1 Heatflow

There are 47 well/site heatflow data, obtained from Hall, 2002, that were used in this geostatistical analysis. Firstly, the quality of the data must be analysed, and it can be done by using the Exploratory Data Analysis (EDA) method. The heatflow data has a mean value of 107.326087, median value of 107, and mode value of 110. In addition, histogram of this heatflow data is positively skewed. Therefore, the EDA method shows that the 47 well/heatflow data are not normally distributed (Figure 4). If the skewness value is 0.5-1, it is necessary to transform the data using square roots. Meanwhile, if the skewness value is > 1, it is necessary to transform the data using logarithms (Kitanidis, 1997). The skewness value of 1.7. So, data can be transformed into more normally distributed data by logarithmic transformation. After logarithmic transformation, the value of mean and median are same: 2.03 mode value of 2.04 and the histogram has zero skewness as well.

Spatial correlation between these heatflow data can be analysed using semi variogram after EDA method. Best variogram model for this data are gaussian model with lag distance 10000 m, sill 0.001, nugget 0.0014 dan range 25000 that obtained from try and error. This variogram model can then be used for interpolation using ordinary kriging method with limiting distance value of 43000. The result of interpolation shows that temperature anomaly can be found in northeast and southwest region which is Jambi sub-Basin and South Palembang sub-basin (Figure 6).

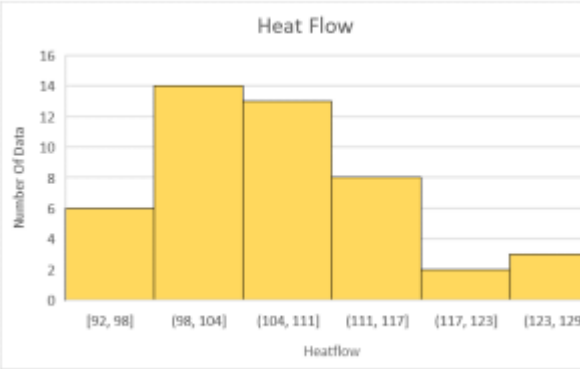


Figure 4: Histogram of Heatflow.

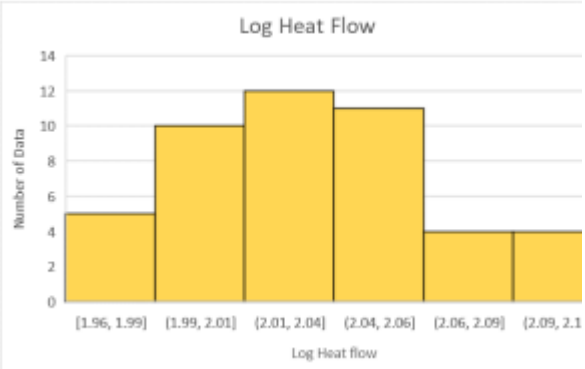


Figure 5: Histogram of Log Heatflow.

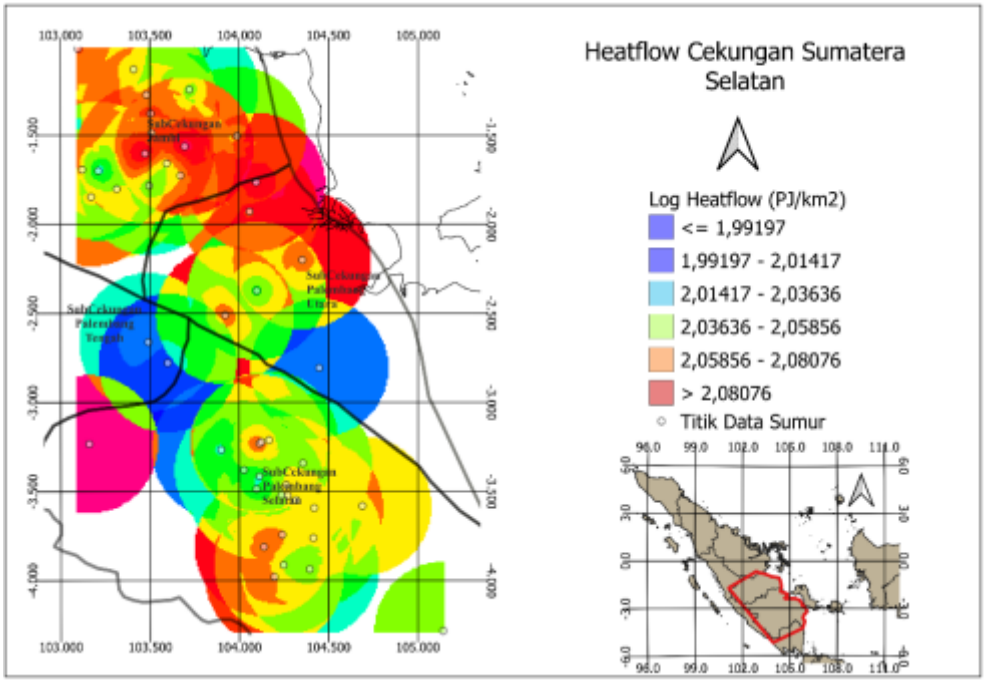


Figure 6: Heatflow map of South Sumatera Basin.

4.2.2 Temperature

There are 41 well temperature data, obtained from Hall, 2002, that used in this geostatistical analysis. Firstly, quality of the data must be analysed, and it can be done by using Exploratory Data Analysis (EDA) method. The temperature data has mean value of 106, median value of 104, and mode value of 104. In addition, histogram of this temperature data is positively skewed. Therefore, EDA method show that the 41 well/site temperature data are not normally distributed (Figure 7). If the skewness value is 0.5-1, it is necessary to transform the data using square roots. Meanwhile, if the skewness value is > 1, it is necessary to transform the data using logarithms (Kitanidis, 1997). The skewness value of 1.2. So, data can be transformed into more normally distributed data by logarithmic transformation. After logarithmic transformation, the value of mean, median, and mode are same: 2.01 and the histogram has zero skewness as well.

Spatial correlation between these temperature data can be analysed using semi variogram after EDA method. Best variogram model for this data are spherical model with lag distance 9000 m, sill 0.0013, nugget 0.0012, and range 4000 that obtained from try and error. This variogram model then can be used for interpolation using ordinary kriging method with limiting distance value of 43000. The result of interpolation show that temperature anomaly can be found in northeast and southwest region which is Jambi sub-basin and Central Palembang sub-basin (Figure 9).

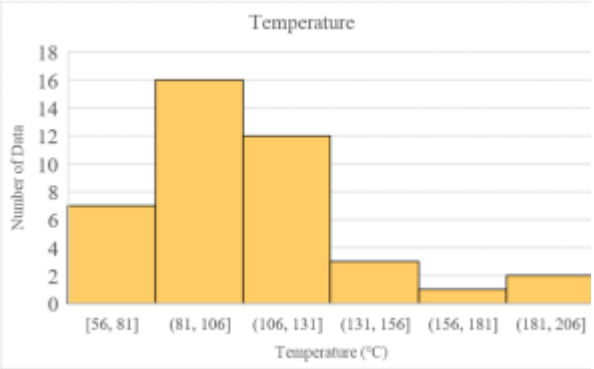


Figure 7: Histogram of Temperature.

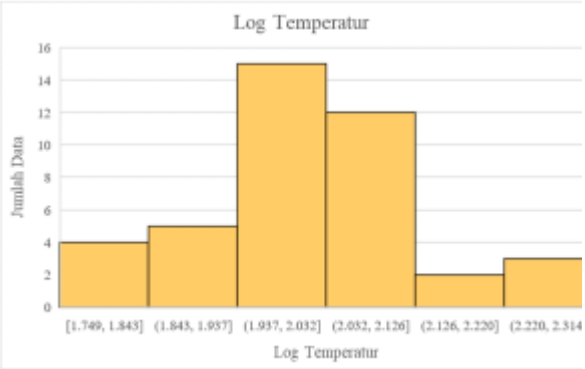


Figure 8: Histogram of Log Temperature.

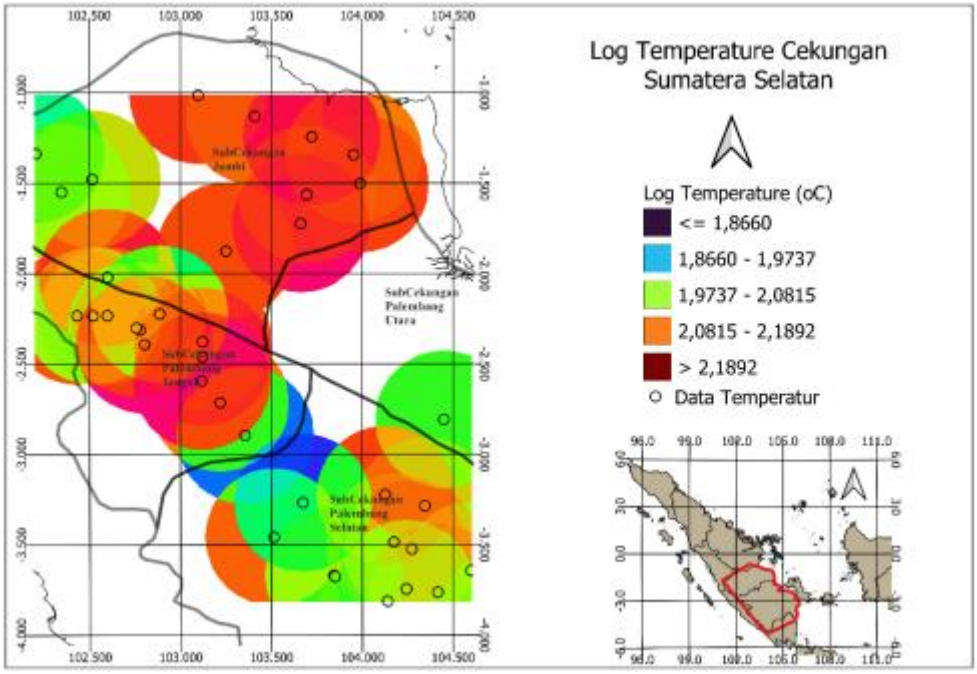


Figure 9: Temperature map of South Sumatera Basin.

4.3 Discussion

Based on table 3, the highest to lowest heat in place values are in Central Palembang Sub-basin, Jambi Sub-basin, South Palembang Sub-basin, and North Palembang Sub-basin. This is supported by the results of geostatistical analysis as validation and determination of potential locations. Based on the geostatistical analysis, the heatflow data showed differences with the analysis of heat in place calculations which showed anomalies in Jambi Sub-basin and South Palembang Sub-basin. This is influenced by the small amount of data in the Central Palembang Sub-Basin. Meanwhile, the temperature section has the same results as the heat in place calculation results. Anomalous values in the Jambi sub-basin are in the Northeast and Central Palembang in the Southeast

5. CONCLUSION

Based on the analysis conducted, the South Sumatra Basin has a large heat in place value with the highest value being in the Central Palembang Sub-basin with a value of 4.5 × 108 PJ/km2, and the second is in Jambi Sub-basin with a value of 4.3 × 108 PJ/km2, the results of the geostatistical analysis validate this. The geostatistical analysis shows that the temperature anomaly is in the Northeast in the Jambi Sub-basin and Southeast in the Central Palembang Sub-basin, this shows areas that have more prospects for the development of hot sedimentary aquifers because of higher temperatures.

REFERENCES

Bishop, M. G. (2001). South Sumatra Basin Province, Indonesia: The Lahat/Talang Akar-Cenozoic Total Petroleum: USGS.

Kementerian Koordinator Bidang Perekonomian Republik Indonesia. (2023, Maret 7). Pemerintah Terus Mendorong Percepatan Transisi Energi di Dalam Negeri Guna Mencapai Target Net Zero Emission pada 2060. Accessed from https://www.ekon.go.id/publikasi/detail/4996/.

Kementerian Energi Dan Sumber Daya Mineral. (2020, Desember). Potensi Pengembangan Energi Panas Bumi di Indonesia. Accessed from https://ebtke.esdm.go.id/lintas/id/investasi-ebtke/sektor-panas-bumi/potensi.

Kitanidis, P.K. (1997), Google-Books-ID: ZvoibTTS9QwC, Introduction to Geostatistics: Applications in Hydrogeology, Cambridge University Press, Cambridge.

Maxant, J. (1980). Variation of density with rock type, depth, and formation in the Western Canada basin from density logs, GEOPHYSICS, 45, p. 1061-1076.

Mijnlieff, H. (2020). Introduction to the geothermal play and reservoir geology of the Netherlands. Netherlands Journal of Geosciences. 99. 10.1017/njg.2020.2.

Moulds, P. J. (1989). Development of the Bengkalis depression, Central Sumatra and its subsequent deformation – a model for other Sumatran grabens?: *Proceedings Indonesian Petroleum Association Eighteenth Annual Convention*, October 1989, p. 217-246.

Pulunggono, A., Haryo, A. S., & Kosuma, C. G. (1992). Pre-Tertiary and Tertiary Fault Systems as a Framework of the South Sumatra Basin; A Study of SAR-Maps: *Proceedings of Indonesia Petroleum Association, 21st Annual Convention*, p. 339-360.

Sudarmono, Suherman, T., & Benny Eza. (1997). Paleogene basin development in Sundaland and its role to the petroleum systems in Western Indonesia: *Proceedings Indonesian Petroleum Association Petroleum Systems of SE Asia*, May 1997, p. 545-560.

Suta, I. N., & Xiaoguang, L. (2005). Complex stratigraphic and structural evolution of Jabung Basin and its hydrocarbon accumulation; Case study from Lower Talang Akar reservoir South Sumatera Basin Indonesia, Jakarta: *Proceedings Indonesian Petroleum Association Annual Convention*.

Verma, A., & Pruess, K. (1986). Enhancement of Steam Phase Relative Permeability Due to Phase Transformation Effects in Porous Media, *Proceedings, 11th Workshop on Geothermal Reservoir Engineering*, Stanford University, Stanford.

Wang, C.T., & Horne, R.N. (1999). Boiling Flow in a Horizontal Fracture, *Geothermics*, 29, 759-772.

Xiong, J., Lin, H., Ding, H., Pei, H., Rong, C., & Liao, W. (2020). Investigation on thermal property parameters characteristics of rocks and its influence factors. *Natural Gas Industry B*, 7(3), p. 298-308.

Zeliff, C. W., Trollope, S. W., & Maulana, E. (1985). Exploration cycles in the corridor block, South Sumatra: *Proceedings, Indonesian Petroleum Association Fourteenth Annual Convention*, October 1985, p. 279-400.

Review of Lithium Extraction Suitable for Indonesia Geothermal Brine

Esty Mustika Suud[1], Suryantini[1,2], and Herbert Lubis[3]

[1]Geothermal Master Program, Faculty of Mining and Petroleum Engineering, ITB, Bandung, Indonesia
[2]Applied Geology Research Group, Faculty of Earth Science and Technology, ITB, Bandung, Indonesia
[3]Alumnus Sarulla Geothermal Project and Member of Indonesia Renewable Energy Society, Indonesia

estymustikas@gmail.com, herbert.lubis@gmail.com

Keywords: Lithium, Energy Transition, Net Zero Emissions, Geothermal Brine, Traditional Brine Extraction, Direct Lithium Extraction DLE, Adsorption, Ion Exchange, Solvent Extraction, Capex/Opex, Operating Pilot Plant

ABSTRACT

Lithium is the cornerstone of energy transition for Indonesia to achieve Net Zero Emissions by 2060 or earlier. This energy transition will drive the Indonesia demand projection for Electric Vehicle Battery and Energy Storage System and in turn will demand much more lithium for this transition effort. Many studies have been conducted to find the sources of lithium, one of them is geothermal brine. Indonesia has enormous geothermal resources; some fields have lithium content that can potentially be extracted. Various methods in the extraction process of lithium from the geothermal brine have been developed, both on laboratory and pilot projects. The geothermal brine is typically pumped to the surface by a geothermal power plant, used for energy generation, and then returned to the underground reservoir via an injection well. Prior to reinjection the geothermal brines contain in the temporary ponds whereas the lithium extraction points may occur here or any point suitable for the extraction technology. Typically there are three phases in the lithium extraction, like end-to-end process technology solutions, namely 1) Lithium Brine Extraction-depending on the geothermal brines field compositions, pre-treatment may be employed to remove any contaminants or unwanted constituents from the brines, then selective absorbents are used to separate lithium from other elements 2) Concentration with membrane system to concentrate lithium at a desired concentration 3) Deposition using chemical precipitation and purification for saleable lithium production. This paper reviews traditional brine extraction and direct lithium extraction (DLE) in general and specifically in geothermal brine. The study is based on a desktop study and aims to summarize the knowledge, method, technology, and techniques of lithium extraction from geothermal brine that has already been used and to find out which extraction method is suitable for the Indonesian geothermal field. Our finding indicates the adsorption end-to-end process includes pretreatment, lithium extraction, purification, and lithium product production steps such as electrodialysis (a form of ion exchange) and reverse osmosis to yield high recovery rates. The adsorption DLE solution has been used on a commercial scale, in Argentina and China and it has a fifty-year development and implementation history, higher lithium recovery, lower water and chemicals consumption, shorter lead time to production, minimal footprint, potential for no carbon emissions, and an additional revenue stream from unused brine resources for geothermal power producers. There is unlikely a one size fits all solution, hence a complete pilot plant to simulate the real condition of geothermal field brines is important. The other important points are to keep the project commercial operation date punctuate with faster, cheaper, better and rapid speed of technology implementation.

1. INTRODUCTION

Lithium is the cornerstone of energy transition because of the following two reasons, the first reason is that it has the key ingredient in batteries for electric cars and renewable power storage, making it a critical commodity for the energy transition to reduce emissions of greenhouse gases. And the second reason is that Lithium is a big enabler of the energy transition from a battery perspective as we move to electric vehicles and add energy storage to electricity grids, allowing for greater penetration of renewables. As a result, lithium is increasingly being seen as a critical mineral by governments, where they want to secure supplies for that transition, and that has made it an increasingly important commodity. In line with this cornerstone of energy transition, Indonesia is committed to achieve Net

Zero Emissions by 2060 or earlier and is beginning to put in place the policies and frameworks that can help reach this target while moving towards advanced economy status.

Lithium is a light and highly reactive metal that offers excellent heat and electrical conductivity. Because of its high reactivity, pure elemental lithium is not found in nature but is instead present as a constituent of salts or other compounds. Lithium is found in three main types of deposits: pegmatites (crystalline hardrock), saline subsurface waters (lithium brines) and sedimentary deposits. The primary commercial sources of lithium are hard rock deposits in Australia and China approximately 60%, and brine deposit in Argentina, Chili, China, and the rest of the world approximately 40%. The three main types of lithium brine deposits include salt-lakes or salt-flats (salars), geothermal, and oil field deposits. Future potential for geothermal brine to supply demand is recognized as an important brine source of lithium.

For both geothermal and conventional lithium resources, there is interest in developing technology, and processes for the direct extraction of lithium from brines. Unlike conventional methods for producing lithium, the so-called *Direct Lithium Extraction* (DLE), a potential game changing technology, uses filters, membranes or resin materials to extract mineral from brine water. And as such DLE may significantly increase the supply of lithium, nearly doubling production from same resource and improving project returns through a process that may be more sustainable. A number of proven DLE technologies are emerging and being tested at scale, with a handful of projects already in commercial construction. While there may still be challenges around scalability and water consumption/brine reinjection. With the ongoing efforts, DLE could be implemented between 2024- 2030 in USA, between 2024-2030 in Europe, and between 2025-2030 in both Chile and Argentina.

2. TECHNOLOGY FOR LITHIUM EXTRACTION METHODS

The following table summarizes the processes for hard rock, traditional brine ponds, and key DLE technologies and their detailed comparisons.

Table 1: Lithium Extraction Methods in Hard Rock, Evaporation and Direct Lithium Extraction in Brine (Goldman Sachs, 2023).

Lithium extraction methods	Hard Rock	Brine	
	Mining	Evaporation	DLE
Production times (extraction to production)	Weeks to months	Months to years	Hours to days
Lithium recovery rates	~60-80% (processing)	~40-60%	~70-90%+
Costs	Medium-High	Low	Low-Medium
Capex	Varied on grade/ chemical conversion	~US$23-34,000/tpa LCE	~US$26-34,000/tpa LCE
Opex		~US$3,300-4,900/t LCE	~US$2,800-3,600/t LCE
Lithium product	Spodumene (~5-6% Li_2O)	Lithium Carbonate (Li_2CO3) / Lithium Chloride (LiCl)	Lithium Carbonate (Li_2CO3)/ Lithium Chloride (LiCl)
Process	Heating, cooling, crushing, and roasting	Staged atmospheric evaporation, plant processing	Adsorption (Ad), Ion Exchange (IX), Solvent Extraction (SX), Membrane
Further processing requirements	Yes	No (subject to end use)	No (subject to end use)
Land area requirement	High	High	Low
Weather dependance	Yes	Yes	No
Water consumption	High	Medium-High	Low-Medium (subject to reinjection availability)
Energy Consumption	High	Low (free solar evaporation)	Medium
Emissions	High	Low	Low

The traditional lithium extraction method from well-established producing countries like from hard rock (Australia & China) and from brines (Chile, Argentina, and China), to countries with recently mapped resources and reserves such as the United States, Europe, Mexico, Canada, Bolivia, and Ukraine, to locations typically not associated with lithium such as United Kingdom, Peru, Siberia, and Thailand, exploration for traditional deposits of "white diamond pearl" is happening globally.

The non-traditional brines deposits (geothermal, oilfield brines) will come additional brines with grades of 100 to 200 part per million (ppm). The first option focuses on providing both clean geothermal energy

and lithium supply. Although nothing has been proven on a commercial scale as yet, there are already financially confirmed projects in Europe and North America sites. With technology development and proof of concepts, more geothermal lithium-brine operations will appear on the global map, with some automotive companies supports like General Motors, Renault, and among others.

2.1 Traditional Evaporation versus Brine Direct Lithium Extraction

Traditionally, lithium produced from brine water is stored in evaporation ponds. As the water evaporates, the other elements of the brine such as magnesium or calcium precipitate out, leaving the brine more concentrated to produce lithium carbonate. The evaporation process, however, yields only 40% to 60% of the potential lithium in the brine. DLE has the potential to yield 80% to 90% or more. It's also much faster. The evaporation process can take nine to 18 months depending on the type of project and weather conditions. With DLE, that process can be shortened to days or even hours. And you don't need all the land for the pond evaporation process. What's more, you can potentially reinject the remaining brine water after the process, which further reduces the environmental impact.

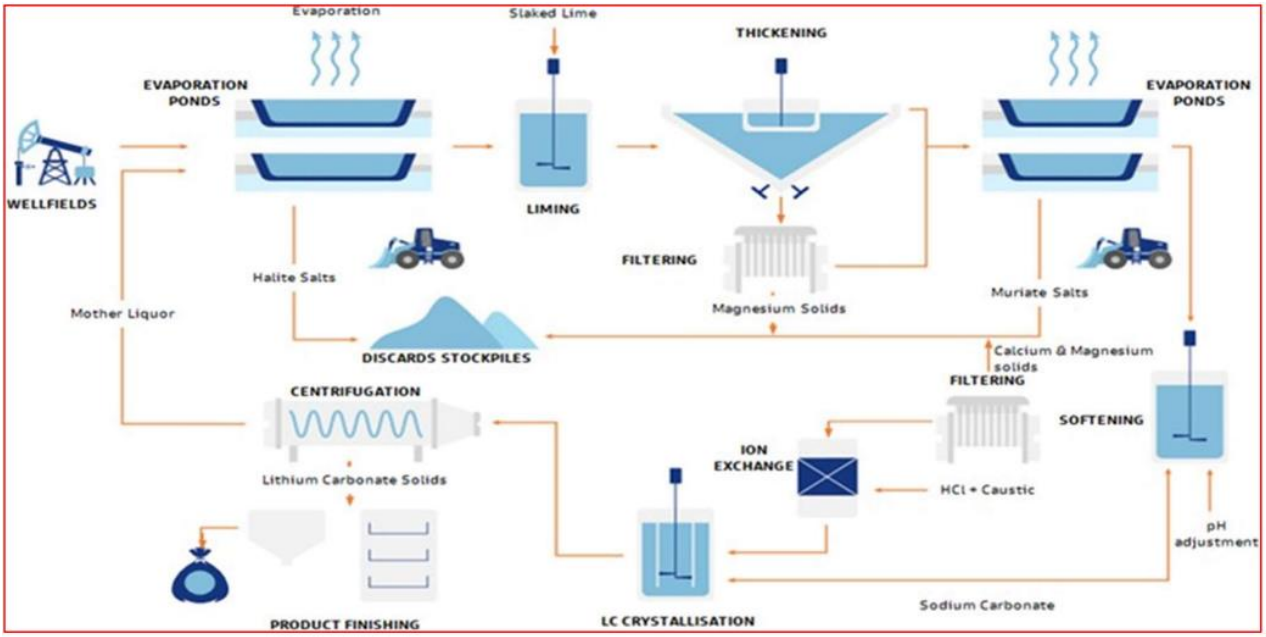


Figure 1: Traditional Brine Pond Flowchart (Goldman Sachs, 2023).

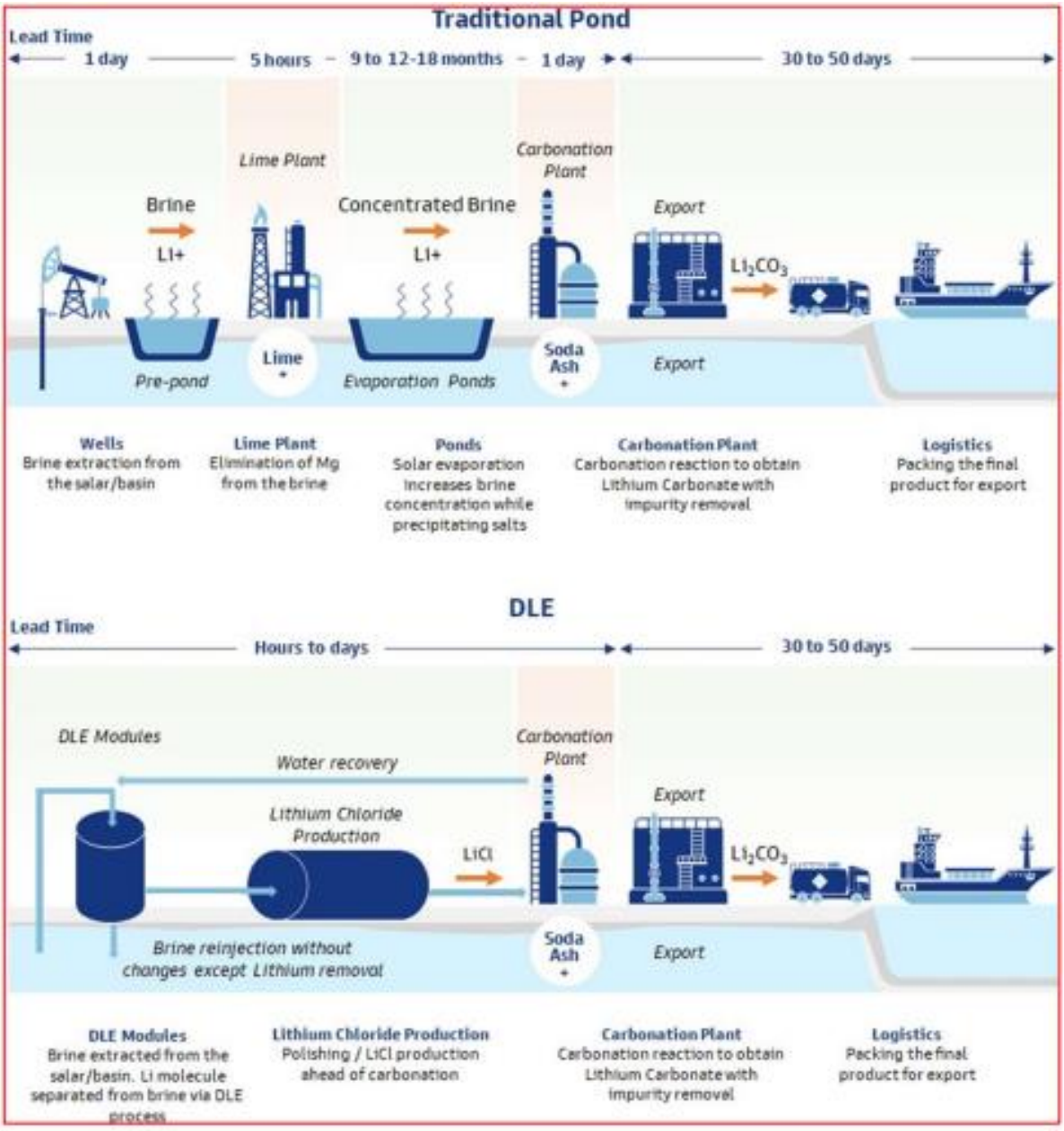


Figure 2: Traditional Process Brine Extraction vs DLE, and Timing of Each stage.

Table 2 outlines 27 global lithium projects that are using or plan to implement DLE, along with a further nine advancing third-party technology developers.

Company	Project	Country	DLE Project stage	DLE technology provider	Lithium extraction technology	Tech Origin	Geothermal	Resource (Mt LCE)	Start date	Capacity (ktpa LCE)
Lithium project developers/operators										
Eramet/Tsingshan	**Centenario-Ratones**	Argentina	Construction	Proprietary	Sorption	-	-	10	2024	~24+50 (P1+P2)
Livent	**Fenix (Hombre Muerto)**	Argentina	Production	Proprietary	Sorption	USA	-	12	1998	~80 (3 expansions)
RIO	**Rincon**	Argentina	Pilot	Proprietary	Sorption	-	-	12	2024	30
Lake Resources	**Kachi Project**	Argentina	Pilot	Lilac Solutions	IX	USA	-	4	2024	25
Allkem	**Olaroz enhanced recoveries**	Argentina	Study	TBD (in testing phase)	TBD	TBD	-	-	-	-
Tibet Summit Resources	**Angeles**	Argentina	Construction	SunResin	Sorption	China	-	2	2024	25 (P1)
Eon Minerals	**Amanecer**	Argentina	Pilot	Proprietary	Sorption	Argentina	-	-	-	-
Albemarle	**Atacama**	Chile	Pilot	Proprietary LiET / Third party testing	TBD	TBD	-	11	2023	-
SQM	**Atacama**	Chile	Pilot	Proprietary / Third party testing	TBD	TBD	-	68	2024	220-250
CleanTech Lithium	**Laguna Verde**	Chile	Pilot	SunResin	Sorption	China	-	2	2026	20
CleanTech Lithium	**Fransisco Basin**	Chile	Pilot	TBD (in testing phase)	TBD	TBD	-	1	-	-
Lanke Lithium	**Yiliping Lake**	China	Production	SunResin	Sorption	China	-	-	2017	20
Zangge lithium	**Chalkhan Lake**	China	Production	SunResin	Sorption	China	-	-	2018	20
Jintai Lithium	**Mahai Lake**	China	Production	SunResin	Sorption	China	-	-	2019	7
Tibet National	**Qinghai**	China	Commissioning	SunResin	Sorption	China	-	-	-	-
Yiwei Lithium	**Qinghai Salt Lake**	China	Construction	SunResin	Sorption	China	-	-	-	-
Anson Resources	**Paradox Lithium**	USA	Pilot/DFS	SunResin	Sorption	China	-	-	-	-
Compass Minerals	**Great Salt Lake**	USA	Pilot	Energy Source Minerals (ILiAD)	Sorption	USA	-	2	2025	35
Berkshire Hathaway	**Salton Sea**	USA	Pilot	Proprietary	Sorption	USA	Yes	-	-	90
Energy Source Minerals	**Salton Sea (Project ATLIS)**	USA	Pilot	Proprietary (ILiAD)	Sorption	USA	Yes	-	2024	20
Controlled Thermal Resources	**Salton Sea**	USA	Pilot	Lilac Solutions	IX	USA	Yes	-	-	25
Controlled Thermal Resources	**Hell's Kitchen**	USA	Offsite Pilot	Lilac Solutions	IX	USA	Yes	3	2024	25
Standard Lithium	**Smackover (Lanxess Project)**	USA	Demonstration	Proprietary (LiSTR)	IX	USA	-	3	-	22
American Battery Materials	**Lisbon Lithium Project**	USA	Pilot	TBD (in testing phase)	TBD	USA	-	-	-	-
E3 Metals Corp	**Clearwater**	Canada	Pilot	Proprietary	IX	Canada	-	7	2025	20
LithiumBank	**Boardwalk**	Canada	Pre-PEA	Conductive Energy	IX	Canada	-	6	-	-
Vulcan Energy	**Upper Rhine Valley**	Germany	Pilot	Proprietary (VULSORB)	Sorption	Germany	Yes	16	2024	48
Technology developers										
Summit Nanotech	-	-	Pilot/Demo	Proprietary (denaLi)	Sorption	Canada	-	-	-	-
SunResin	-	-	Commercial (growing scale)	Proprietary	Sorption	China	-	-	-	-
International Battery Metals (IBAT)	-	-	Demo/Commercial	Proprietary	Sorption	USA	-	-	-	-
Koch Technology Solutions	-	-	Lab/Pilot	Proprietary (Li-Pro)	Sorption	USA	-	-	-	-
Lilac Solutions	-	-	Demo/Commercial	Proprietary	IX	USA	-	-	-	-
Conductive Energy	-	-	Pilot/Demo	Proprietary	IX	Canada	-	-	-	-
EnergyX	-	-	-	Proprietary (LiTAS)	Membrane	USA	-	-	-	-
Geo40	-	-	Lab	Proprietary (GeoSieve)	Membrane	NZ	Yes	-	-	-
Solvay	-	-	Pilot	Proprietary (CYANEX 936P)	SX	Belgium	-	-	-	-

Table 2: Twenty Seven (27) Global Lithium Projects That are Using or Plan to Implement DLE, along with a Further Nine Advancing Third-Party Technology Developers (Goldman Sachs, 2023).

For geothermal or oilfield brines to succeed as a source of lithium supply, a proven process for DLE will be required. There are a number of companies testing various DLE approaches. While their ideas differ, the concept remains the same: letting the brine flow through a lithium-bonding material using adsorption, ion-exchange, membrane-separation, or solvent-extraction processes (Figure 3), followed by a polishing solution to obtain lithium carbonate or lithium hydroxide (Figure 4).

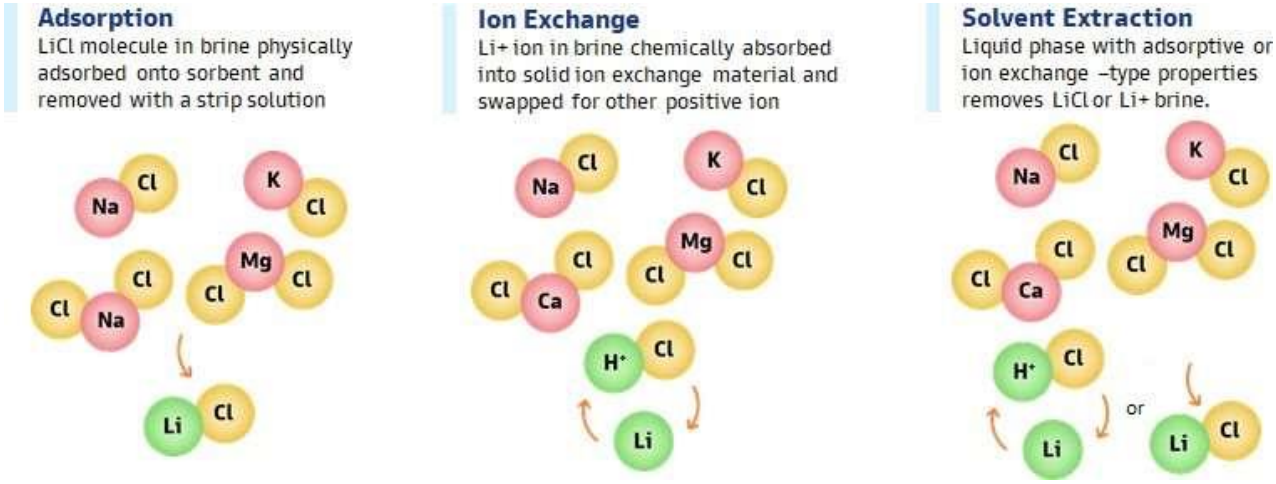


Figure 3: Details of the 3 Different Types of DLE Processes (Goldman Sachs, 2023).

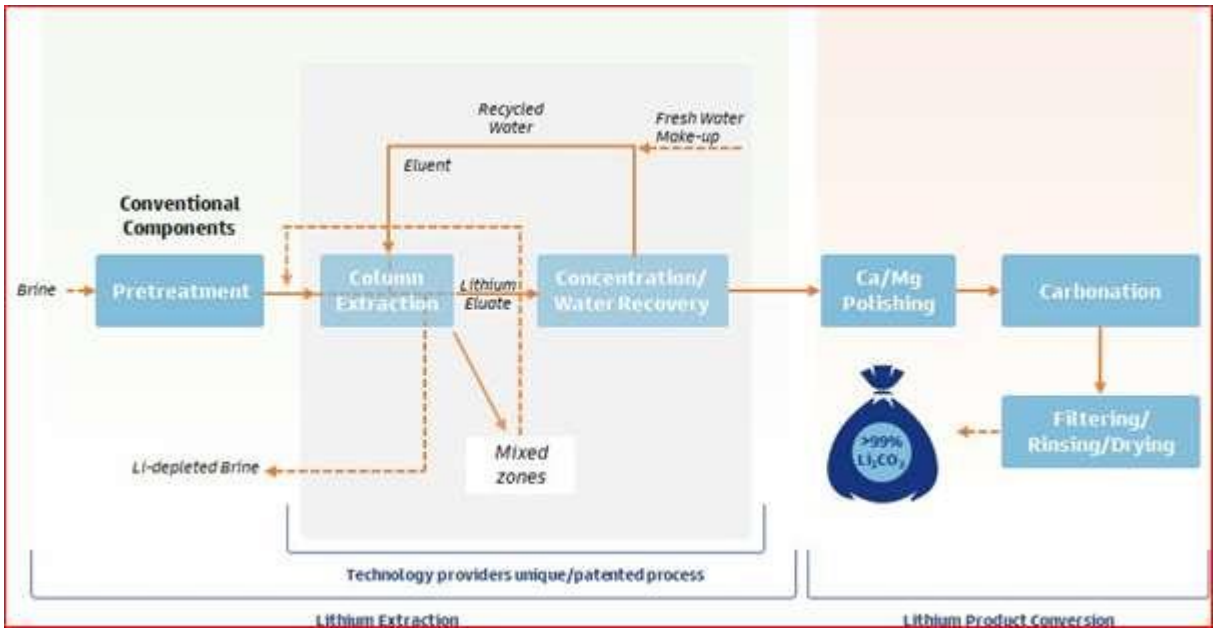


Figure 4: DLE Flow Chart (Goldman Sachs, 2023).

2.1.1 Adsorption

Adsorption is the most developed DLE technology globally, using adsorbents to adhere to the lithium for selective removal. Some sorbents developed can recover >90% of the lithium present, including recently tested lithium aluminum layered double hydroxide chloride sorbent, or LDH (Lithium-Aluminum Double Hydroxide Chloride). During more recent testing, the LDH sorbent was made by intercalating (inserting) aluminum hydroxide with lithium chloride, which made several $[LiAl_2(OH)_6]$+layers in the sorbent. These layers were separated by water molecules and hydroxide ions that created spacing requirements to allow lithium chloride to enter more readily than other ions, such as sodium and potassium. After the sorbent was loaded with the lithium chloride, it was washed with a

diluted lithium chloride stream to remove unwanted ions, then washed a second time to unload the lithium chloride.

The Pros of Adsorption: (i) does not require reagents or solvent extraction, instead water is used to recover lithium chloride with soda ash to convert to carbonate (ii) less impacted by brine composition, weather conditions, with lower waste generation (iii) lithium extraction efficiency of greater than 90% (iv) may combine processing steps such as electrodialysis (a form of ion exchange) and reverse osmosis to yield high recovery rates (v) produce high quality lithium chloride/carbonate.

The Cons of Adsorption: (i) requires temperature lower than 40^{o}C (ii) lower eluate (extracting a substance process) LiCl concentration than ion exchange (iii) some implementation may difficult to prevent contamination with the brine (iv) the adsorption equipment can be expensive (high upfront cost).

2.1.2 Ion Exchange

Ion exchange systems separate ionic contaminants from solution through a physical-chemical process where undesirable ions are replaced by other ions of the same electrical charge. This reaction occurs in an IX (ion exchange) column or vessel where a process or waste stream is passed through a specialized resin that facilitates the exchange of ions.

The Pros of Ion Exchange: (i) simple process (ii) high selectivity for lithium and reduced risk of impurity contamination in the product stream (iii) high capacity and high concentration of lithium in the strip solution, can be suitable for low lithium concentration brines (iv) low energy/water consumption (v) continuous operation.

The Cons of Ion Exchange: (i) high upfront cost (ii) high opex due large amount of base and acid inputs (iii) some IX material may degrade in acidic conditions.

2.1.3 Solvent Extraction (SX)

Solvent extraction uses an organic solution containing solvent and extractant to extract lithium from brines. The organic solution comprises of kerosene (or similar material) and an extractant that very high selectivity toward lithium over sodium and magnesium.

The Pros of Solvent Extraction: (i) high concentration of lithium can be produced from brine with high recovery rate, and not effected by weather conditions (ii) low opex costs (iii) lithium solvent extraction is essentially a stand-alone process.

The Cons of Solvent Extraction: (i) less applicable with higher impurity (ii) organic solvents are environmentally challenging (iii) fire risk with high temperature brines (iv) expensive relative to other technologies (v) the residual brine that remains after lithium extraction may require post-treatment to remove leached solvent.

The following figure shows the effectiveness and readiness of direct lithium extraction technologies.

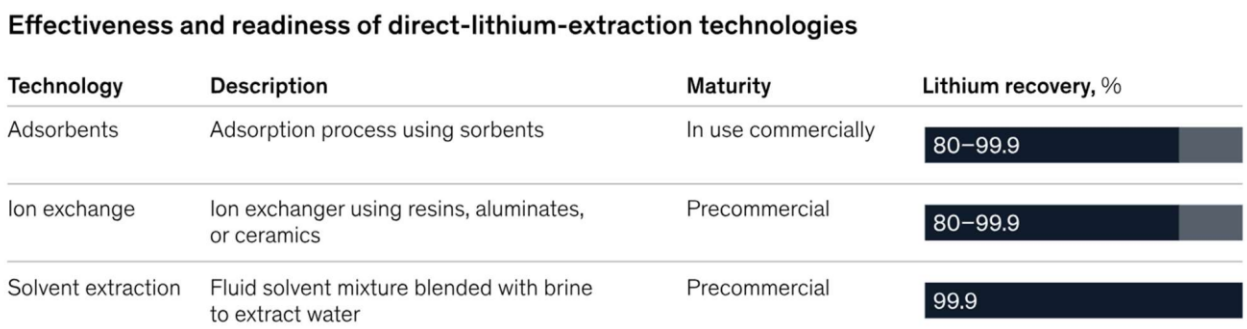
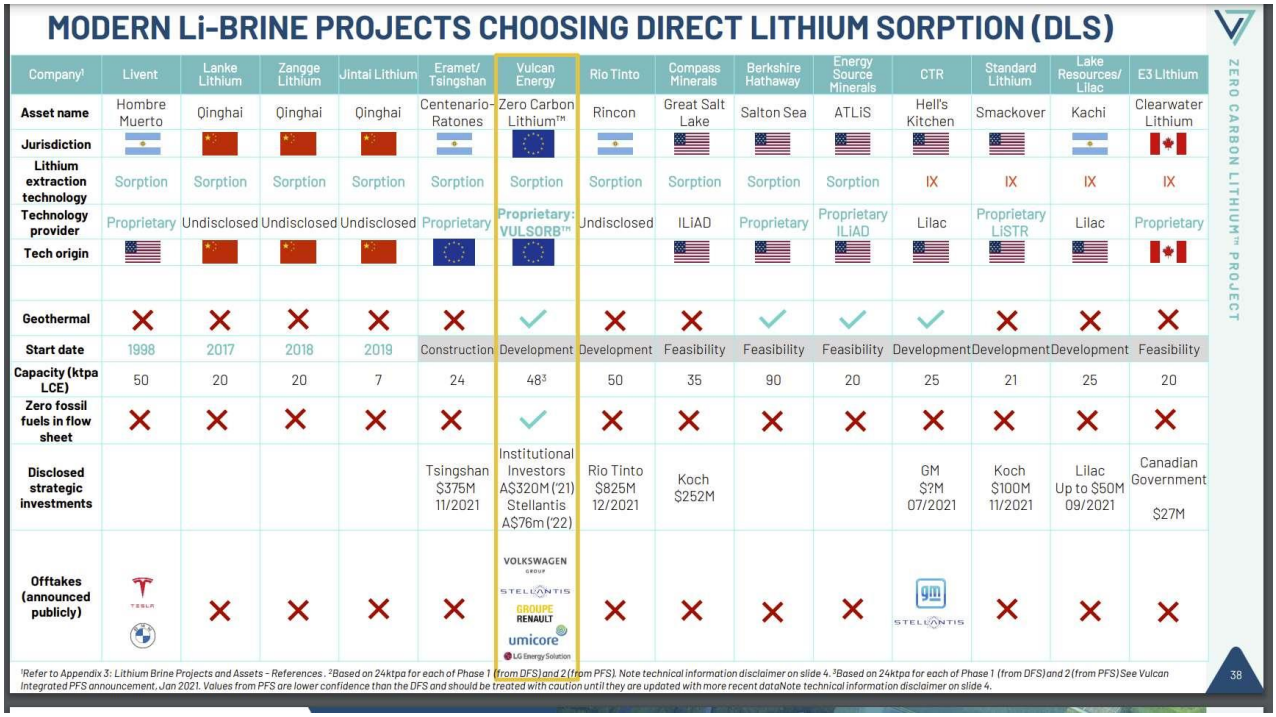


Figure 5: Effectiveness and Readiness of DLE Technologies (McKinsey & Company, 2022).

Promising DLE technology is currently being considered not only by unconventional players but also by companies that traditionally develop "typical" brine assets. DLE has several potential benefits, including:

1. eliminating/reducing the footprint of evaporation ponds
2. decreasing production times compared with conventional brine operation
3. increasing recoveries from around 40 percent to over 80 percent
4. lower usage of fresh water, which can be one of the deciding factors when applying for a mining concession in a region with scarce water resources
5. lower reagents usage and increased product purity (in terms of magnesium, calcium, and boron) compared with conventional brine operations

To date only adsorption DLE has been used on a commercial scale, in Argentina and China. If DLE can be scaled up and spread across brine assets, it will boost existing capacities via increased recoveries and lower operating costs, while also improving the sustainability aspects of operations.



Company[1]	Livent	Lanke Lithium	Zangge Lithium	Jintai Lithium	Eramet/ Tsingshan	Vulcan Energy	Rio Tinto	Compass Minerals	Berkshire Hathaway	Energy Source Minerals	CTR	Standard Lithium	Lake Resources/ Lilac	E3 Lithium
Asset name	Hombre Muerto	Qinghai	Qinghai	Qinghai	Centenario-Ratones	Zero Carbon Lithium™	Rincon	Great Salt Lake	Salton Sea	ATLiS	Hell's Kitchen	Smackover	Kachi	Clearwater Lithium
Jurisdiction														
Lithium extraction technology	Sorption	Sorption	Sorption	Sorption	Sorption	Sorption	Sorption	Sorption	Sorption	Sorption	IX	IX	IX	IX
Technology provider	Proprietary	Undisclosed	Undisclosed	Undisclosed	Proprietary	Proprietary: VULSORB™	Undisclosed	ILiAD	Proprietary	Proprietary ILiAD	Lilac	Proprietary LiSTR	Lilac	Proprietary
Tech origin														
Geothermal	✗	✗	✗	✗	✗	✓	✗	✗	✓	✓	✓	✗	✗	✗
Start date	1998	2017	2018	2019	Construction	Development	Development	Feasibility	Feasibility	Feasibility	Development	Development	Development	Feasibility
Capacity (ktpa LCE)	50	20	20	7	24	48[3]	50	35	90	20	25	21	25	20
Zero fossil fuels in flow sheet	✗	✗	✗	✗	✗	✓	✗	✗	✗	✗	✗	✗	✗	✗
Disclosed strategic investments					Tsingshan $375M 11/2021	Institutional Investors A$320M ('21) Stellantis A$76m ('22)	Rio Tinto $825M 12/2021	Koch $252M			GM $?M 07/2021	Koch $100M 11/2021	Lilac Up to $50M 09/2021	Canadian Government $27M
Offtakes (announced publicly)		✗	✗	✗	✗		✗	✗	✗	✗		✗	✗	✗

[1]Refer to Appendix 3: Lithium Brine Projects and Assets – References. [2]Based on 24ktpa for each of Phase 1 (from DFS) and 2 (from PFS). Note technical information disclaimer on slide 4. [3]Based on 24ktpa for each of Phase 1 (from DFS) and 2 (from PFS) See Vulcan Integrated PFS announcement, Jan 2021. Values from PFS are lower confidence than the DFS and should be treated with caution until they are updated with more recent dataNote technical information disclaimer on slide 4.

Figure 6: Modern Li-Brine Projects Choosing Direct Lithium Sorption (DLS) (Vulcan Energy, 2023).

DLE Adsorption is a commercial technology adapted to our local resource for the following reasons:

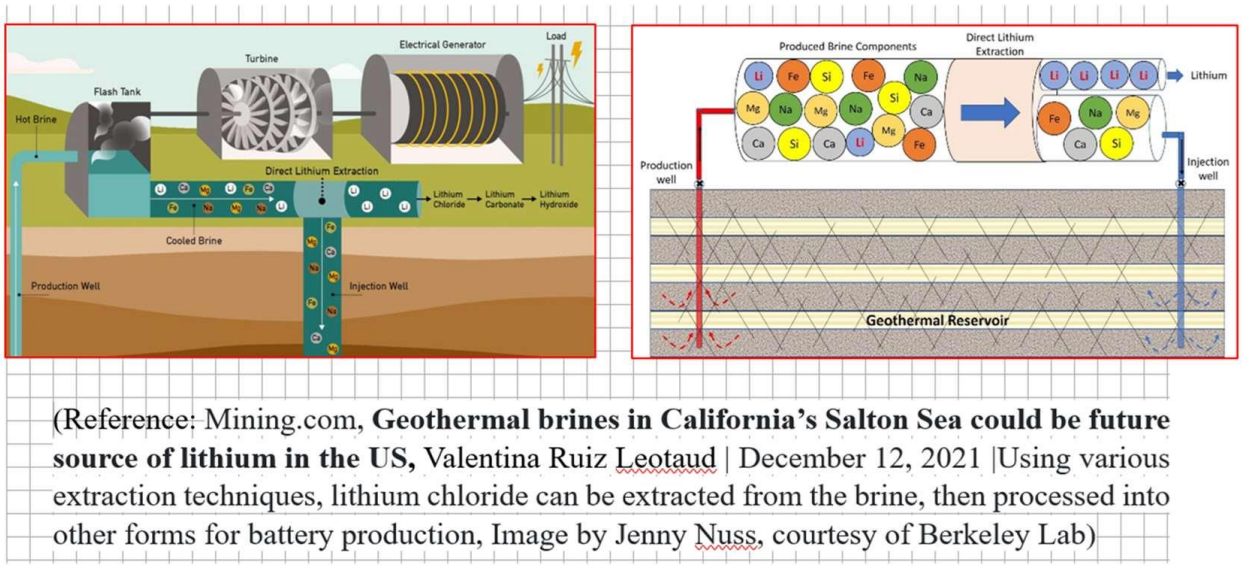
1. DLE using sorption has a fifty-year development and implementation history;
2. DLE Adsorption practiced commercially in South America for 26 years by Livent. More recently DLE Adsorption has been commercially deployed in China;
3. Large investment in DLE projects have recently been made in Argentina by Rio Tinto and Eramet;
4. DLE Adsorption includes several key advantages compared to traditional brine evaporation such as higher lithium recovery, lower water and chemicals consumption, shorter lead time to production, minimal footprint;
5. DLE Adsorption associated with geothermal brine adds the following no need to heat the brine with natural gas, potential for no carbon emissions, additional revenue stream energy.

2.2 Early Review of Indonesia Geothermal Brine Lithium Extraction

The paper written by Suud et al. (2023) reviewed the lithium extraction from the geothermal brine by direct extraction methods using solvent extraction, adsorption and ion exchange, membrane, and electrodialysis. Multiple-stages solvent extraction from geothermal brine well in one of Indonesian Geothermal working areas performed by Suud et al. (2023) demonstrated an extraction efficiency of 94% and indicated an opportunity to be further investigated for lithium extraction from one of the Indonesian geothermal brines.

3. CASE STUDY TO IMPLEMENT DIRECT LITHIUM EXTRACTION IN GEOTHERMAL BRINES

Lithium is an alkali metal that typically occurs in brine as LiCl. This LiCl solution is concentrated and purified through various processes and is then converted to high-purity Lithium Carbonate Li_2CO_3 and/or Lithium Hydroxide Monohydrate $LiOHH_2O$ commercial products. In the produced geothermal brines as shown in the following figure, consisted of the following chemical components such as Li, Fe, Si, Ca, Mg, Na and may include additional components such as K, B, Al, Sr, Mn, Cu, Ba, Zn, Ni, Cr.



(Reference: Mining.com, **Geothermal brines in California's Salton Sea could be future source of lithium in the US,** Valentina Ruiz Leotaud | December 12, 2021 |Using various extraction techniques, lithium chloride can be extracted from the brine, then processed into other forms for battery production, Image by Jenny Nuss, courtesy of Berkeley Lab)

Figure 7: Geothermal Brines in California's Salton Sea (Mining.com, 2021).

To refresh our memory on these geothermal brine components the following Periodic Table is presented here to comprehend where those brine components located in the Table from US National Institute of Standards & Technology (https://www.nist.gov/).

The most well-investigated and technologically advanced method for direct lithium extraction from geothermal brines from the Salton Sea, with information available in the public domain, is IliAD (Integrated Lithium Adsorption Desorption) (Stringfellow and Dobson, 2021). The Iliad process includes pretreatment, lithium extraction, purification, and lithium product production steps. In the ILiAD process, removal of zinc and manganese precedes the lithium extraction process. Iron, silica, and manganese are removed and recovered in sequential steps before lithium extraction. Lithium is removed with AlOH or AlOx sorbents using continuous bed process. According to the patent, the lithium chloride selective adsorbent may be a resin-based alumina imbibed adsorbent, a lithium alumina intercalate adsorbent, an alumina imbibed ion-exchange resin, or an alumina-based adsorbent. Iron and silica are removed by precipitation and zinc and manganese are removed by solvent extraction with Cyanex 272 or similar solvents using counter-current contactor. Post-extraction purification and processing include processes for removal of calcium and magnesium by ion exchange and further purification of the lithium chloride stream by precipitation and solvent stripping reactions. Lithium

hydroxide is produced by electrolysis and lithium carbonate is produced by the addition of sodium carbonate and purified by cycles of crystallization and dissolution. The process is designed to be modular, with each process module sized for production of approximately 3,000 metric tons LCE (Lithium Carbonate Equivalent) per year, depending on brine lithium concentrations. Pilot trials demonstrated the ability to produce high-purity lithium products (>99.9% pure) at a 90% lithium recovery rate.

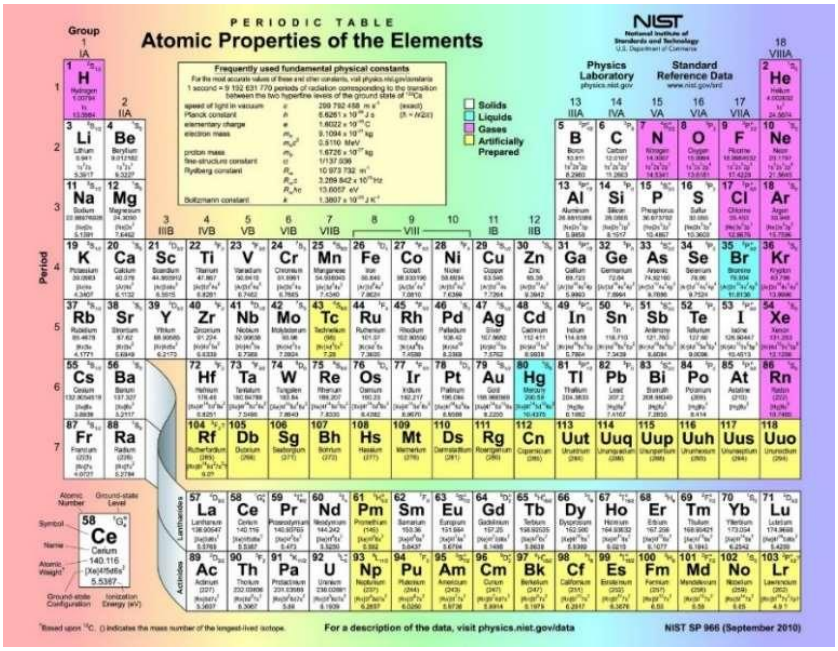


Figure 8: Periodic Table (https://www.nist.gov/).

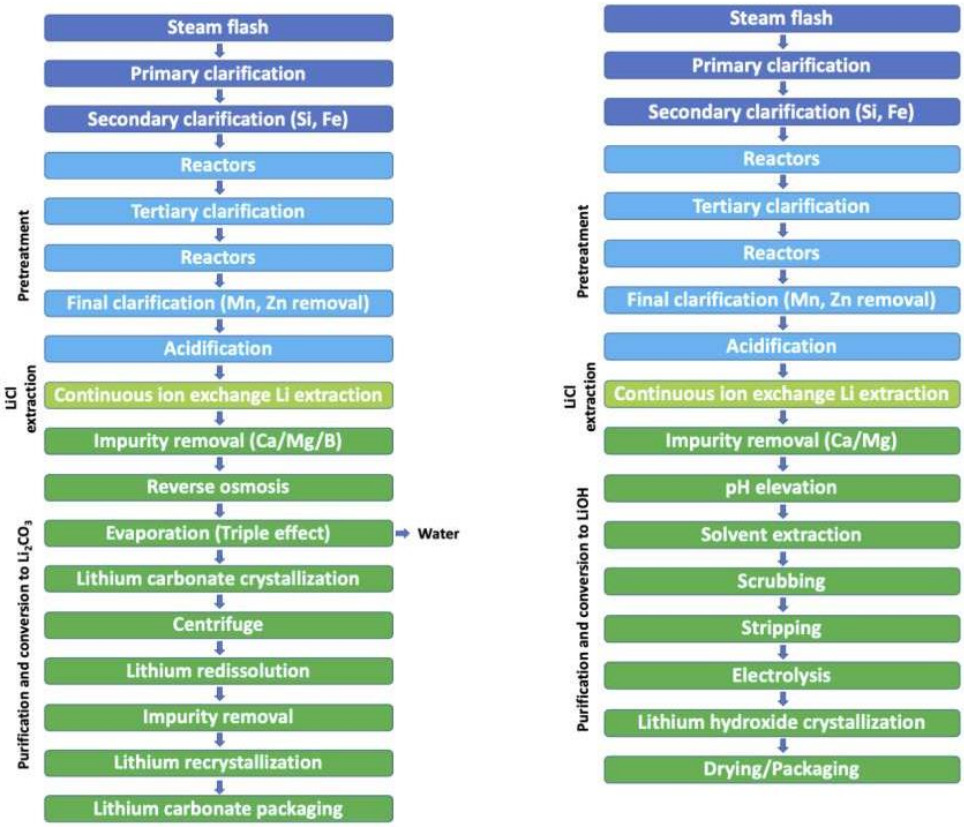


Figure 9: The ILiAD (Integrated Lithium Adsorption Desorption) Process (Stringfellow and Dobson, 2021).

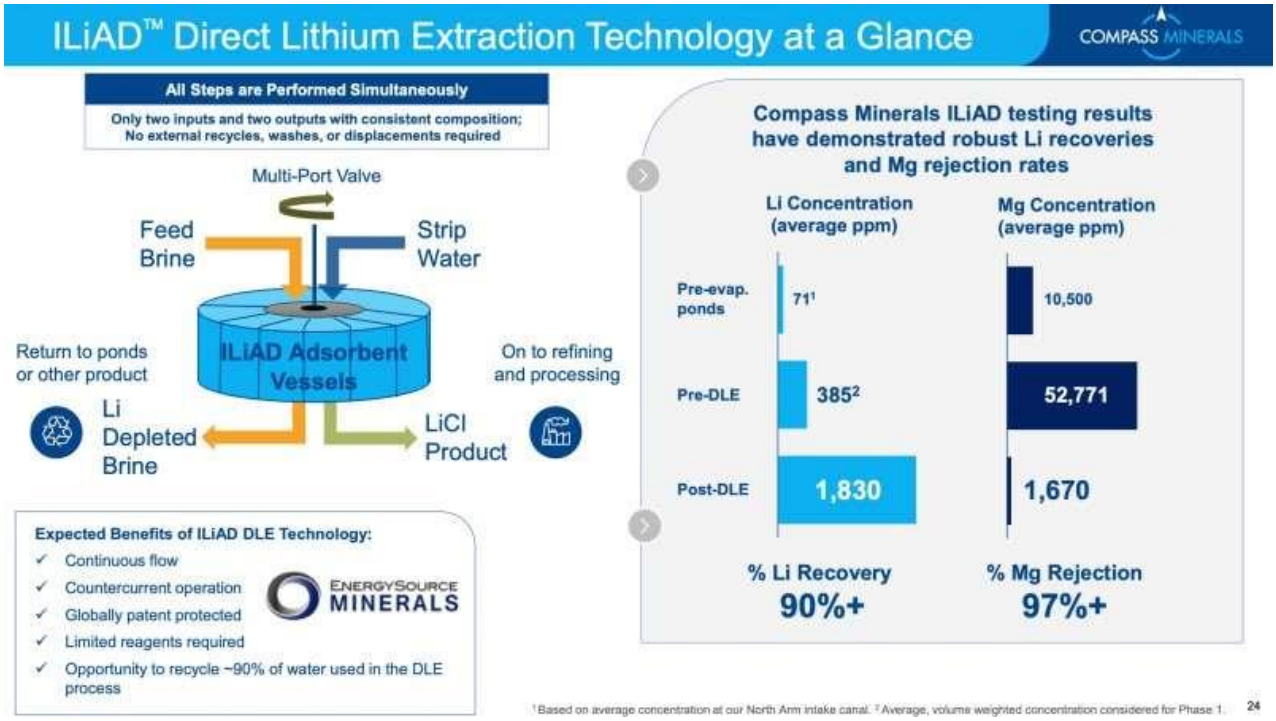


Figure 10: ILiAD Direct Lithium Extraction Technology at a Glance (Energy Source Minerals, 2023).

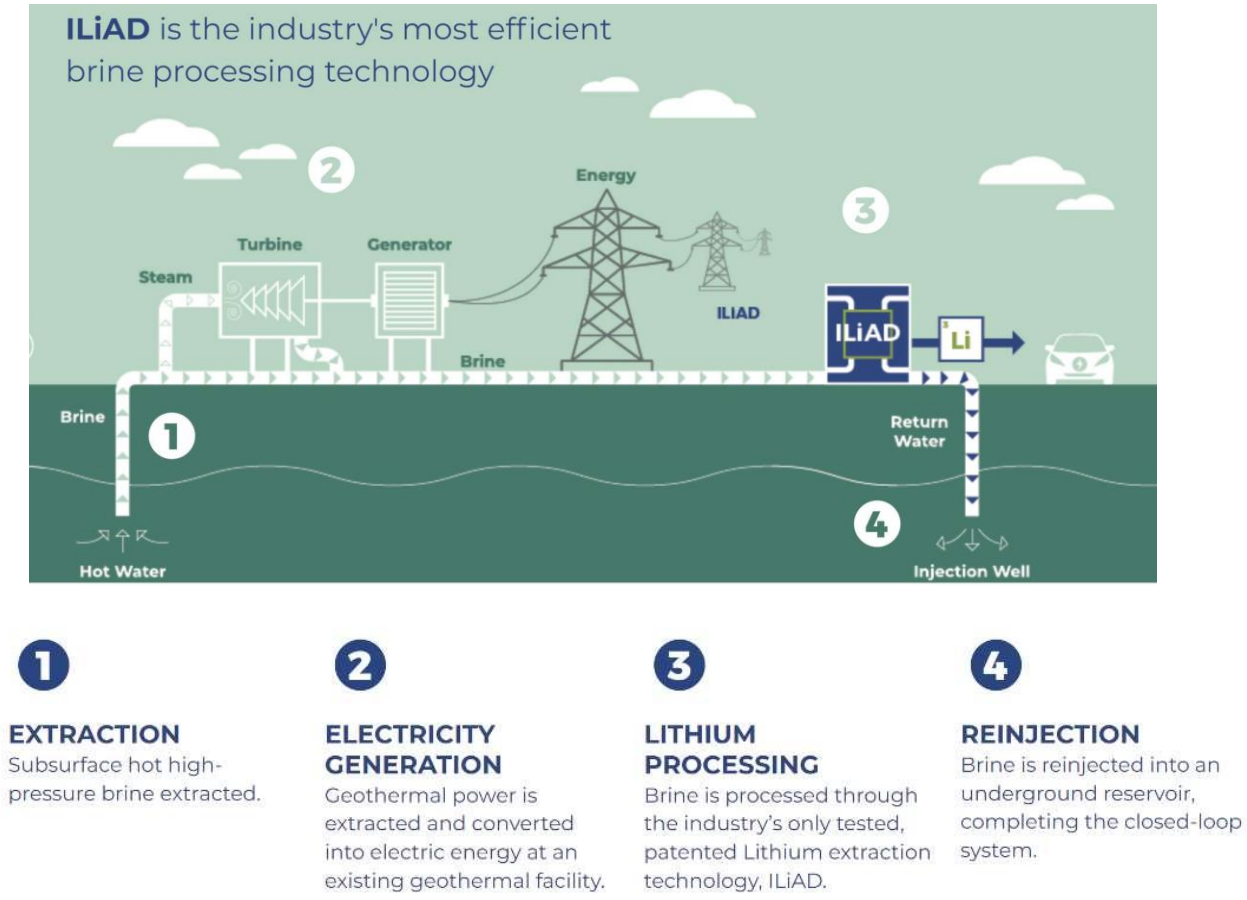


Figure 11: ILiAD Processing Technology (Energy Source Minerals, 2023).

4. SUPPLY/DEMAND IMPLICATION OF NEW DIRECT LITHIUM EXTRACTION SUPPLY FROM 2025+

Table 3 shows the global production lithium and in 2022 (Statistical Review of World Energy, 2023) the total global production was 130,400 tonnes. The largest lithium producers are Australia, Chile, and China. The need for lithium has increased significantly due to the growing demand for electric vehicles. The demand forecast for lithium is expected to reach 1.5 million tonnes of lithium carbonate equivalent by 2025 and over 3 million tonnes by 2030 (World Economic Forum, 2023).

The new technologies for lithium extraction, such as DLE which extracts lithium from brine, has the potential to revolutionize the production, timing and environmental impact of lithium extraction. While there may still be challenges around scalability and water consumption/brine reinjection. With the ongoing efforts, there will be more brine supply if DLE could be implemented between 2024-2030 in USA, between 2024-2030 in Europe, and between 2025-2030 in both Chile and Argentina.

Table 3: Lithium Production and Reserves (Statistical Review of World Energy, 2023).

Lithium production and reserves
Thousand tonnes of Lithium content

												Growth rate per annum		Reserves Share	at end of		
Thousand tonnes	2012	2013	2014	2015	2016	2017	2018	2019	2020	2021	**2022**	2022	2012–22	2022	2022	Share	R/P ratio
Argentina	2.7	2.5	3.2	3.6	5.8	5.7	6.4	6.3	5.9	6.0	**6.2**	3.9%	8.7%	4.8%	2700	11.7%	435
Australia	12.7	10.1	12.4	11.9	14.0	21.3	57.0	45.0	39.7	55.3	**61.0**	10.3%	17.0%	46.8%	6200	26.9%	102
Brazil	0.2	0.4	0.2	0.1	0.2	0.3	1.0	2.2	1.4	1.7	**2.2**	29.4%	30.8%	1.7%	250	1.1%	114
Chile	12.3	10.5	10.8	9.8	13.6	14.2	17.0	19.2	21.6	28.3	**39.0**	37.8%	12.2%	29.9%	9300	40.4%	238
China	4.5	4.7	2.3	2.0	2.3	6.8	7.1	10.8	13.3	14.0	**19.0**	35.7%	15.5%	14.6%	2000	8.7%	105
Portugal	0.3	0.3	0.3	0.3	0.4	0.8	1.2	0.9	0.3	0.9	**0.6**	-33.3%	6.8%	0.5%	60	0.3%	100
US	1.0	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.9	**0.9**	–	-0.6%	0.7%	1000	4.3%	1065
Zimbabwe	1.1	1.0	0.9	0.9	1.0	0.8	1.6	1.2	0.4	0.7	**0.8**	12.7%	-2.8%	0.6%	310	1.3%	388
Rest of World	–	–	^	–	^	0.1	3.0	0.4	0.1	0.1	**0.6**	420.8%	–	0.5%	1204	5.2%	1892
Total World	**34.7**	**30.4**	**31.0**	**29.5**	**38.2**	**50.9**	**95.1**	**86.9**	**83.7**	**107.9**	**130.4**	**20.8%**	**14.1%**	**100.0%**	**23024**	**100.0%**	**177**

Sources: includes data from US Geological Survey, British Geological Survey ©UKRI and World Mining Data.
^ less than 0.05.
Rest of World is the sum of only recorded reserves.

5. THE TECHNO-ECONOMIC ANALYSIS

Pre-Feasibility Study and/or Pilot Scale in the Technical Feasibility Study of Direct Lithium Extraction (DLE), with reasonable assumptions, can provide guidance for estimating costs of lithium extraction from geothermal brines. The following table summarizes reported in National Renewable Energy Laboratory (NREL) US Department of Energy in May 2021 (Warren, 2021) on DLE Project Economics. The main focus of this present study was limited to understanding techniques and costs made publicly available by companies with projects advanced to stages of development and investment that require formal reporting to pertinent institutions. These projects were focused on geothermal, salar (brine from salt-flat or lakebed), oilfield, and evaporite brines, all of which were informative for estimating costs of lithium extraction from geothermal brines. Eventually, a specific geothermal fluid will require a best-lithium extraction processes, or combination of processes, based on fluid composition and physical and chemical requirements related to power generation and reservoir management. The estimated lithium production cost of $ 3,485/mt Lithium Carbonate Equivalent LCE using ion exchange technology.

The scenario economics (Figure 12) (Goldman Sachs, 2023) assume a hypothetical brine resource is extracted at the same grade and volume at ~25ktpa contained LCE over a 20-yr production life to produce and sell the same quality of lithium carbonate product, both as a DLE (which ramps up 18mths faster vs. traditional ponds though with higher nominal Capex/Opex) and a traditional evaporation pond project.

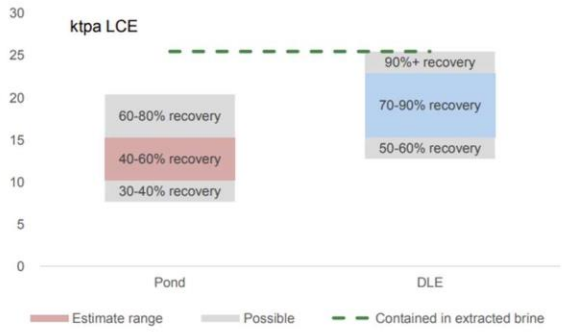
The DLE project achieves recoveries of ~70-90% producing ~18-23ktpa LCE, while a traditional brine pond achieves recoveries of ~40-60% producing ~10-15ktpa LCE . The plant and processing infrastructure drive a higher upfront Capex for a DLE project, which more than offsets the lack of traditional pond infrastructure.

Table 4: Summary of DLE Project Economics (Warren, 2021).

Company	SRI International	Vulcan Energy Resources	Standard Lithium	E3 Metals Corp	Anson Resources	Pure Energy Minerals	Lake Resources
Project	Salton Sea	Upper Rhine Valley	Lanxess Smackover	Clearwater	Paradox Stage 3 (Li)*	Clayton Valley	Kachi
Location	California, USA	SW Germany	Arkansas, USA	Alberta, Canada	Utah, USA	Nevada, USA	Argentina
Document	DOE, CEC reports	PFS	PEA	PEA	PEA	PEA	PFS
Brine type	Geothermal	Geothermal	Evaporite (Br tail brine)	Oilfield	Evaporite	Evaporite	Salar
Resource (1,000 kg LCE)	NA	15,850,000	3,140,000	2,200,000	192,000	217,700	1,010,000
Lithium concentration (mg/L)	400	181	168	74.6	100–500	65–221	289
Production (mt/yr)	20,000**	40,000	20,900	20,000	15,000	11,500	25,500
Production cost ($/mt)	3,845	3,217***	4,319	3,656****	4,545	3,217*****	4,178
CAPEX ($1,000)	52,300	1,287,600	437,162	602,000	120,000	358,601	544,000
OPEX ($1,000/yr)	76,900	128,688	90,259	73,200	68,180	36,516	106,539
Modeled product price ($/mt)	12,000	14,925	13,550	15,160	13,000	12,267	11,000
Pre-tax IRR (%)	268	31	41.8	32	106	24	25
Technology	Ion exchange	Adsorption	Ion exchange	Ion exchange	Ion exchange	Solvent extraction******	Ion exchange
Lithium recovery	90%	90%	90%	>90%	75%	90%	83.20%
Product	Li2CO3	LiOH·H2O	Li2CO3	LiOH·H2O	Li2CO3	LiOH·H2O	Li2CO3
Comments	Bench-scale testing and ASPEN modeling of hybrid sorbent with nanostructured manganese oxide embedded within Li-imprinted polymer beads using synthetic brine.	Known geothermal resource with measured chemistry and temperature. Bench-scale testing of two commercially available adsorbents using Upper Rhine Valley brine.	Bench- and mini-pilot-scale confirmation of process using ceramic adsorbent and crystallization process to convert concentrated LiCl into high-purity Li2CO3.	Bench-scale testing demonstrated high Li selectivity and recovery. Full process yet to be tested.	Multi-stage development with stage 3 producing 60,000 mt/yr NaBr and 15,000 mt/yr Li2CO3. Production cost reported as All-in Sustaining Cost.	Bench-scale testing of brine and synthetic equivalents informed the solvent extraction process developed by Tenova.	Nano-coated, porous ion exchange beads, tailored composition, and continuous column process.

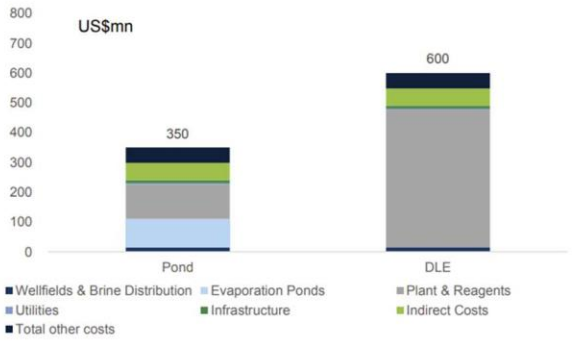
*Estimated based on lithium component of operations; Phase 3 PEA retracted in June 2020 due to amounts of inferred resources. This does not affect estimates of CAPEX and OPEX.
**Estimated commercial production with costs and performance informed by bench-scale experiments and ASPEN modeling (Ventura et al. 2020).
***Euro to USD exchange rate 1.2; $3,656/mt Li2CO3.
****$4,155/mt Li2CO3

Exhibit 4: DLE can increase lithium recoveries to 70-90%, from 40-60% for traditional ponds
Annual lithium carbonate production (ktpa LCE) on modeled scenario lithium recoveries



Source: Company data, Goldman Sachs Global Investment Research

Exhibit 5: Plant and processing infrastructure are likely the bulk of higher DLE capex
Pond vs. DLE project indicative capex split for mid-point of scenario modeling (US$mn)



SdV Stage 1 & 2 technical study (2022) split for pond capex, apportioned to mid-point of capex scenario estimates; DLE plant capex taken as balancing item of capital items (as no pond capex) for illustrative purposes.

Source: Company data, Goldman Sachs Global Investment Research

Figure 12: Scenario Economics & Real World Asset Benchmarking (Goldman Sachs, 2023).

6. LITHIUM EXTRACTION METHOD SUITABLE FOR INDONESIA GEOTHERMAL FIELD

The extraction methods for mining geothermal brine for lithium has been recognized for decades, yet many methods and technologies, which are still being tested and have yet to break through commercially, can be inefficient or costly. So which method is suitable for geothermal brine sources in Indonesia? The variations between brine resources such as concentrations of lithium and any other elements or impurity ratios mean there is unlikely a one size fits all solution; however, solutions may still offer some transferability of successful direct lithium extraction technologies between resources. There are still some concerns on type of end products (lithium carbonate or chloride), project finishing capacity, scalability, and brine reinjection not dilutive to the resource; in short, the implementation of DLE technologies has the potential game changing technology to significantly increase the supply of lithium from brine projects.

One of the methods project and technology providers continue to pursue such as adsorption end-to-end process includes pretreatment, lithium extraction, purification, and lithium product production steps. Adsorption method may combine processing steps such as electrodialysis (a form of ion exchange) and reverse osmosis to yield high recovery rates. To date only adsorption DLE has been used on a commercial scale, in Argentina and China. If DLE can be scaled up and spread across brine assets, it will boost existing capacities via increased recoveries and lower operating costs, while also improving the sustainability aspects of operations.

DLE Adsorption is a commercial technology possibly could be adapted and suitable to Indonesia Geothermal Fields for the following reasons it has a fifty-year development and implementation history, practiced commercially in South America for 26 years and recently in China, higher lithium recovery, lower water and chemicals consumption, shorter lead time to production, minimal footprint, potential for no carbon emissions, and an additional revenue stream from unused brine resources for geothermal power producers.

Lithium extraction from geothermal brines requires complex technologies and systems. The question probably will be: How much does it cost to extract lithium from geothermal brine? Estimating the complicated cost of end-to-end process such as includes pretreatment, lithium extraction, may combine processing steps such as electrodialysis (a form of ion exchange) and reverse osmosis to yield high recovery rates, purification, and lithium product production is difficult. So, what are the main factors of lithium extraction system cost?

The main factors of geothermal extraction cost will depend on the following twelve (12) factors such as brine contaminants (to remove these impurities first and lithium second, other front-end contaminants such as silica, sulfates, iron, calcium, magnesium, hardness, and any suspended solids), lithium concentration (the less concentration in the liquid stream the more cost to concentrate it), flow rates (the higher the flow rate for lithium extraction and polishing the bigger equipment the more capital cost), up-front planning (concepts, designs, and regulatory requirements), space requirement (the footprint will affect cost), installation rates (installation rates in geothermal fields or consider prepackaged modules vs build-in-facilities), level of system automation needed (higher level of automation with less operators and less human errors or lesser automation with less capital cost), turnkey and prepackaged systems (save time in construction time with about the same cost or less), shipping the system to the plant (factor in freight cost where the system can be constructed near the field), operation cost (factor in system operating costs over time), other possible costs and fees (hidden costs and fees might be), and treating costs of secondary waste produced by the system.

The bottom line is a complete pilot plant to simulate the real condition of geothermal field brines. A complete operating pilot plant installed may run for 1/10 to 2/10 of the lithium extraction facilities. The most important point is to keep the project commercial operation date punctuate with faster, cheaper, better and rapid speed of technology implementation.

7. CONCLUSION

Lithium is a big enabler of the energy transition from a battery perspective as we move to electric vehicles and add energy storage to electricity grids, allowing for greater penetration of renewables. That is why lithium is increasingly being seen as a critical mineral by governments, where they want to secure supplies for that transition, and that has made it an increasingly important commodity.

Traditionally, lithium produced from brine water is stored in evaporation ponds and the process can take nine to 18 months depending on the type of project and weather conditions. With Direct Lithium Extraction DLE, that process can be shortened to days or even hours. And you don’t need all the land for the pond evaporation process. What’s more, you can potentially reinject the remaining brine water after the process, which further reduces the environmental impact.

Various DLE technology consists of the following three (3) methods such as adsorption, ion-exchange, membrane-separation or solvent-extraction processes. The next step is a polishing solution to obtain lithium carbonate or lithium hydroxide. To date only adsorption DLE has been used on a commercial

scale, in Argentina and China. DLE Adsorption is a commercial technology possibly could be adapted and suitable to Indonesia Geothermal Fields for the following reasons it has a fifty-year development and implementation history, practiced commercially in South America for 26 years and recently in China, higher lithium recovery, lower water and chemicals consumption, shorter lead time to production, minimal footprint, potential for no carbon emissions, and an additional revenue stream from unused brine resources for geothermal power producers.

How much does it cost to extract lithium from geothermal brine? Estimating the cost of end-to-end process lithium extraction from geothermal brine is difficult but manageable. The main factors of lithium extraction system cost will be depending of the following factors such as brine contaminants, lithium, flow rates, up-front planning, space requirement, installation rates, level of system automation needed, turnkey and prepackaged systems, shipping the system to the plant, operation cost, other possible costs and fees, and treating costs of secondary waste produced by the system.

The bottom line is a complete pilot plant to simulate the real condition of geothermal field brines. A complete operating pilot plant installed may run for 1/10 to 2/10 of the lithium extraction facilities. The most important point is to keep the project commercial operation date punctuate with faster, cheaper, better and rapid speed of technology implementation.

REFERENCES

Energy Source Minerals Website: https://www.esminerals.com/

Goldman Sachs, Equity Research, Global Metals & Mining, Direct Lithium Extraction: A Potential Game Changing Technology, April 27, 2023.

Mining.com, Geothermal brines in California's Salton Sea could be future source of lithium in the US, MINING.COM, December 12, 2021.

McKinsey & Company, Lithium mining: How new production technologies could fuel the global EV revolution, April 22, 2022.

Statistical Review of World Energy, 2023.

Stringfellow William T. and Dobson Patrick F., Technology for the Recovery of Lithium from Geothermal Brines, Energy Geoscience Division, Lawrence Berkeley National Laboratory, October 18, 2021.

Suud, Esty Mustika et al 2023 IOP Conf. Ser.: Earth Environ. Sci. 1159 012011, Lithium Extraction Method from Geothermal Brine to Find Suitable Method for Geothermal Fields in Indonesia: A Review.

Vulcan Energy, Zero Carbon Lithium, Phase One DFS Presentation 2023.

Warren I., National Renewable Energy Laboratory (NREL), Techno-Economic Analysis of Lithium Extraction from Geothermal Brines, May 2021.

World Economic Forum, This Chart shows which countries produce the most lithium, January 5, 2023.

Surface Thermal Manifestation Characteristics and Hydrology Conceptual Model of Hu'u Daha Geothermal Prospect Area, East Sumbawa

Joshua Satriana Benyamin, Juni Sianipar, Marina Sari, Muhammad Asri, Rachmat Pratiwinda, and Petto Mawajaya

PT Sumbawa Timur Mining, Hu'u, Dompu Regency, West Nusa Tenggara

Joshua.Benyamin@vale.com

Keywords: East Sumbawa, Hu'u, geothermal, manifestations, hydrology

ABSTRACT

PT Sumbawa Timur Mining (PT STM) has been appointed by the Directorate General of New, Renewable Energy, and Energy Conservation since 2018 to survey and assess the potential geothermal resource in Hu'u Daha Area. This campaign also consists of a geothermal geochemistry survey to characterize and interpret the conceptual model of the hydrology system in this area. Several surface thermal manifestations, including thermal springs, solfatara, gas seepage, and altered ground have been mapped and sampled for further analysis. In this study, additional samples from cold springs and meteoric waters were also carried out as complementary data. Thermal springs sampling results show most of the springs are Bicarbonate type with one sample from Limea having Sulphate-Chloride type. The thermal springs have occurred due to the steam-heated process of H_2S and CO_2 gasses in shallow groundwater. The steam heated process is also reflected in surface alteration that shows in Wadubura Crater with Argillic (kaolinite±illite), residual silica, and native sulfur deposition filling vug.

Surface manifestations sample analysis and rock alteration indicated the subsurface degassing derived from magmatic origin gasses. Since there's an isotope shifting from the meteoric water line during this process, it also indicated that rock-water interaction is not significant. The hydrology conceptual model shows the recharge area located on the eastern side of the study area that infiltrated through volcanic aquifers. It flows to the lower elevation on the western side and is discharged as outflows.

1. INTRODUCTION

The geothermal geochemical survey is one of the exploratory methods to obtain information on hydrological characteristics and estimates of hydrothermal fluid flow in a prospect area. This survey aims to determine the process of hydrothermal fluid circulation below the surface, including identifying potential geothermal reservoirs. The purpose of this study is to provide an overview of the characteristics of thermal manifestations on the surface and describe subsurface hydrology in the form of a conceptual model. The method used in this research is to analyze the fluid composition of several water samples from thermal manifestations, cold springs, and rainwater (meteoric). The analysis was carried out by plotting the results of chemical analysis on the ternary diagram and graphs of 2H to 18O for stable isotopes. Data acquisition was carried out in 2019 as part of the Hu'u Daha PSPE geochemical survey activity.

1.1 Research Area

The study area is located in Hu'u District, Dompu Regency, West Nusa Tenggara Province. It was designated as the WPSPE Hu'u Daha in August 2018 by the Minister of Energy and Mineral Resources (ESDM). There are around 27.000 ha of survey areas, with mainly located in the protected forests. Access to the study area can be attained by traveling over the national highway for two hours from Bima (Figure 1).

Figure 1: Hu'u Daha WPSPE location map.

1.2 Regional Geology

The area of Hu'u, Dompu Regency, West Nusa Tenggara, is part of the Sunda-Banda Volcanic Arc, also known as Lesser Sunda Island (LSI). The series of island arcs formed along the LSI is the result of the subduction of the Indo-Australian plate against the Eurasian sub-plate in the eastern part during the Miocene. This subduction process produces tertiary volcanic products in the southern part of Lombok and Sumbawa Islands, while active quaternary volcanism such as Mount Rinjani, Tambora, and Sangeang Api are relatively located in the northern part of the LSI.

Based on the Geological Map of the Sumbawa Sheet, Nusa Tenggara (Sudrajat et al., 1998) in the Figure 2 below, the volcanic rocks in Hu'u area are composed of andesitic Breccia-Tuff Units (Tmv), with intercalated sandy tuff, pumiceous tuff, and tuffaceous sandstone; locally contains lahar, andesitic and basaltic lavas. The rock unit is propylitised, locally, quartz and calcite veins are recognized. This unit was deposited in the Early Miocene to Middle Miocene (5 Mya) and interpreted as a submarine volcanic deposit.

Detailed geological mapping in the Hu'u area shows lithology formed from volcanism, such as basalt-andesitic, pyroclastic breccia and crystal tuff. The lava unit has dark to light grey characteristic, porphyritic, plagioclase and hornblendes as phenocryst, minor pyroxene and magnetite; fractured sheeting joint is locally found due to geological structure event. Lava units are often found in the central part of the Hu'u Volcanic Complex. Other lithology is a pyroclastic rock unit composed of pyroclastic breccias and crystalline tuff with characteristics, grain size from coarse ash to lumps, poor sorting, and locally showing clear bedding areas. Pyroclastic units are distributed in the distal part with a relatively sloping morphological appearance.

Young sediment deposits exposed in the Hu'u District area include thin layers of coral limestone are formed as a result of the tectonic uplift of Sumbawa Island while loose deposits resulting from river erosion and sedimentation processes. The erosion process that has continued until now has deposited unconsolidated Alluvial Units (Qal) in the form of gravel, sand, clay, silt, and sand, scattered along the Hu'u-Lakey Beach.

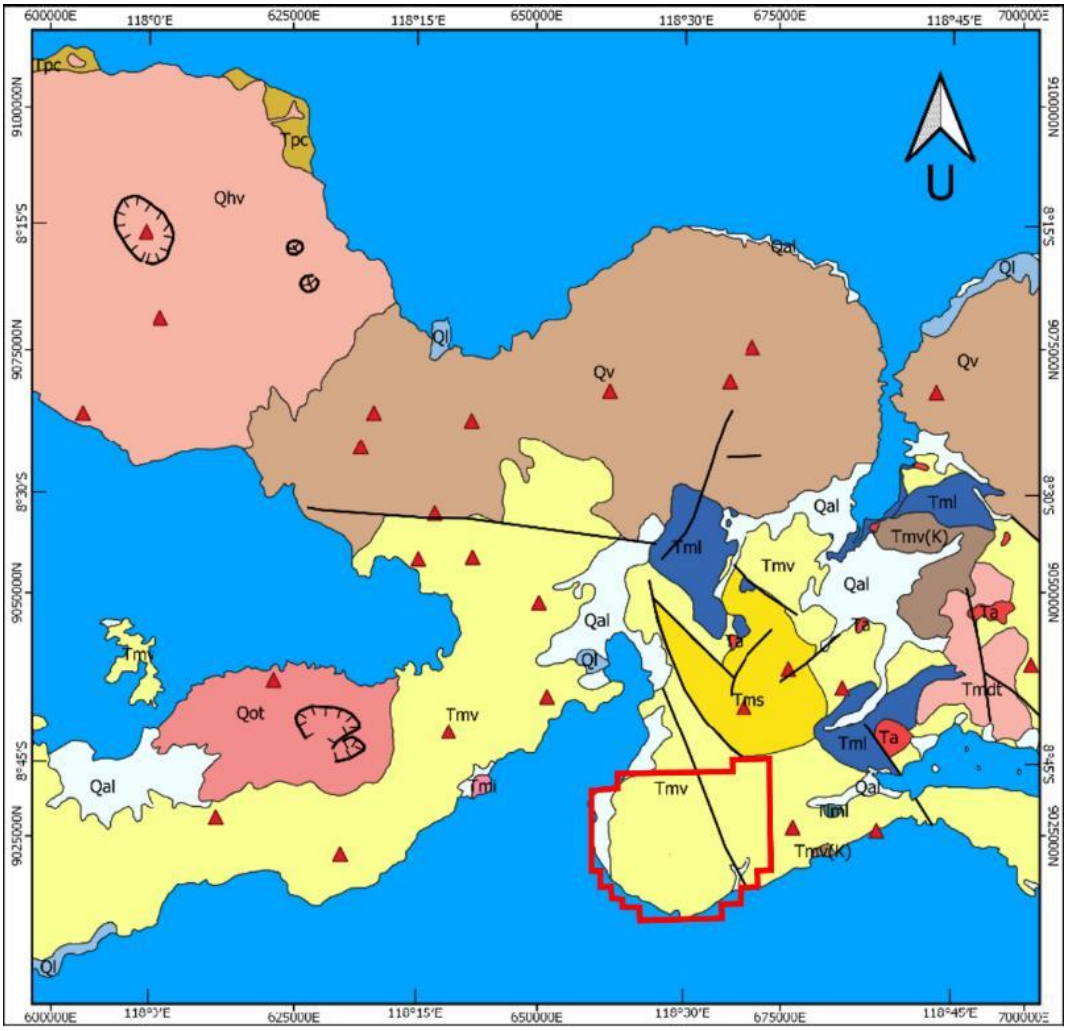


Figure 2: Regional geology map from Eastern part of Sumbawa Island (modified by Fary, 2022 from Sudrajat et al., 1998; Ratman and Yasin, 1978).

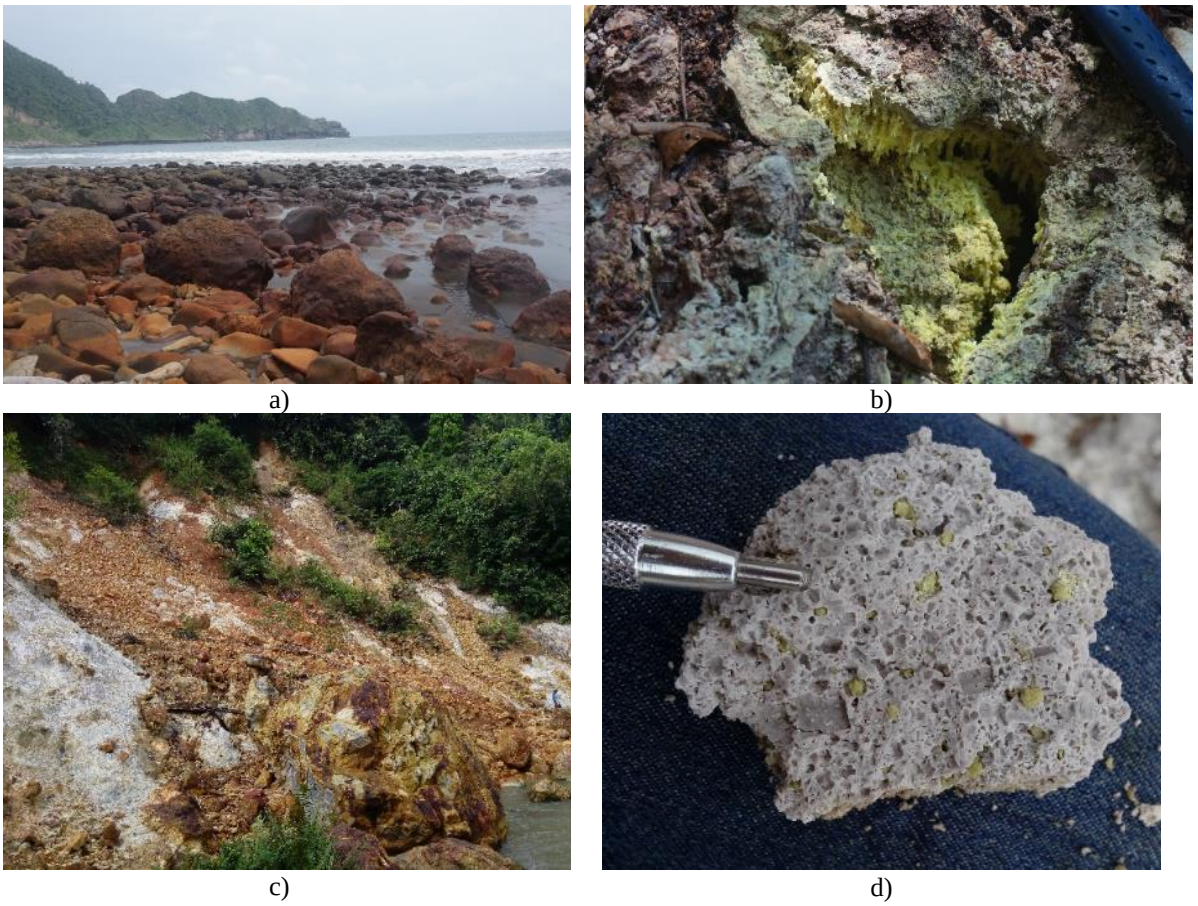
Table 1: Regional stratigraphic in Eastern Sumbawa Island (modified by Fary, 2022 from Sudrajat et al., 1998; Ratman and Yasin, 1978).

Umur \ Sumber Produk		Sudrajat dkk., (1998)				Ratman dan Yasin, (1978)		
		Endapan Permukaan	Batuan Sedimen	Batuan Gunungapi	Batuan Terobosan	Batuan Terobosan	Batuan Gunungapi	Batuan Sedimen
Kuarter	Holosen	Qal	Ql	Qhv, Qv, Qot				
	Plistosen						Qtv	
Tersier	Pliosen		Tpc, Tmcl					
	Akhir				Tmi	Ta	Tmv, Tmdt	
	Tengah							
	Awal		Tms, Tml, Tmv					Tlml

2. SURFACE MANIFESTATIONS

2.1 Alteration

Field mapping results show the distribution of alteration which is dominated by neutral clay, acidic clay, and residual silica. These altered minerals are formed due to a steam-heated process near the surface which changes the initial rock in the form of andesitic lava, tuff, and pyroclastic breccias. If the temperature of the thermal fluid is relatively cold, but the pH is still relatively acidic, changes in mineral oxides such as goethite or hematite will be formed. Alterations of the native sulfur type are often found in the Hu'u Daha geothermal prospect area because apart from being located in a location close to high sulfidation deposits, the presence of this sulfur also indicates the existence of an active geothermal system today which is likely to be associated with magmatic or young volcanoes (Figure 3).



a) b) c) d)

Figure 3: Surface alteration in WPSPE Hu'u Daha that consist of; (a) oxide boulder near Oi Pana Beach, (b) native sulfur, (c) altered ground with clay type alteration, and (d) vug filling sulfur.

2.2 Thermal Springs

Several geochemistry surveys campaign have been conducted by the Geological Agency (2004), Geothermex (2014), LAPI ITB (2019), and PT STM during the PSPE period in 2019. Several sampling activities that were carried out consist of sampling from hot springs, warm springs, and cold springs as well as gas sampling from solfatara and bubbling springs.

Surface thermal manifestations in the Hu'u-Daha PSPE area consist of hot springs, warm springs, solfatara, and silica sinter (Figure 4). There are at least 5 hot springs, all of them are located in the Limea area in the southern part of the PSPE area with temperatures ranging from 60.5-82.7°C, with a relatively low pH of 2.53-4.59, and high TDS (Total Dissolved Solid) values i.e. more than 1564 ppm.

Figure 4. Thermal manifestations appearance in the Hu'u Daha PSPE area.

There are at least 43 warm springs distributed in the Hu'u-Daha PSPE area where their occurrence is generally controlled by geological structures. Several springs are found at the contact of lithology. There are also many cold springs with low to neutral pH. Geochemistry sampling during the PSPE period was conducted by LAPI ITB and PT STM in 2019 (Figure 5). Water samples were taken from 1 hot spring in Limea, 9 warm springs, 2 low-pH cold springs, and 1 sample from a shallow well in the PT STM staging area. Gas sampling was also conducted at 2 locations at Limea Solfatara, and Oi Wou bubbling pool (Figure 5).

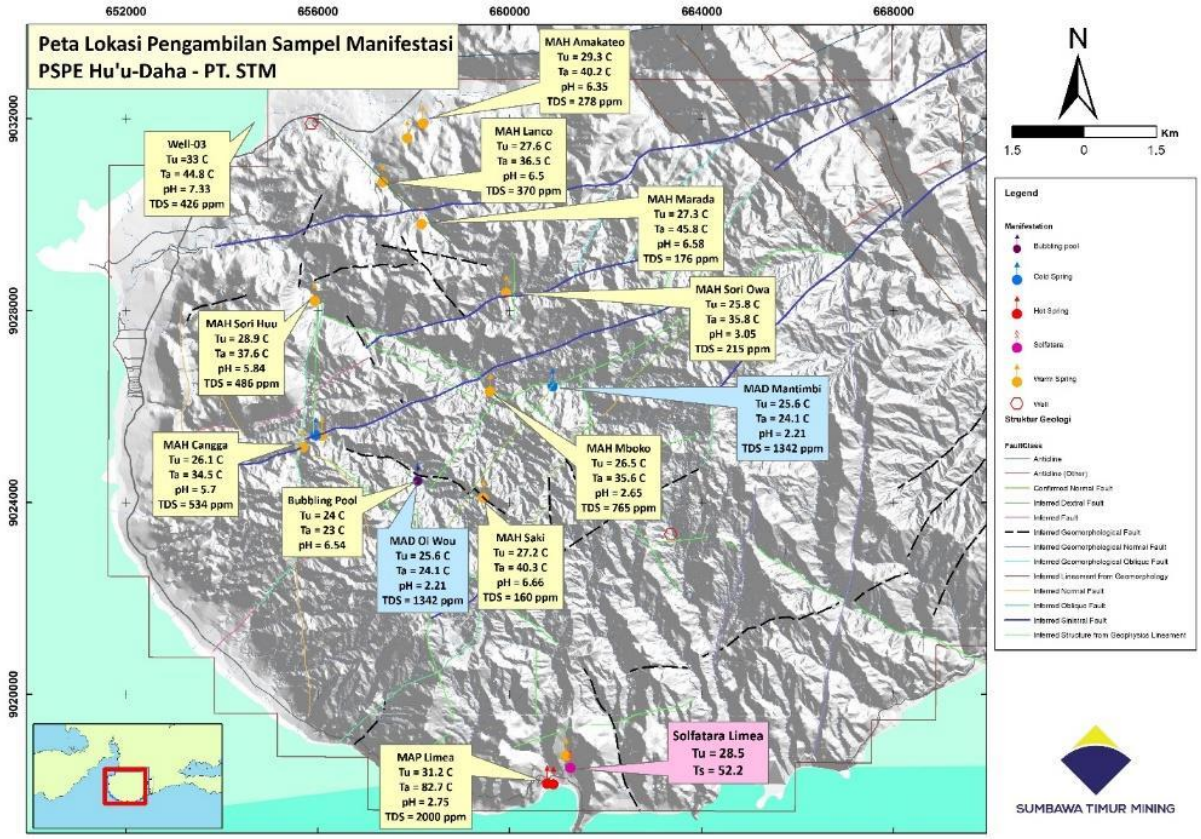


Figure 5: Map of manifestation sampling locations.

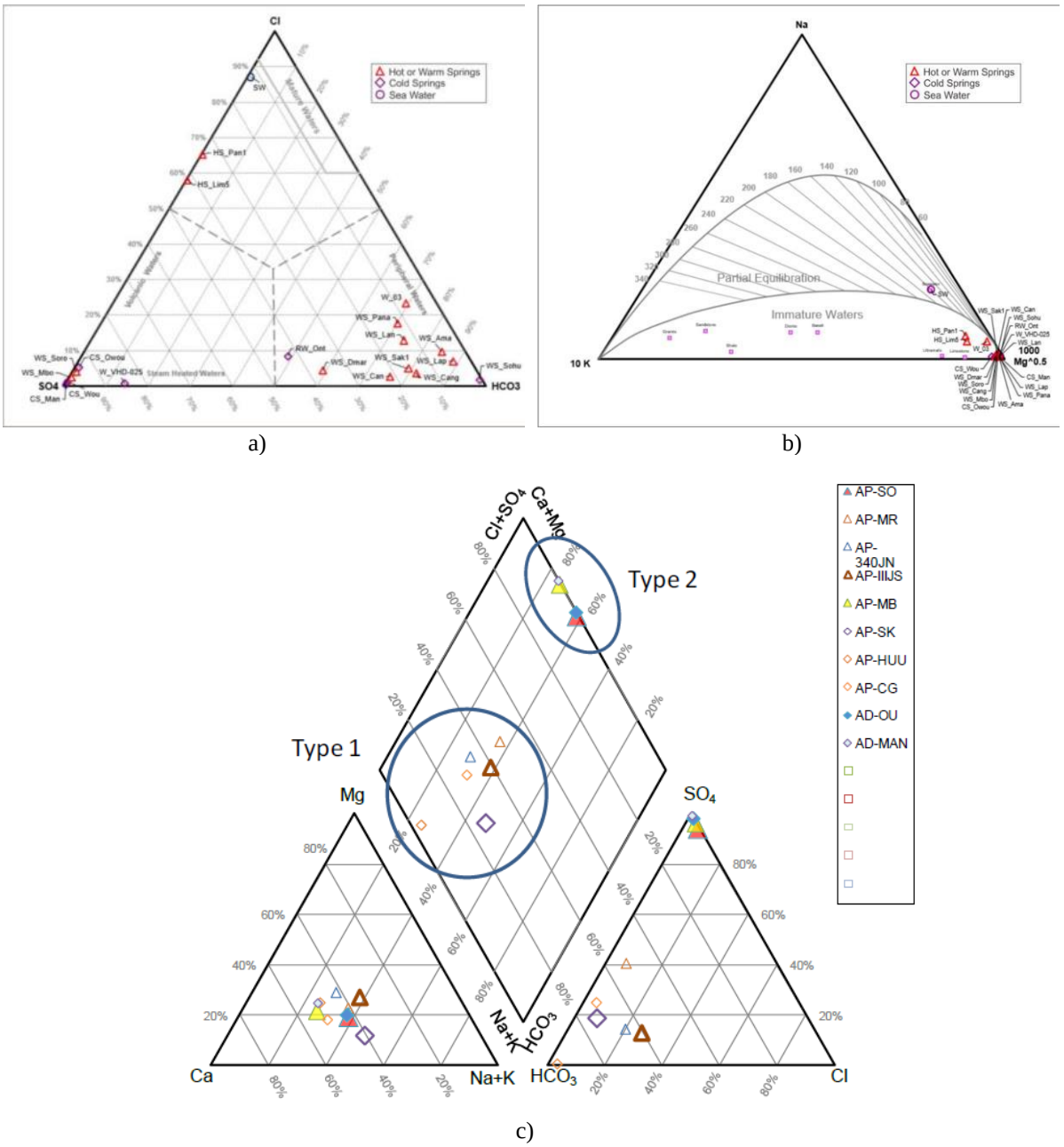
2.3 Gas Discharge

Solfatara is emerged in the southern part of the Hu'u-Daha PSPE area with a temperature of 62°C when it was first discovered. Traces of dormant solfatara are also found with a strong odor in the northern part of the active solfatara. In the survey area, a bubbling spring was also found on the Oi Wou River with cold springs of the sulfate water type. In addition to indicating the presence of a permeable zone, this indicates that both CO2 and H2S are released intensively.

3. ANALYSIS AND DISCUSSION

3.1 Ternary Plot

Water chemistry data shows that the warm springs in the Hu'u-Daha PSPE area generally consist of two types of water: sulfate-rich steam-heated water and bicarbonate water (Figure 6). The Mboko warm spring, Sori Owa warm spring, Mantimbi cold spring, and Wou cold springs are sulfate-rich water that originated from the steam-heated process. Cangga, Sori Huu, Saki, Marada, Amakateo springs, and a water sample from shallow wells (Well-3) at PT STM new staging office are bicarbonate water types.



a) b)

c)

Figure 6: (a). Cl-HCO3-SO4 ternary plot, (b). Na-K-Mg ternary plot, and (c) Piper Diagram.

All water samples taken from thermal springs indicate immature or Mg-rich fluid based on Na-K-Mg ternary diagram. Therefore, the samples should be used with caution for further analysis.

Geoindicator

The immature condition of the sample made it difficult to interpret the fluid origin. Thus, an approach through the calculation of the Cl/B ratio was chosen. The Cl/B ratio is often used to indicate the source of the fluid. However, it should be noted that fluids originating from the same reservoir may show different ratio values. This can be caused by lithological changes or Boron depletion during the lateral fluid flows. This is also shown in the Cl-Li-B ternary diagram that indicated clustered manifestations sample on Cl apex (Figure 7). Based on the Cl/B ratio, there are 3 categories or groups of fluid origin, namely Pili, Wadubura, and Limea (Table 2).

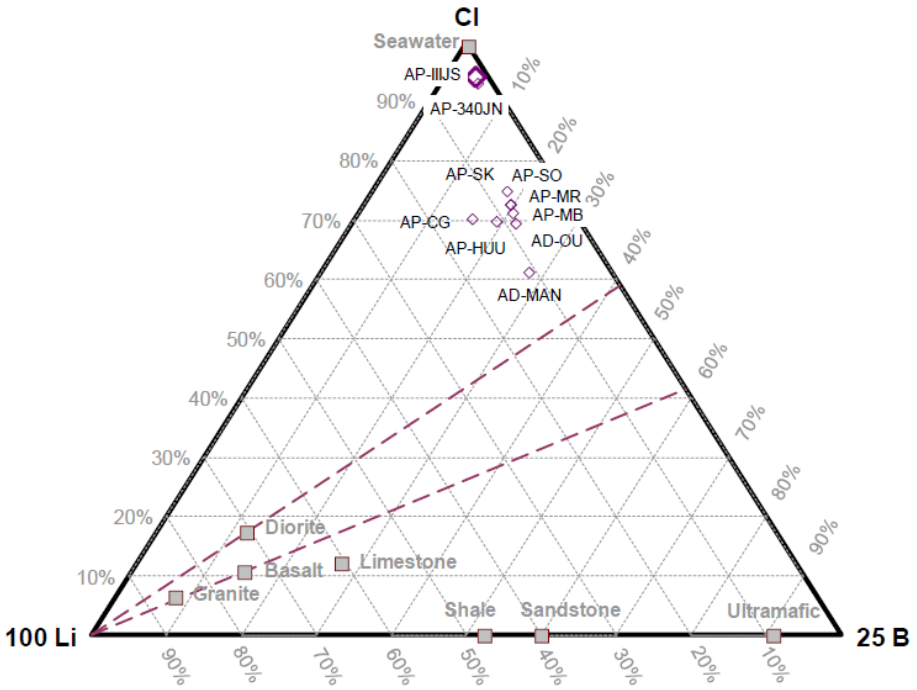


Figure 7: Ternary diagram of Cl-Li-B.

Table 2: Cl/B ratio calculation based on major cation and anion.

Area	Cl/B Ratio
Pili	~20-25
Wadubura	~25-30
Limea	>30

3.2 Stable Isotope

The ^{18}O and D isotope plotting shows that all samples are plotted in the local meteoric water line. It's indicating the samples come from shallow groundwater aquifers that have a steam-heated process (Figure 8). There is no indication of an isotope shifting trend means the samples are not influenced by reservoir fluid. It's shown by the Oi Pana samples stable isotope plot that is located on the meteoric line and there is no significant isotope shifting. Thus, it concluded that there is no mixing with seawater in Limea/Oi Pana hot spring samples.

Further analysis to determine the recharge zone has been carried out by PT STM. This analysis includes isotope analysis of D and ^{18}O from meteoric water. This study aims to delineate the recharge areas of

shallow aquifers and deeper aquifers based on the intersection of linear trend lines of meteoric water isotopic composition with respect to elevation (Hendrasto and Hutasoit, 2007). This method is a retracing of the location or elevation of rainwater precipitation that fill the aquifer zone.

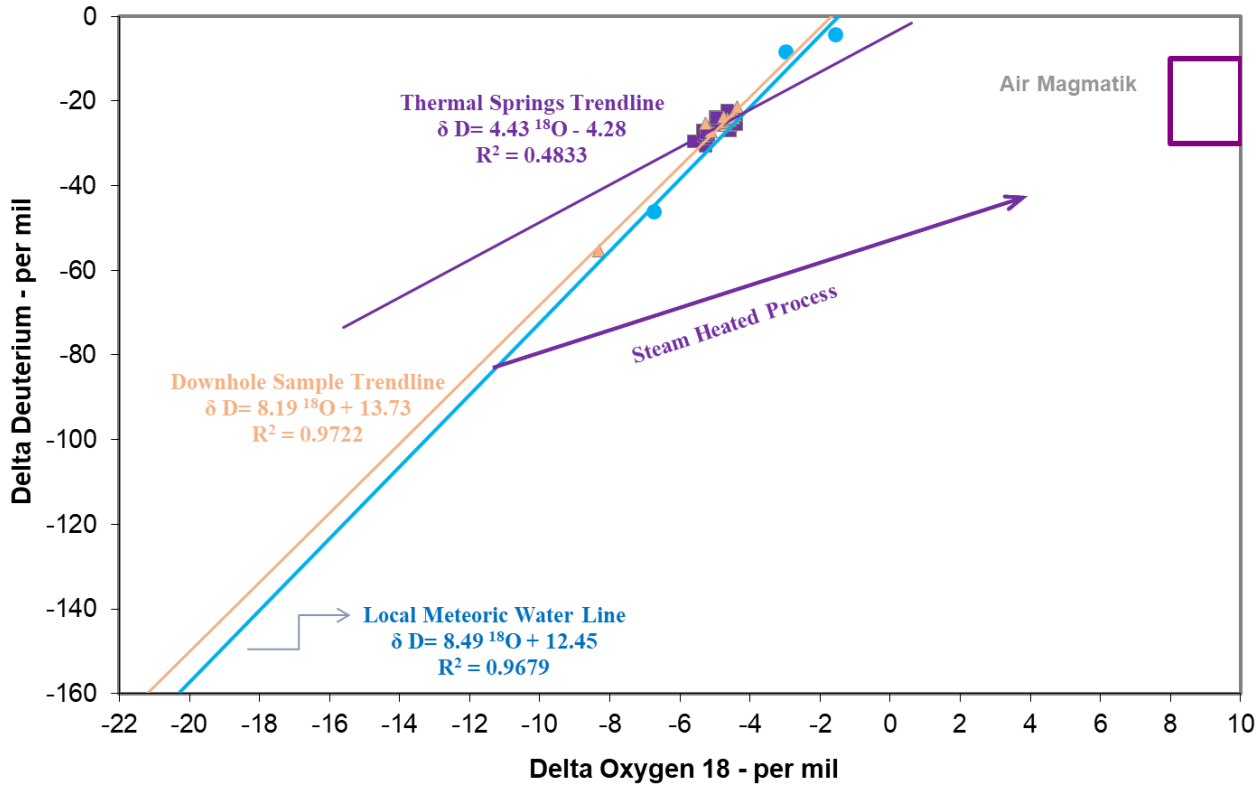


Figure 8: Stable isotope plot (18O dan D).

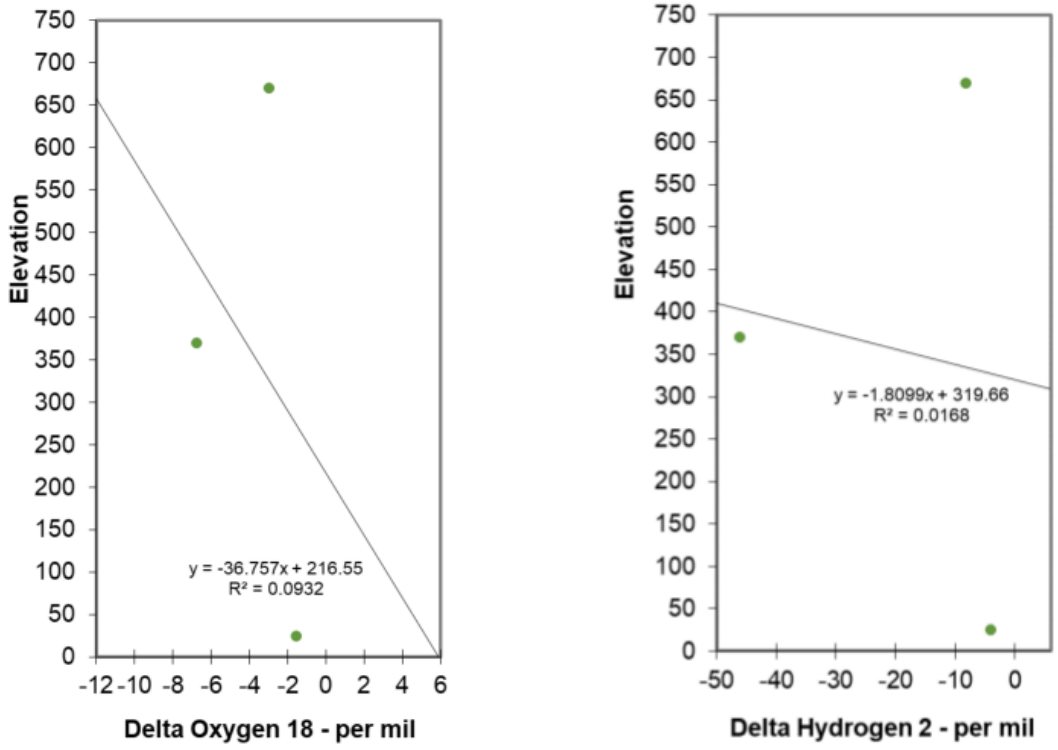


Figure 9: (a) ^{18}O equation and (b) ^{2}H equation vs sampling elevation.

The intersection values of the trend lines of the thermal springs intersect with LMWL at -4.12 ^{18}O and -22.52 ^{2}H, while the intersections for the drill hole samples are at 4.29 ^{18}O and 48.91 ^{2}H. If these two values are included in the function of ^{18}O and ^{2}H ith respect to elevation, the infiltration zone of thermal springs is at an elevation of 360-370 masl and samples of wells or deep aquifers are at an elevation of 58-231 masl. In regional hydrogeological mapping, the catchment area will fill small productive aquifer units, and locally significant and rare groundwater areas (Ridwan and Singgih, 2001) which are scattered as part of the Brigade Hu'u volcanic rock. The delineation of the predicted recharge area is shown in Figure 10.

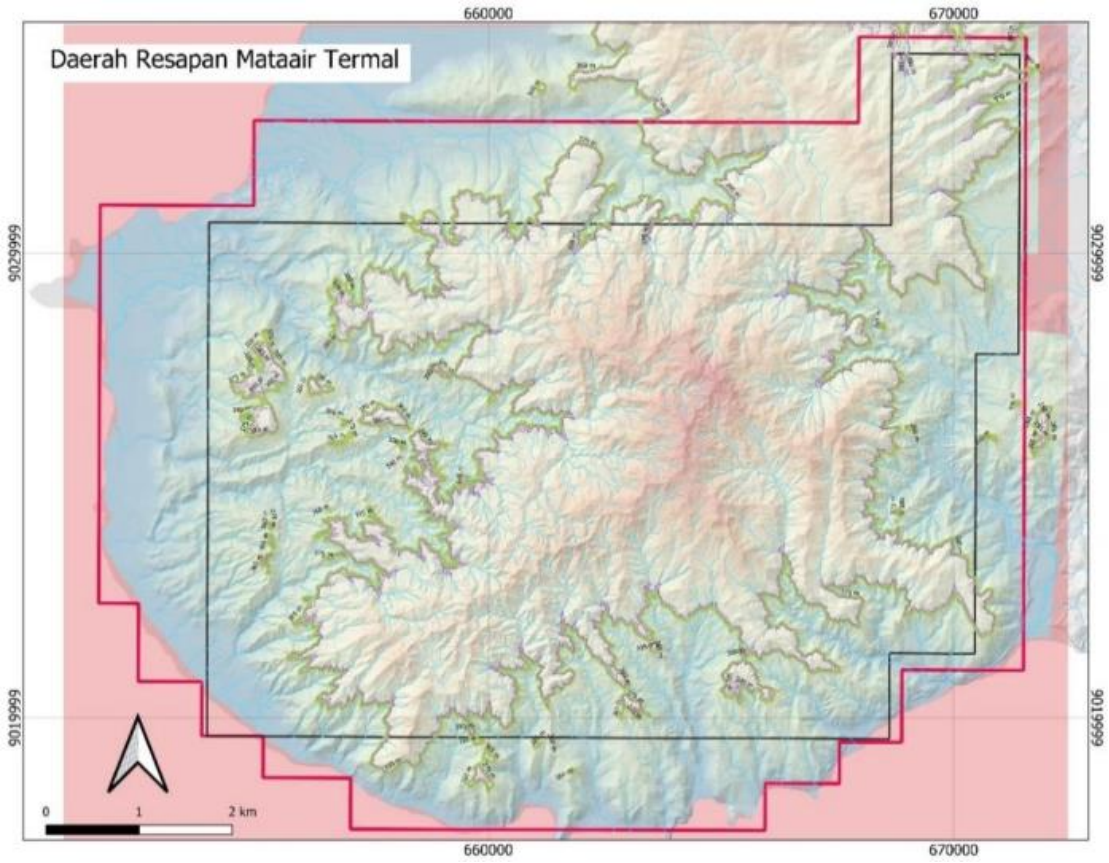


Figure 10: Recharge area identification for thermal springs (shallow aquifer).

4. HYDROLOGY CONCEPTUAL MODEL

The plotting results on the ^{2}H to ^{18}O graph show that there is a change in the trend line of thermal springs to local meteoric water This shows that there has been a process of interaction between groundwater and rock or steam heated process. If compared to isotope samples from several wellbore, the linear equation result is showing no difference from the local meteoric water sample equation. Further review of anion and cation composition concludes that samples from the wellbore are still experiencing a steam-heated process but the shifting process has not been seen significantly occurred due to the minimal interaction with the wall rock. The period of fluid flow is too short or the temperature at that interval is relatively not high enough.

The regional hydrological flow pattern shows that the direction of fluid flow originates from the eastern part of the PSPE area PSPE on the highest elevation, infiltrated through fracture into the hot area, experiencing the steam heated process and discharging to the surface through fracture or contact of lithology (Figure 11).

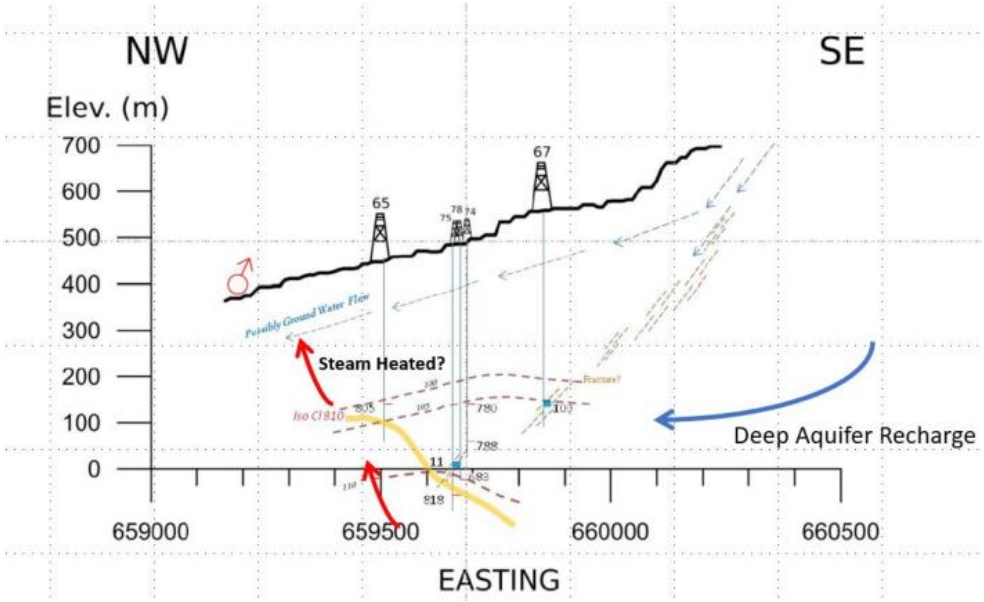


Figure 11: Preliminary hydrology conceptual model of Hu'u Daha Area (modified from Suryantini, 2019).

5. CONCLUSION

The occurrence of thermal manifestations such as solfatara, hot springs and warm springs in the Hu'u Daha area indicates the presence of geothermal system in the Hu'u Daha PSPE area. The result of water chemistry analyses shows that all water samples are immature water which has most likely experienced mixing with shallow groundwater. Geoindicator plot result showing that there are 3 categories or groups of fluid origin namely Pili, Wadubura, and Limea. Isotope analysis of those thermal springs shows that there is no indication of rock-water interaction. The samples come from shallow groundwater aquifers that have steam heated process. Isotope analysis of ^{18}O and ^{2}H conclude the recharge elevation is at an elevation of 360-370 masl. The regional fluid flow originates from the eastern part, entering the geothermal reservoir and discharging through the geological structure such as fault and lithological contact.

REFERENCES

Geothermex: *Task 4 Report Updated Geothermal Resource Evaluation for the Hu'u Mineral Exploration Project Island of Sumbawa, Indonesia*, A report for PT Vale Eksplorasi Indonesia, (2017), 79 p. Unpublished.

Hall, R.: Late Jurassic–Cenozoic reconstructions of the Indonesian region and the Indian Ocean, *Tectonophysics*, 570-571, 1-41, https://doi.org/10.1016/j.tecto.2012.04.021

Hutasoit, L. M., and Hendrasto, F.: Daerah Resapan Lapangan Panasbumi Wayang Windu Berdasarkan Kandungan Isotop ^{18}O dan ^{2}H Fluida. *Jurnal JTM*, 14(2), (2007), 67-77.

PT LAPI: *Integrated Intensive Literature Study Hu'u Daha Geothermal Prospect, Dompu, Sumbawa Island, Indonesia*. A report for PT Sumbawa Timur Mining, (2019), 100 p. Unpublished.

Ratman N. and Yasin A.: *Peta Geologi Lembar Komodo, Nusatenggara*, (1978), Pusat Penelitian dan Pengembangan Geologi.

Ridwan, T. and Singgih, B.S.H.: *Peta Hidrogeologi Pulau Sumbawa Bagian Timur Skala 1:250.000*, (2001), Departemen Energi dan Sumber Daya Mineral.

Sudrajat A., 1998, *Peta Geologi Lembar Sumbawa, Nusatenggara*, Pusat Penelitian dan Pengembangan Geologi.

Suryantini: *Geochemistry Report PT STM – July 2019*, (2019), 9 p., unpublished.

Understanding Technical Document Requirements in Geothermal Exploration Funding in Indonesia

Dorman Purba[1,2], Andreas Suseno[1], Desak Nyoman Inten Apriani[1], Agung Hardinugroho[1], Eviyanti[1], Afandi[1], Aryani Amir[1], and Ery Surandaru[1]

[1]PT Sarana Multi Infrastruktur (Persero), Sahid Sudirman Center 49th floor, Jakarta, Indonesia
[2]PT ENERKA Bhumi Pratama, Cibis Park 11th floor, Jakarta, Indonesia

desak@ptsmi.co.id, dorman.purba@enerklaz.com

Keywords: geothermal, exploration, resource, risk, derisking, feasibility, assessment, due diligence, lender, proposal, drilling, commercial, finance, funding, GREM, GEUDP, PISP, cost, scheme, government, red flags, fatal flaw, techno-economic, Indonesia

ABSTRACT

In recent years, public awareness of using clean and renewable energy, such as geothermal, in a more significant portion is starting to increase. Indonesia is one of the countries that have the most considerable geothermal energy potential, but it has yet to be utilized optimally. The Government of Indonesia aims to achieve 5,486 MWe geothermal energy utilization by 2030. Therefore, Indonesia is expected to see many geothermal development projects in the next eight years, with more attention to exploration projects.

With the increasing number of geothermal projects in Indonesia, the government and the geothermal developer companies will need more funds to finance project expenditures in the exploration and development stages. However, lenders generally prefer to fund the development phase of a project rather than the exploration phase because the risks associated with the project are acceptable, and the potential return on investment is more certain in the development phase. This preference is comprehendible since the project's success in the exploration phase is uncertain, and the potential rewards are largely speculative. The exploration phase also involves greater uncertainty and risk, as the geology and potential resources still need to be fully understood.

The funding can come from various financial institutions, either Indonesia or International institutions, where they will require prospective borrowers to submit multiple documents as part of the assessment process. This practice will be straightforward for geothermal development companies familiar with the due diligence process in accessing funding facilities, but preparing these documents will be a challenge for companies that are not used to it. Integrating indirect and limited data of exploration projects to justify the relatively high drilling costs will require much effort.

This paper discusses the process that is generally gone through by geothermal development companies seeking to obtain funding from financial institutions for their geothermal exploration project. To provide background, the authors will first discuss a geothermal exploration project's cost estimate and challenges. Then, it will focus on the proposal submission and evaluation process and the critical information that is expected to be included in the submitted document. The discussion in this paper is based on the results of a literature study and interviews with various financial institution personnel who have experience financing geothermal project activities in Indonesia.

1. INTRODUCTION

1.1 Challenges in Developing Geothermal Energy in Indonesia

The history of geothermal energy in Indonesia can be traced back to the early 20th century when the Dutch colonial government began exploring geothermal energy potential on Java Island. However, it was in the 1970s that the Indonesian government started actively pursuing the development of geothermal energy as a source of electricity.

1. Exploration: In the 1970s, the Indonesian government began to explore the potential for geothermal energy in several areas of the country, including the Kamojang area in West Java. This involved drilling test wells and conducting geophysical surveys to assess the size and quality of the geothermal resources in the area.

2. Early development: The first geothermal power plant in Indonesia, the Kamojang Geothermal Power Plant, was built in the Kamojang area in the 1980s. It was one of the first geothermal power plants in the world and had an installed capacity of 55MW.

3. Expansion and growth: In the following decades, the Indonesian government continued to invest in geothermal energy development. Indonesia's Kamojang power plant expanded several times, and in parallel, they gradually built new geothermal power plants in other areas. By 2023, Indonesia had become one of the world's largest geothermal energy producers, with an installed capacity of over 2,356 MW (Direktorat Panas Bumi, 2022; ThinkGeoEnergy, 2023).

In recent years, the Indonesian government has set ambitious targets for developing geothermal energy by having 5,486 MWe installed capacity by 2030 (Direktorat Panas Bumi, 2022) to align with the country's effort to mitigate climate change. However, from the time Kamojang commercial power plant was commissioned for the first time in 1983 until the end of 2022, the development of geothermal energy in Indonesia has only reached 2,356 MW installed capacity (ThinkGeoEnergy, 2023). This additional rate is equivalent to a 54 MW per year development rate to the installed capacity of geothermal power plants, which is still below the expected 375 MW per year to reach the national geothermal target in 2030.

From the world's perspective, Indonesia is the country with the second largest installed geothermal power plant (PLTP) after the United States (ThinkGeoEnergy, 2023). However, compared to the total reserves of geothermal energy owned, Indonesia only uses ±11%. In comparison, New Zealand has used 38% of its total potential, while the United States has used 21% of its total potential (Asokawaty et al., 2020). Similar to other countries worldwide, Indonesia faces many challenges in developing its geothermal energy, including (Ibrahim et al., 2005; IGA, 2014; Poernomo, 2015; Darma, 2016; Purba, 2018; Umam et al., 2018; Purba et al., 2019; Purba et al, 2020; Utami, 2010):

1. High exploration and development costs: Geothermal projects can be expensive to explore and develop, especially in the early stages. Drilling test wells and conducting geophysical surveys can be costly, and there is always the risk that a project will not yield a viable resource.

2. Complex and uncertain regulatory environment: Geothermal projects are subject to various national, regional, and local regulations. This uncertainty can make it difficult for developers to navigate the regulatory environment and can increase the risk of project delays or cancellations.

3. Lack of infrastructure: Many geothermal resources in Indonesia are located in remote areas, making them difficult and expensive to access. These infrastructures can include building roads, power lines, and other infrastructure to support a geothermal project.

4. Environmental impacts: Geothermal projects can have various environmental impacts, such as deforestation and the potential for groundwater contamination. Mitigating these impacts can be costly and time-consuming.

5. Social and community impact: Geothermal projects can also have social and community impacts, such as displacement of local communities and land-use conflicts. Developers need to address these impacts and engage with local communities to ensure their support and minimize the risk of project delays or cancellations.

6. Technical challenges: Building geothermal power plants and drilling geothermal wells require a high level of technical expertise and knowledge, which can be challenging. Additionally, geothermal wells can be more prone to clogging and scaling than oil or gas wells, leading to production issues and increased maintenance costs.

7. Electricity single-buyer regulation: The Indonesian government regulates the electricity sector, including setting tariffs and determining the energy mix. This policy limits PLN's flexibility in responding to market conditions and changing customer demands.

The Ministry of Energy and Mineral Resources (Direktorat Panas Bumi, 2022) reported that the government had issued 63 geothermal concessions with an estimated capacity of 13,517.5 MW. The data indicates that 22 locations are still under the exploration stage, with an estimated capacity of 4,011 MW (Table 1).

Table 1: List of Indonesia's Geothermal Prospect Areas/ Concession Areas in the Exploration Stage (Direktorat Panas Bumi, 2022).

No	Name of the Prospect Area / Concession Area	Location	Estimated Capacity (MWe)	Developer
1.	Tulehu	Maluku	31	PT PLN (Persero)
2.	Gn. Ungaran	Central Java	150	PT PLN (Persero)
3.	Atadei	East Nusa Tenggara	40	PT PLN (Persero)
4.	Songa Wayaua	North Maluku	42	PT PLN (Persero)
5.	Danau Ranau	South Sumatera	210	PT PLN (Persero)
6.	Oka Ile Ange	East Nusa Tenggara	50	PT PLN (Persero)
7.	Kepahiang	Bengkulu	254	PT PLN (Persero)
8.	Gn. Sirung	East Nusa Tenggara	152	PT PLN (Persero)
9.	Tangkuban Perahu	West Java	375	PT PLN (Persero)
10.	North Patuha (WKP Patuha)	West Java	55	PT Geo Dipa Energi
11.	Candradimuka (WKP Dieng)	Central Java	50	PT Geo Dipa Energi
12.	Candi Umbul Telomoyo	Central Java	92	PT Geo Dipa Energi
13.	Gn. Arjuno Welirang	East Java	302	PT Geo Dipa Energi
14.	Gn. Rajabasa	Lampung	283	PT Supreme Energy Rajabasa
15.	Rawa Dano	Banten	385	PT Sintesa Banten Geothermal
16.	Baturaden	Central Java	258	PT Sejahtera Alam Energy
17.	Telaga Ngebel	East Java	120	PT Bakrie Darmakarya Energi
18.	Seulawah Agam	Aceh	223	PT Geothermal Energi Seulawah
19.	Gn. Lawu	Central Java & East Java	332	PT Pertamina Geothermal Energy
20.	Kotamobagu	North Sulawesi	410	PT Pertamina Geothermal Energy
21.	Jaboi	Aceh	107	PT Sabang Geothermal Energy
22.	Gn. Talang – Bukit Kili	West Sumatera	90	PT Hitay Daya Energy
TOTAL			**4,011**	

Table 1 shows the list of the 22 geothermal prospect areas or concession areas still in the exploration stage and is expected to contribute in achieving the national geothermal target. Despite the compelling opportunity presented by the untapped geothermal resources, the effort to translate this opportunity into actual megawatt is quite challenging given the high uncertainty and substantial upfront capital expenditure required to drill deep geothermal exploration wells. To achieve its national target of 5,486 MW in 2030, around eight years from now, Indonesia must address these exploration project challenges, which require technical expertise, careful planning, and engagement with local communities and stakeholders.

1.2 Risks in the Exploration Stage

Geothermal exploration can be challenging, as it involves identifying and assessing the potential for geothermal resources in a specific area. The fundamental objective of a geothermal exploration program is to identify and characterize a geothermal resource that can be economically developed by applying an optimized design based on the exploration results.

Therefore, it is common for geothermal developers or investors to face dilemmas with making investment decisions in the exploration stage. The difficulty is created by the requirement to spend high upfront capital but relying on information that is still very minimal and has a very high level of uncertainty. Additionally, the most significant cost component of an exploration project comes from the drilling activities and the construction cost of supporting infrastructures such as access roads, well pads, and other supporting facilities. This portion could significantly impact the total project costs if not planned and managed correctly.

The main challenges of geothermal exploration in Indonesia are summarized as follows (IGA, 2014; Poernomo, 2015; Darma, 2016; Purba, 2018; Umam et al., 2018; Purba et al., 2019; Adityatama, 2020; Purba et al., 2020):

1. Difficulty in locating the "hottest area": Geothermal resources are not always visible at the surface and can be challenging to locate without conducting detailed geological, geochemical, and geophysical (3G) surveys and drilling test wells. The unclear indications or thermal manifestations from surface studies can make it challenging to identify the most promising areas for exploration and increase the risk of drilling dry wells.

2. High exploration costs: Conducting 3G surveys, developing a reliable conceptual model, and drilling test wells can be expensive, and there is always the risk that a project will not yield a viable resource. The high upfront capital and resource uncertainties can make it difficult for developers to secure funding for exploration activities.

3. Complex geology: Geothermal resources in Indonesia are mainly located in a volcanic area with complex geological environments, making it difficult to understand the subsurface conditions and identify the most promising areas for exploration.

4. Lack of direct and reliable data: In some cases, there may be a need for more data on the geology and geochemistry of an area, making it challenging to identify potential resources and plan the exploration activities.

5. Environmental impacts: Exploration activities can have various environmental impacts, such as air and surface water pollution, soil degradation, hazardous noise, release of hazardous gases, landslides, deforestation, and the potential for groundwater contamination. Mitigating these impacts can be costly and time-consuming.

6. Social and community impacts: Exploration activities can also have social and community impacts, such as displacement of local communities and land-use conflicts. Developers need to address these impacts and engage with local communities to ensure their support and minimize the risk of project delays or cancellations.

7. Uncertain regulations: Geothermal exploration is subject to various national, regional, and local regulations. The uncertainty can make it difficult for developers to navigate the regulatory environment and can increase the risk of project delays or cancellations.

Given the high uncertainty and risks involved in the exploration stage, most commercial lenders are still reluctant to provide financing facilities for this purpose. Even international financial institutions (IFI) are reluctant to fund up-front exploration and typically will provide financing only once 50% or more of the steam resource is proven (Asian Development Bank and The World Bank, 2015). With this consideration, exploration drilling generally requires the sponsor's equity, which may only be recovered if the drilling reveals that the resource is technically sufficient and economically viable for exploitation.

Meanwhile, from the developers' point of view, to mobilize the up-front equity needed for exploration, they will also consider the adequacy of the tariff, which adds to the challenges faced by the developers given the single buyer model applied in Indonesia.

One way that GoI has taken to tackle the challenges in the exploration stage is by launching the Infrastructure Financing for Geothermal Sector fund / Pembiayaan Infrastruktur Sektor Panas Bumi ("PISP Fund") through PT Sarana Multi Infrastruktur (Persero), as stipulated in the Minister of Finance Regulation No. 80 in 2022. This solution can be an alternative funding scheme that the developers may consider financing their exploration program, of which the typical funding application process will be described in the latter section.

1.3 Research Questions and Method

This paper begins by providing an overview of the typical activities carried out by developers in the exploration stage, along with estimated costs and duration of these various activities. After that, this paper briefly discusses various funding options for geothermal exploration projects.

While as the central part, this paper will discuss in more detail the process of submitting proposals and the completeness of documents that must be prepared by developers who plan to access funding facilities from financial institutions to finance geothermal exploration projects that will be carried out, particularly from the technical and commercial aspects. Most of the information described in this paper will use the exploration financing facility that will be channeled through PT Sarana Multi Infrastruktur (Persero) under the PISP Fund facility provided by the government as a reference. Although each financial institution may have a mechanism that may differ from one another in processing funding proposals, the authors of this study believe that there are fundamental similarities in the aspects assessed from the proposals submitted.

This study was conducted using the literature study method combined with interviews with several experts who have knowledge and experience relevant to this study. The objective of this paper is to provide general guidelines for investors or geothermal development companies who wish to access funding from financial institutions to finance geothermal exploration projects in Indonesia.

The research questions that will be explored in this paper are as follows:

1. What is the estimated cost of geothermal exploration in Indonesia currently?
2. What options are available to finance geothermal exploration projects in Indonesia?
3. What are the pros and cons of each funding option?
4. How long does it take to process a funding proposal?
5. What is the critical information that required in a funding proposal?

2. EXPLORATION PROJECT COST ESTIMATE IN INDONESIA

2.1 Geothermal Regulation in Indonesia

Geothermal business in Indonesia is regulated in Law (Undang-undang / UU) No. 21 / 2014 and Government Regulation (Peraturan Pemerintah / PP) No. 7 / 2017, with some relevant detail shown in Table 2. Understanding the definition of exploration is very important because one of the criteria for the success of an exploration project is when the project complies with regulations related to geothermal exploration in Indonesia.

Table 2: The Detail of UU 21/2014 Explaining Exploration and Exploitation Definition (GGGI, 2023).

No.	Regulation	Article and Section	Description
1	UU No 21 / 2014	Article 1, section 7	Definition of "Exploration".
2	UU No 21 / 2014	Article 1, section 9	Definition of "Exploitation".
3	UU No 21 / 2014	Article 1, section 11	Definition of "Geothermal Indirect Utilisation".
4	UU No 21 / 2014	Article 20	Description on the geothermal indirect utilisation business and developers' obligation.
5	UU No 21 / 2014	Article 31	Duration of "Exploration"
6	UU No 21 / 2014	Article 32, section 1	Duration and when "Exploitation" and "Utilisation" starts.
7	UU No 21 / 2014	Article 32, section 2	Description of the developers' obligation to submit Feasibility Study Report to get approval from Minister of Energy and Mineral Resources.

2.2 Stages in Developing Geothermal Energy in Indonesia

Like other countries, geothermal development projects in Indonesia typically involve several stages (Figure 1), including (IGA, 2014, Direktorat Panas Bumi, 2022):

1. Preliminary survey and exploration: These are the first stage of a geothermal development project and involves identifying areas with potential geothermal resources and conducting surveys to gather information on the geology and geochemistry of the area. The main activities include 3G (geology, geochemical, geophysical) surveys, hydrology study, topographic mapping, construction of conceptual model, drilling test wells.

2. Feasibility study / resource assessment: Once a viable resource has been identified, the resource assessment phase begins, which includes determining the size of the resource and the potential for energy production. Engineers will also conduct various studies such as environmental impact assessment, social impact assessment, and feasibility study.

3. Exploitation (field development and construction): After the resource assessment is done, the next step is the development and construction of a geothermal power plant. Activities may include drilling production wells, building power plants and transmission infrastructure, and connecting the plant to the grid. This phase also includes the installation of power generation equipment, such as turbines and generators.

4. Operation and maintenance: After the construction of the steamfield and power plant are finished, the operators will operate and monitor the power plant's performance, make repairs and improvements as necessary, and ensure that it complies with relevant regulations.

5. Decommissioning: At the end of the life of the power plant, decommissioning phase will take place, which includes disposal of hazardous waste and the management of contaminated sites with the goal is to ensure that the power plant site is safe and suitable for future use, and that the environment is protected from any negative impacts.

As the information obtained increases, the level of risk should decrease at each stage of the project, assuming that the information obtained is accurate and reliable. Table 3 summarizes the activities at each stage of the geothermal development project, along with the level of risk and potential funding sources. The table shows that project funding schemes through commercial loans can generally only be accessed when the project risk level has reached moderate to low, typically achieved after exploratory drilling has been completed.

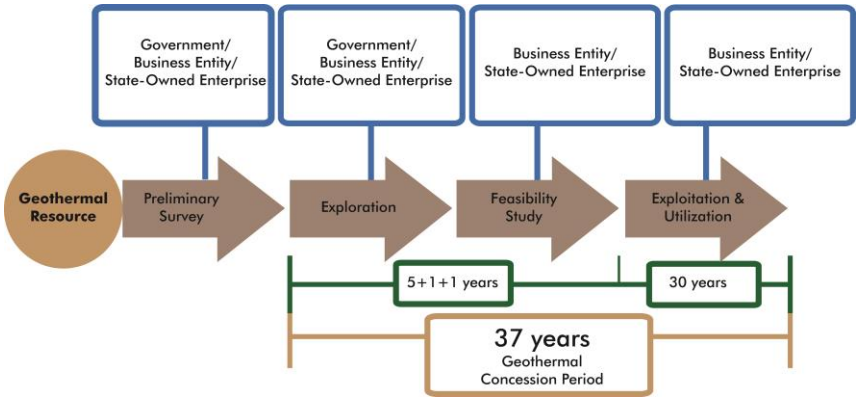


Figure 1: Geothermal development stages in Indonesia (modified from Purba, 2018; Adityatama, 2020; Purba et al., 2021; Direktorat Panas Bumi, 2022).

Table 3: Geothermal energy development project activities, risk levels, and potential funding sources (modified from Direktorat Panas Bumi, 2022; Purba, 2018; Purba et al., 2019; Adityatama, 2020; Purba et al., 2021; IGA, 2014).

Stages	Key Activities	Level of project risk	Possible funding source(s)
Preliminary Study / Reconnaissance study	Electricity demand analysis, infrastructure assessment, study on regulation, political, environmental, and social issues, study on available geoscientific and drilling data, remote sensing survey, preliminary site visit/geoscience study, go/no-go decision-making on proceeding to the preliminary survey.	Very High risk	Government, grant, sponsor's equity
Preliminary Survey and Exploration (PSAE)	Detailed geoscientific surveys (geology, geochemistry, geophysics), geotechnical study, environmental and social study, temperature gradient well or deep slimhole drilling (at least one exploration well), conceptual model, resource estimation and Pre-feasibility study, go/no-go decision-making on proceeding to the exploration drilling.	High risk	Government, grant, sponsor's equity
Exploration drilling	Exploration drilling infrastructures construction, exploration drilling (2-5 wells), downhole data acquisition (mud logging, wireline logging, cutting sampling, coring), well testing, conceptual model updating, preliminary field development concept, preliminary reservoir numerical model.	High to moderate risk	Government, sponsor's equity, GREM, GEUDP
Feasibility Study	Resource assessment and confirmation, feasible development size, justification to proceed to the development stage, forecast of reservoir performance, field development strategy, delineation, and development drilling plan, steamfield and power plant design, project budge and revenue projection, economic analysis, environmental and social study, go/no-go decision-making on proceeding to the field development stage.	Moderate risk	Sponsor's equity
Exploitation: Field development and power plant construction	Drilling infrastructure construction, development drilling (production and injection wells), conceptual model update, reservoir numerical model update, engineering design, procurement, steamfield and power plant construction, commissioning.	Moderate to low risk	Sponsor's equity, commercial loan
Utilization: Operation & maintenance	Operation and maintenance, well intervention, well service, workover, make up well drilling, annual inspection, major overhaul	Low risk	Sponsor's equity, commercial loan

2.3 Geothermal Exploration Project Cost Estimate

Cost estimates help identify potential risks and ensure adequate funds are available to complete the project successfully. Additionally, cost estimates serve as a baseline for monitoring and controlling project costs and can help to ensure that projects are completed within budget.

Each geothermal company trying to access funding for an exploration project may have different cost estimates, which is acceptable if the prospective borrower can show a reasonable estimation basis. However, geothermal developers must ensure the accuracy of the cost estimate for exploration costs submitted because it will significantly affect the proposal evaluation process and the project's success later. Some of the factors that may cause inaccuracy in the cost estimate are as follows:

1. The cost estimate based on complete and accurate information about the scope of work, resources required, or market rates can lead to incorrect cost estimates. A half-baked plan with plenty of possibilities for changes often causes incomplete information and many assumptions.
2. Assign the task to cost estimators with limited experience or personal biases that lead to incorrect assumptions or estimates.
3. Fail to consider all costs. The cost estimates focusing on direct costs, such as labour and materials, may not account for indirect costs, such as overhead and profit. The cost estimators often need to remember to include contingencies for risks or uncertainties.
4. The cost estimator needs to consider the experience from the industry, including actual project data, best practices, lessons learned, market fluctuation, annual inflation, material shortage, and equipment availability.
5. The cost estimate is not based on the latest or up-to-date market survey.
6. The cost estimate is based on underestimated task/work duration, which needs to reflect the sufficient time/duration required to complete a task.

Table 4 shows the rough cost estimate of each critical activity in a geothermal exploration project. The table shows that drilling activities require the most funds and take the longest to implement than surface survey (geology, geochemistry, geophysical) activities.

Table 4: Exploration work cost and duration estimates (modified from IGA, 2014; GeothermEx, 2010; Kristianto, 2018; Purwanto et al., 2018; Purba et al, 2019; Purba et al., 2020; Adityatama, 2020; Purba et al., 2021).

Activity	Cost estimate (US$)	Estimate work duration	Activities and Assumptions	Considerations
Geology survey	300,000 – 700,000	4-8 months	The assumption is geological mapping on an area of 400 km2—the work package includes pre-field-work study, rock sampling and identification, structural mapping, QA/QC, and reporting.	The accuracy might be affected by terrain, weather, and field personnel experiences. The wider the area and the more detailed the survey is, the cost and duration will increase.
Geochemistry survey	200,000 – 500,000	4-8 months	The work package is assumed to include a pre-field-work study, liquid and gas sampling from 30 locations, QA/QC, laboratory analysis, and reporting.	The sampling method (minimizing contamination) and laboratory competencies might affect the accuracy. The more the thermal manifestation sample is investigated, the higher the cost and duration.
Geophysical survey	1,000,000 – 2,000,000	4-8 months	The work package is assumed to include a pre-field-work study, 100 MT stations, 150 Gravity stations, QA/QC,	The accuracy might be affected by noise during data acquisition and data processing methods, including personnel interpretation. The more stations

			interpretations, and reporting.	deployed, the higher cost and duration will be.
Initial conceptual integration and well targeting	100,000 – 300,000	3-6 months	The activities include integrating all data and report from 3G surveys to create several scenarios of conceptual models, including peer review. The more reliable the data used, the more reliable the conceptual model constructed, which is very important for the basis of later decision-making in the drilling phase.	The accuracy might be affected by 3G data accuracy and personnel experiences and interpretation. The more data analyzed and integrated, the higher the cost and duration.
Exploration drilling	15,000,000 – 45,000,000	24 - 36 months	It is assumed to use 3 (three) standard/big hole type or 5 (five) slimhole type. The cost estimate includes infrastructure construction costs to support the drilling operation. The duration estimate includes procurement, preparation, equipment mobilization, drilling, well testing, and demobilization.	Drilling deep wells allow personnel to acquire downhole data directly from the reservoir, which is valuable for more accurate resource assessment but requires higher cost and time than the 3G survey. The total drilling cost will be impacted by the well type chosen, the number of wells, the rig used, and the difficulties of the drilling infrastructure construction.

3. FUNDING OPTIONS FOR GEOTHERMAL EXPLORATION PROJECT IN INDONESIA

As mentioned earlier, financing the geothermal exploration project is still considered a high-risk business for lenders as the resource uncertainty is still high. This section will further discuss the funding options for the geothermal exploration project that is currently available in Indonesia.

3.1 Own Equity

Most developers use their equity as the financing source for the geothermal exploration project. The cost estimate of a geothermal exploration project in Indonesia is around USD 15-50 million (Table 4), which depends mainly on the drilling strategy and little dependency on the size of the development project. Typically, the developers raise the equity from parent company loans and shareholder loans. The other options are issuing bonds and shares, but they can only do this after the resource is confirmed.

The primary consideration in using own equity is the risk borne solely by the developers. With such a considerable capital cost, there is still high possibility that the exploration found no economic geothermal resource. Or in some cases, the resource characteristic needs to be more attractive to be developed, which requires the developers to spend more capital to drill more exploration wells. In this stage, the developer has a high risk of losing all the equity spent on exploration activities.

3.2 Infrastructure Financing for Geothermal Sector (*Pembiayaan Infrastruktur Sektor Panas Bumi*, or PISP) Fund

The government of Indonesia has allocated around IDR 3.1 trillion (equivalent to approximately USD 200 million) from the government budget to support geothermal development in Indonesia. This fund will be leveraged with another funding source from international financial institutions, donors, and other stakeholders to collaborate in the de-risking funding scheme of geothermal exploration. This fiscal incentive is regulated by Ministry of Finance Regulation No.80/PMK.08/2022 Regarding Geothermal Development Support using *Pembiayaan Infrastruktur Sektor Panas Bumi* (PISP) Fund at PT Sarana Multi Infrastruktur ("PT SMI").

PT SMI is a state-owned enterprise (SOE) under the Ministry of Finance (MoF) assigned to manage the PISP fund. Ministry of Energy and Mineral Resources (MEMR) will use this fund to support a geothermal exploration program called Government Drilling. Other than that, the fund will be used as a financing facility for SOE and private developers with the de-risking feature for SOE developers. This feature allows the developer to not fully bear the risks and costs of exploration in the event of an exploration failure.

The overview of geothermal exploration de-risking facilities available in Indonesia that just discussed is illustrated in Figure 2.

3.2.1 Geothermal Energy Upstream Development Project (GEUDP) or Government Drilling

Geothermal Energy Upstream Development Project (GEUDP) is a government-sponsored exploration drilling collaboration program between the Government of Indonesia and the World Bank. The program aims to develop greenfield geothermal areas that have yet to be tendered, especially in eastern Indonesia, where the area's electrification ratio is low compared to the other parts of Indonesia (Apriani et al., 2018). The source of funds for the GEUDP program comes from the PISP Fund of USD 49 million, with matching grants from the Clean Technology Fund (CTF) of USD 49 million and the Global Environment Facility of USD 6.25 million. The program also received grants from the New Zealand Ministry of Foreign Affairs and Trade (NZ MFAT) in the form of technical assistance that equals the amount of NZD 2.13 million.

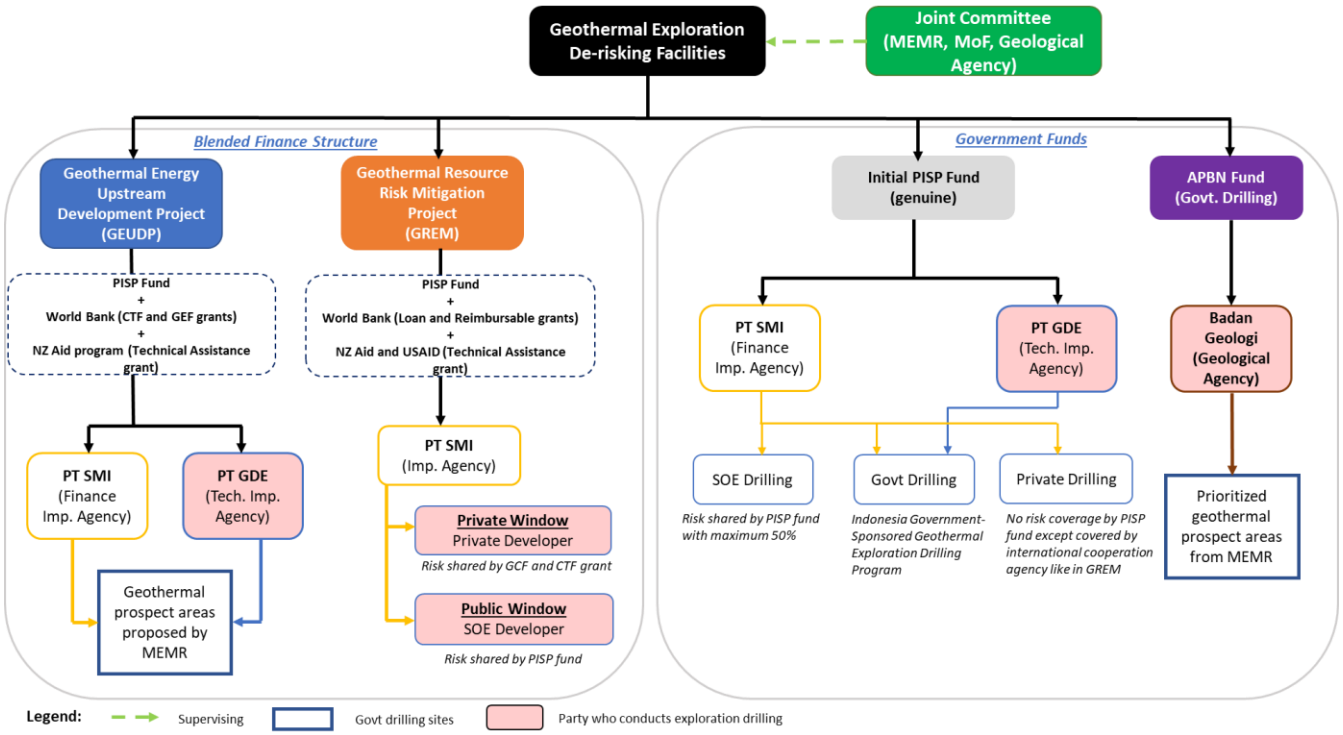


Figure 2: Overview of Geothermal Exploration De-Risking Facilities in Indonesia (PT SMI, 2022a).

MEMR, as the beneficiary of this program, will propose a geothermal prospect area to MoF to seek exploration support under the GEUDP program. Then, as the technical implementing agency, PT Geo Dipa Energi ("GDE") will conduct a preliminary assessment to see whether the proposed area is feasible to continue exploration drilling. Suppose the result shows that the proposed prospect area is viable; MoF will issue an assignment letter to GDE as the technical implementing agency and PT SMI as the financial manager to conduct the exploration drilling activities, which is supported under the GEUDP scheme.

The data acquired in the exploration drilling will be assessed by an independent party and discussed in the Joint Committee meeting to decide if the geothermal resource in the prospect area is proven and

sufficient to be tendered by MEMR. Assuming that resource is now de-risked, then MEMR will proceed with the tender process of WKP. In this stage, the participation of both public and private sector geothermal developers in the tender process is expected to increase as the geothermal resource risk has significantly reduced. Suppose the drilling exploration result shows that the resource is not economically attractive enough to be further developed; the government funds and donor funds will cover the exploration cost. Figure 3 shows the business model of GEUDP.

However, since most of the geothermal prospect area under GEUDP has yet to be tendered and awarded to the geothermal developers, the beneficiary of this facility is MEMR. MEMR will use the fund to undertake the exploration drilling to improve the quality of information available at the time of tender. The winning geothermal developer will reimburse the exploration costs at the time of the concession award. In other words, GEUDP is designated for something other than a geothermal developer who already holds a geothermal working area license or concession.

Aside from GEUDP, the Geological Agency of Indonesia, under MEMR, also conducted exploration drilling in several geothermal prospect areas in Indonesia, namely Nage, Bittuang, and Cisolok-Cisukarame. The activities include preliminary survey, land acquisition, permits, infrastructure construction work, drilling, well testing, and pre-FS document updating. The source of funds to support these activities comes from the state budget (APBN), and the risks are covered 100% by the government.

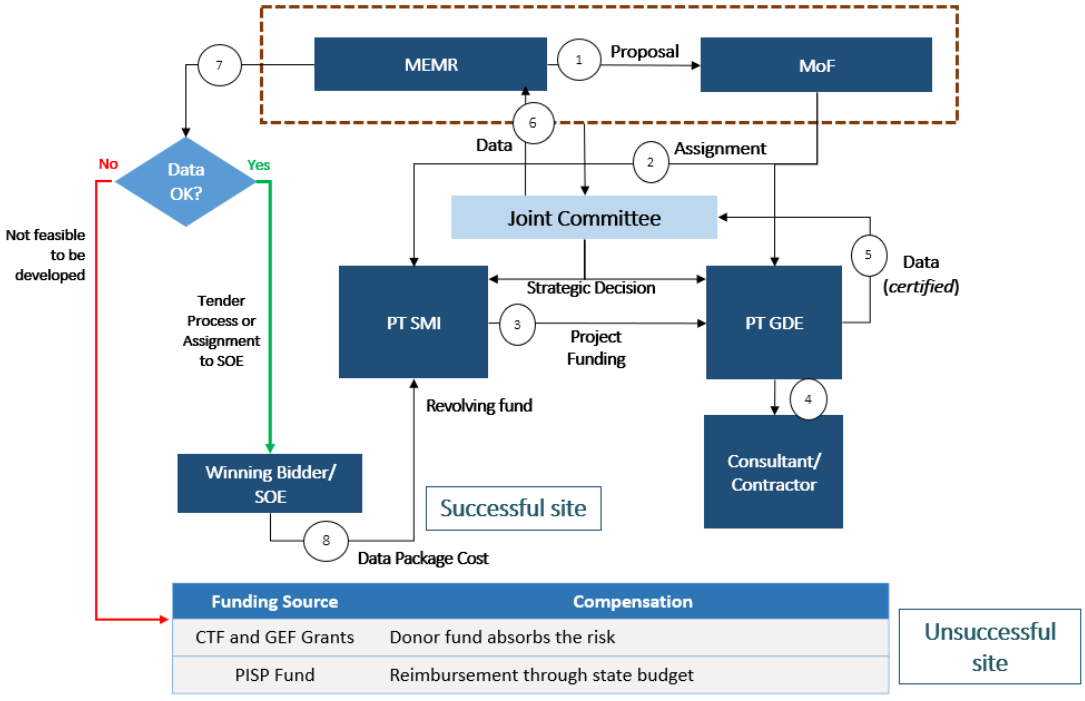


Figure 3: GEUDP Business Model (modified from PT SMI, 2022b).

3.2.2 Geothermal Resource Risk Mitigation Project (GREM)

The government of Indonesia, through PT SMI and the World Bank, has developed a geothermal exploration financing facility called Geothermal Resource Risk Mitigation Project (GREM). In contrast to GEUDP, GREM is designated to support the exploration drilling undertaken by geothermal developers who already hold the license or concession of geothermal working areas. One of the prerequisites for the geothermal developers to access this facility is that they already have the preliminary data of the prospect area/WKP. The data and information could be obtained from Preliminary Surveys, such as 3G surveys and other related studies. This information should assist the geothermal developers in concluding the feasibility of the geothermal area to proceed to the development stage so that further exploration drilling is deemed required. The unique feature of GREM

is the availability of a de-risking facility or a risk-sharing scheme at which, in the event of an exploration failure, the developer does not fully bear the risks and costs of exploration. GREM facility is intended for SOE developers/subsidiaries of SOEs ("GREM Public Window") and private developers ("GREM Private Window").

The total commitment of GREM funding is USD 651.25 million. The pledge comes from a combination of multilateral funds, namely the International Bank for Reconstruction and Development (IBRD), Green Climate Fund (GCF), Clean Technology Fund (CTF), Global Infrastructure Facility (GIF), and PISP funds. The overview of the institutional arrangement and flow of funds of the GREM facility is shown in Figure 4.

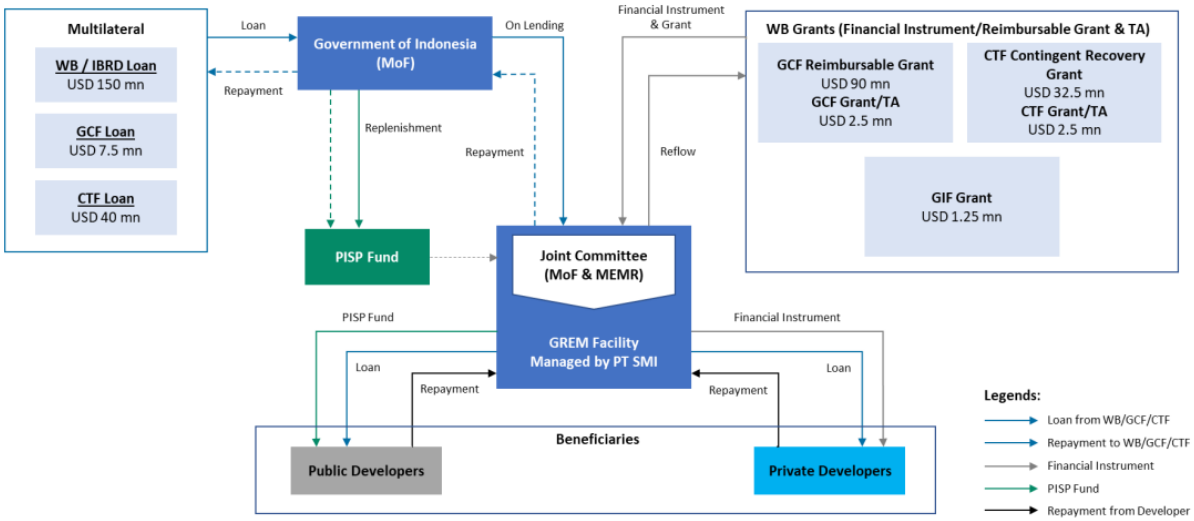


Figure 4: Overview of Institutional Arrangement and Flow of Funds of GREM Facility (PT SMI, 2022a).

GREM Public Window facility will support geothermal exploration activities to public developers (SOE/subsidiaries of SOE) by providing loan and de-risking facilities with a maximum total limit of USD 30 million. Half of the facility is a blended loan from IBRD/GCF/CTF, while the other half is de-risking from the PISP fund. The risk coverage is provided when exploration and political risks occur, with the maximum risk coverage being 50% of the total loan (Figure 5). The forgiveness calculation of the facility will be assessed in the projected project value (PPV) financial model and further decided by Joint Committee.

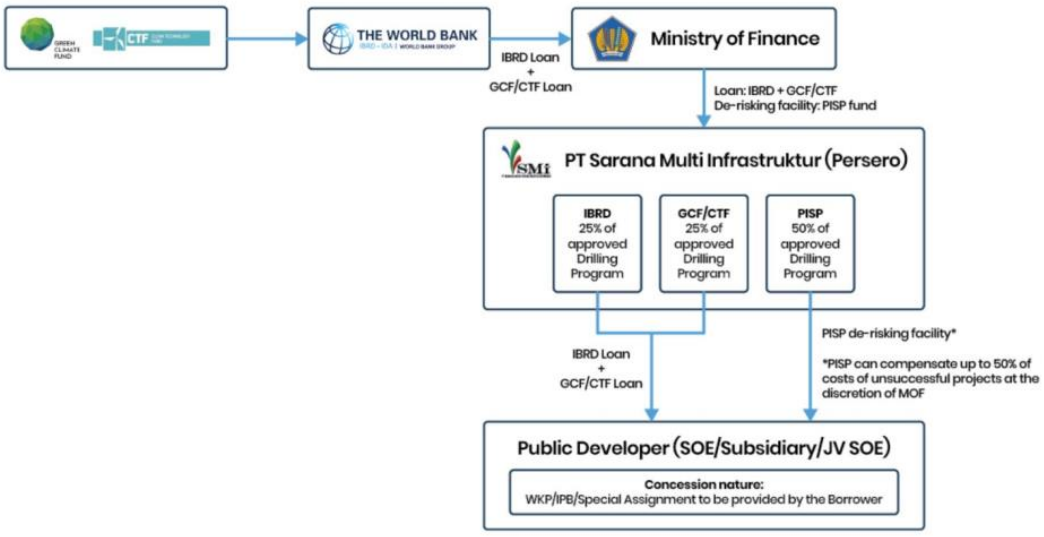


Figure 5: GREM Public Window Facility Scheme (PT SMI, 2022a; PT SMI 2022b).

To access the GREM Public Window facility, public developers shall have a valid geothermal exploration license or *Izin Panas Bumi* (IPB), a minimum proven track record of 3 (three) years, and a minimum equity portion of 25% of the total project cost. They must also possess geothermal data from a preliminary survey that still needs to be proven by exploration drilling to conclude the resource feasibility. Additionally, all or most of the land for exploration purposes in the working area must be legally controlled or licensed and is not currently the object of a case/dispute in any court. Finally, the implementation of the exploration project must comply with the World Bank ESS (Environmental Social Safeguards) and Procurement Standards.

GREM Private Window facility will support geothermal exploration activities to private developers by providing loan and de-risking facilities through the purchase of financial instruments (FI) that developers issue, with a maximum total limit of USD 30 million. The facility is divided into two categories: Facility A, a blended loan from IBRD, and Facility B, FI de-risking from GCF/CTF reimbursable grants (Figure 6).

The Private developers that are eligible to access the GREM Private Window facility shall have a valid geothermal exploration license or *Izin Panas Bumi* (IPB), a minimum proven track record of 3 (three) years, and a minimum equity portion of 25% of the total project cost. They must also possess geothermal data from a preliminary survey that still needs to be proven by exploration drilling to conclude the resource feasibility. Additionally, all or most of the land for exploration purposes in the working area must be legally controlled or licensed and is not currently the object of a case/dispute in any court. Finally, the implementation of the exploration project must comply with the World Bank ESS (Environmental Social Safeguards).

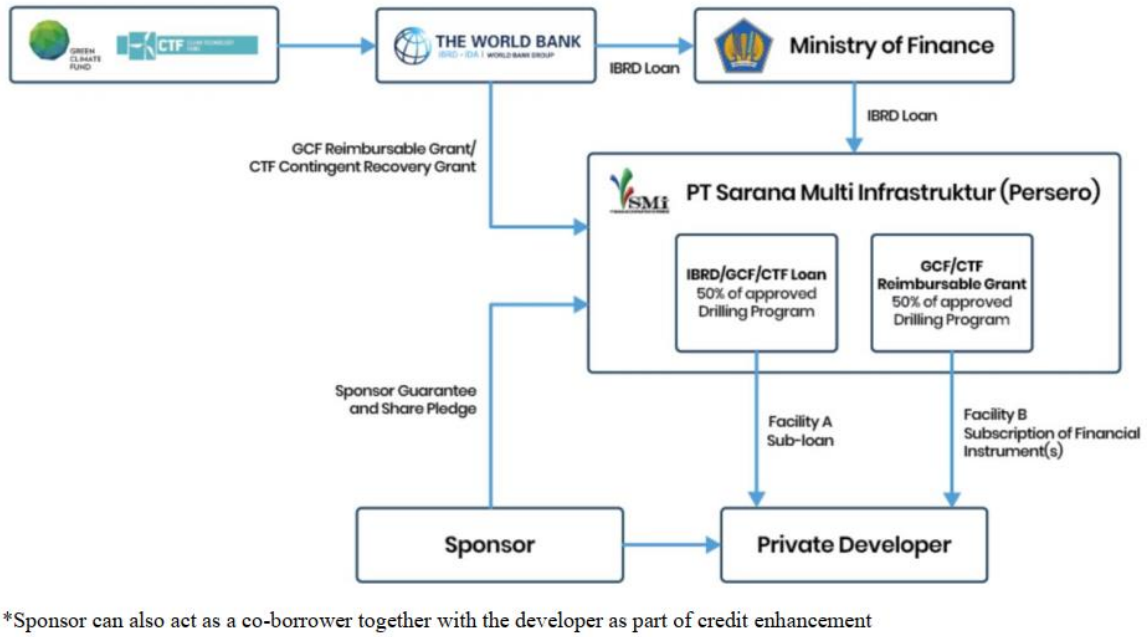


Figure 6: GREM Private Window Facility Scheme (PT SMI, 2022a; PT SMI 2022b).

3.3 Assessment on the Funding Options for Geothermal Exploration Project in Indonesia

This section aims to give insights to the developer and its sponsor in deciding which financing scheme is suitable for their geothermal exploration project by assessing the pros and cons of available funding options in Indonesia. The assessment summary is provided in Table 5.

Table 5: Assessment Summary of Geothermal Exploration Project Funding Options.

Funding Options	Pros	Cons
Own Equity	Geothermal developers do not have to prepare application proposals to get funding which usually takes time and effort.	1. Developers bear the entire risk of unsuccessful geothermal exploration projects. 2. The risks of losing capital are relatively high if geothermal resources are not found or the size of the resources found is considered insufficient to be developed commercially. 3. There is no third party that can help to assess, monitor, and evaluate the project implementation.
Government Funds + IFI Funds: GEUDP (Government-led Exploration Drilling)	1. Geothermal developers do not have to take the entire risk of unsuccessful geothermal exploration projects as the risk is shifted to the government. 2. Developers do not have to prepare equity or cost of capital in the early stage of geothermal exploration as the government will bear the cost of exploration drilling and its risks. The cost of capital only needs to be prepared when the developers join the tender process of the geothermal exploration data package of WKP, at which the resource has been confirmed and sufficient to be developed commercially. 3. Once resource risks are significantly reduced, developers can access debt financing more easily for geothermal exploitation projects.	1. Developers might have to pay higher for the geothermal exploration data package to cover the cost incurred during the exploration project and the risk premium that was borne by the government previously. 2. Developers must carefully check the adequacy of the data package being tendered and ensure that the resource is economically attractive to be developed and meet the return of investment needed by the developer and sponsor.
Government Funds + IFI Funds: GREM (Exploration Financing Facility to Public and Private Developers)	1. Geothermal exploration risks are being shared between the developer and lenders. If the exploration drilling fails to reach the success criteria, the developer is eligible to get forgiveness which the value is agreed upon between developers and the lender. 2. Implementing a cost-efficient risk-sharing mechanism would bring substantial leverage of developers' equity, public funds from PISP, IBRD, and climate finance. 3. Developers can have third-party reviewers assist in monitoring and evaluating the project implementation. 4. When the exploration financing scheme applies and significantly reduces the resource risk, the developer can easily access debt financing to finance the next stage of geothermal development.	1. Geothermal developers must prepare a good application proposal to get funding which usually takes time and effort. 2. GREM facility, developed by the World Bank and the Government of Indonesia, has relatively higher standards to comply especially in the environmental, social, and safeguards standards compared to the national standard/regulation.

4. TYPICAL FUNDING APPLICATION PROCESS

It is expected that when geothermal developers, both public and private, want to access the exploration financing facility, the application proposal shall cover a comprehensive detail of the exploration drilling plan that covers the technical, environmental, social, legal, and financial aspects of the project. A good application proposal from developers will give confidence to lenders to fund the exploration drilling project as the project is considered a risky investment. This section will explain in detail the typical

application process and the critical information required in the funding application proposal of the geothermal exploration project.

4.1 Typical application process

Several geothermal exploration financing facilities are currently available worldwide. GREM, as one of the financing facilities for exploration projects in Indonesia, has the typical application process that follows the provisions stated in the Minister of Finance Regulation / Peraturan Menteri Keuangan (PMK) No. 80 the Year 2022 and then elaborate more in GREM Developers Manual (PT SMI, 2022a).

While in Turkey, a similar scheme is available, called Risk Sharing Mechanism for Resource Validation (RSM). It has the application process divided into two stages. The first stage calls for Expressions of Interest (EoI), and the applicants will be shortlisted and invited to prepare a full proposal (TKYB & The World Bank, 2021). In summary, the typical application process to access the geothermal exploration financing facility is as follows (Table 6):

Table 6: Summary of Funding Application Process (modified from PT SMI, 2022a).

Application Stage	Activities Description	Estimated Duration
Preliminary Assessment and Discussion	Prior to submitting the formal proposal, the developer or sub-borrower shall submit a request to lenders to discuss the plan for proposal submission. In this stage, the developer is also expected to check the conditions and criteria needed to access the financing facility. In some cases, sharing documents about the project between the developer and lender also occurred to conduct a preliminary assessment. A preliminary assessment by the lender will provide early feedback to the developer on the readiness of the proposal, give sufficient time for the developer to meet the level of details expected, and identify if there is any fatal flaw/red flag of the project.	3 months – 1 year (subject to developer's readiness)
Proposal Submission	The timeline of proposal submission may vary for each lender. Some lenders may set the proposal submission at a specific period, while others open for submission at any time. In this stage, the developer is expected to submit the required information in the proposal that includes a comprehensive and detailed plan of the geothermal exploration project.	1 – 3 months (subject to the completeness of proposal)
Proposal Due Diligence	In the due diligence process, lenders will check thoroughly on the geothermal exploration project plan to assess the detail of the exploration project. It includes the geothermal resource assessment, the detailed drilling plan, technical and financial viability of the project, compliance with environmental and social safeguards, appraisal of legal and compliance aspects, and assessment of whether the developer has demonstrated capability to conduct the project. This process is mainly conducted by independent consultant firms/experts of the lenders to ensure a detailed and thorough assessment has been carried out. Aside from the detailed assessment, the process may include a site visit to verify on-site technical, environmental, and social aspects and discussion with related stakeholders such as Ministries if the fund source also comes from government funds.	6 months (may vary depends on the actual condition)
Signing Loan Agreement	Following a positive result of the due diligence process and all the requirements or conditions precedent required has been met by the developer, the loan agreement's signing process can then proceed. The loan agreement will stipulate the financing terms and loan covenants to ensure proper implementation of the project.	-
Implementation and Monitoring	During the financing facility execution, lenders will monitor the implementation of the project and ensure that disbursement has been made for eligible activities. The developer is also obliged to make reporting to the lender during the financing facility period as stipulated in the loan agreement. An independent consultant firm usually assists	2 – 4 years (may vary depends on the actual condition)

Application Stage	Activities Description	Estimated Duration
	the project monitoring in verifying that the arrangement in the loan agreement is maintained.	

4.2 Key Information Required in the Proposal

Due diligence is a critical step in any business transaction, as it helps to identify potential risks and opportunities before making any decision. This process involves thoroughly researching and analyzing a company, a project, or an investment opportunity, including reviewing technical documents, financial statements, legal documents, and other relevant information. By conducting due diligence, lenders, investors, and business owners can make more informed decisions and minimize the potential for financial losses or legal issues. Overall, due diligence is an essential tool for protecting one's assets and ensuring the success of any business venture.

Technical assessment during due diligence is a crucial step for geothermal exploration financing facilities as the project risk is highly allocated in the technical aspect. Thus, the developer must prepare detailed information on the technical part so the lender can assess whether the project is feasible and whether the risks associated with the project have been addressed in the mitigation plan.

As discussed earlier, after the required documents from the initial screening are considered complete, the lender's team will start the financing feasibility analysis, which several independent consultant firms or experts will most likely support. The technical consultant firm typically consists of experts such as geoscientists, reservoir engineers, drilling engineers, civil engineers, environmental engineers, social specialists, and project managers.

Table 7 shows a framework used by lenders in evaluating technical proposals submitted by prospective borrowers. An evaluation framework is important because it provides a structured approach for assessing the effectiveness and impact of programs, projects, or initiatives. It helps ensure that evaluations are comprehensive, rigorous, and consistent and provide useful information for decision-making. Organizations can use a framework to ensure that they are addressing key evaluation questions, gathering relevant data, and using appropriate methods to analyze and interpret the data.

Table 7: Evaluation Framework for Technical Due Diligence Process of a Geothermal Exploration Project Funding Proposal (modified from Jacobs & PT SMI, 2022).

Main Category	Sub-category	Required Key Information	Potential Red Flags
The Project: A high-level overview of the overall project scope & objectives, including developer, physical setting, project history.	Project Status	Concession status, ownership, history of exploration	1. Ownership status is unclear, 2. Fail to provide evidence of project/concession ownership
	Geothermal Resource	Exploration summary (3G), drilling summary, resource conceptual model, data gaps, resource uncertainties and POD (probability of discovery), energy potential, key areas to test by drilling, expected well productivity, expected production enthalpy	1. Fail to provide explanation on previous negative results from drilling (if any), 2. No resource conceptual model is presented, or resource conceptual model presented is inconsistent with data, 3. There are fundamental data gaps (e.g., key resource data is missing or is of poor quality), 4. No resource-related uncertainties are presented, or resource-related uncertainties poorly understood, or the POD is very low < 25%, 5. Energy potential is not estimated, or the resource assessment method used was inappropriate, or energy not technically feasible for development,

Main Category	Sub-category	Required Key Information	Potential Red Flags
			6. Areas to test not identified; no justification indicated for the drilling areas presented, 7. No data presented to indicate expected production enthalpy; expected enthalpy unsupported by data, 8. No well productivity indicated; well productivity indicated is not justified.
	Development Plan	Development size (MW), concept layout, power plant concept, transmission connection, project implementation, schedule/phasing	1. No development description presented; development description presented incompatible with resource conceptual model/information, 2. No development size indicated, development size inconsistent with development description and resource potential, 3. No concept layout/power plant concept/transmission connection plan/project implementation plan/development plan is presented, or the layout/plan are inconsistent with the resource and development description.
	Economic / Financial	Project capital cost, project financial model, macro status of the market, PPA/HoA status with PLN, financing plan	1. Summary cost estimates presented were incomplete or had unclear basis for cost assumptions, 2. Inputs and outputs of the financial model are not described, and project viability not presented, 3. No market opening for project (flat or declining power demand forecast), 4. No financing plan presented; financing plan presented is incompatible with project.
	Environmental / Social	Land ownership/use, social acceptance, environmental, direct heat/direct use project (if any), social engagement plan	1. Unclear land use/access or ownership terms, 2. Significant community issues with no community engagement plan presented, 3. No environmental studies/status summary presented; project environmental context is incompatible with development.
Drilling Proposal: This will include the strategy to achieve the objectives of the sub-project with detail on targets, number of wells, infrastructure requirements, permits, cost estimates and schedules. Information regarding the	Drilling Plan	Drilling strategy, well objectives, well target, drilling sequence, decision tree, well type, well design, drilling rig specification, supervision plan, data acquisition/collection plan, well testing plan, drilling procurement plan, DWOP (drill-well-on-paper) plan, stuck pipe prevention plan, well control plan, risk assessment and	1. The targets are not based on concept model, or have no reasoning provided. Objectives are not stated, 2. Decision sequence is illogical or shows a weakness in the drilling plan that could be fixed with more thought, 3. Well depths are inadequate to meet objective, or designs are unsafe, 4. Rig specification is not suitable for planned well design or has high risk of failure to complete wells, 5. Inadequate or limited supervision is planned, 6. Data collection plans not developed, or no thought given to data,

Main Category	Sub-category	Required Key Information	Potential Red Flags
drilling contract (turnkey, day-rate, combination), including service companies.		mitigation plan, well plug & abandoned (P&A) plan	7. Inadequate identification of tests or how they will be conducted, 8. Major risks, such as well control, stuck pipe, and H_2S release are not addressed properly in the document.
	Infrastructure	Transportation/mobilization plan, existing infrastructure, access road and wellpad plan, water supply system, well testing and disposal, basecamp/laydown area, explosive bunker, site office, evacuation plan, remediation	1. Transportation plan incomplete or indicates major flaws for access to the project, 2. Missing or incorrect information, 3. No access road & pad plans presented; plans presented are incompatible with terrain, environmental and social constraints, 4. No water supply plant/well testing/disposal/site remediation is presented; water supply plan is not viable or compatible with the project
	E&S and Permits	Permitting plan, enviro permits (UKL-UPL), social engagement, land ownership, compensation	1. Information is inadequate or inconsistent, 2. The company has no HSE policy, 3. Major risks related to environmental and social are not presented.
	Implementation	Procurement plan, project team structure, schedule, health, and safety plan	1. There is no plan or statement of how major contracts are to be tendered, 2. Project team is substantially inadequate for the project, 3. Inadequate information on project schedule, HSE plan and target/KPI.
	Cost / Budget	Infrastructure cost, drilling cost, well testing cost, remediation cost, contingency cost	1. Costing missing major elements, flawed, or show the project is not viable, 2. No information on how the project cost was estimated (basis of cost assumptions).
Capability: Showing the technical and financial capabilities of the developer and key stakeholders, relevant to the current phase of project development, must be demonstrated. Basic information on the project's organization and relevant characteristics (joint venture, project funding, etc.) should be included.	Company	SPV/JV proposed, owners, geothermal track record, technical resources, health, and safety (H&S)	1. No description of the JV/SPV proposed, project company unclear, 2. No description of owners and capability available to the project, 3. Geothermal track record is negative, 4. No available technical resources identified, 5. Negative H&S track record; H&S policy is insufficient, and capability is lacking.
	Personnel	Key personnel assigned, support personnel, responsibilities	1. No indicated personnel or organizational chart presented, 2. No responsibility assignment matrix (RACI chart) and key responsibilities document presented.
	Contractors	List and requirements of consultants and contractors, peer reviewers, scope of work/deliverables	1. No information provided on consultants; information provided indicate incompatible consultants to the project, 2. Peer reviewers identified are incompatible with the project/industry.

Main Category	Sub-category	Required Key Information	Potential Red Flags
	Financial	Financial history, credit rating, funding source for drilling,	Found no audited financial statement of the developer and sponsor (in the case that the borrower is a Special Purpose Vehicle, which is required to assess the capacity to fulfill the required equity contribution and loan repayment obligation. Generally, audited financial statements for the last two years are required.

An evaluation framework also provides a means of tracking progress and measuring outcomes over time, essential for continuous improvement and accountability. Ultimately, an evaluation framework helps organizations make informed decisions about allocating resources and improving their operations for maximum impact.

Furthermore, apart from the potential red flags that have been presented in the far-right column in Table 7, several things that must be considered by prospective borrowers when preparing technical and commercial proposal documents for funding geothermal exploration projects in Indonesia are:

1. Get a clear understanding of the lender's needs and requirements. It is important to fully understand the lender's needs, expectations, and requirements to ensure that the proposal meets their specific needs, which will save a lot of due diligence process time.

2. Explain the factors that support the decision to progress from the surface survey stage to the exploration drilling stage as clearly as possible, considering that exploration drilling activities have a great difficulty level, higher risks, and cost much higher than 3G surveys.

3. Communicate the data gaps, major risks, uncertainties, and opportunities of the project, supported by clear evidence in a written format such as study/survey reports, basis of design (BoD), detailed design, engineering calculation, model, analysis, peer-review reports, and raw data as necessary.

4. Present the availability, quality, and limitations of data used for the basis of exploration drilling planning. Provide clarity of plan if any additional data is required to enhance the success of the proposed exploration drilling project.

5. In presenting technical and commercial proposals, provide a high-level overview of the project by linking it to other important social, environmental, and legal aspects. Integrating all aspects helps to identify potential risks and plans for risk management strategies, reducing the likelihood of project delays or failures.

4.3 Preparing the Proposal

Effective communication of exploration project plans is crucial during the proposal drafting process, as it significantly impacts the due diligence process and the likelihood of successful funding. The proposal drafting team should prioritize a clear and comprehensive presentation of all aspects of the project plan in the written document.

Lenders typically begin their evaluation by reading the high-level summary of the proposal. This summary would provide an overview and determine whether the lender will investigate further. Therefore, it is imperative to include the necessary level of detail requested by the lender in the summary section.

Providing the requested level of detail to avoid complications during the due diligence process is very important. Lenders rely on comprehensive information to assess the project's feasibility, risks, and potential returns. Incomplete or insufficient details may result in a prolonged due diligence process, as

lenders will require additional information or clarification before proceeding. The half-baked document can also necessitate the resubmission of the proposal, causing delays and reducing the project's chances of securing funding.

During the proposal preparation process, it is customary for the drafting team to engage in informal consultations with the lender. These consultations serve to seek clarification, exchange information, and address any concerns or questions about the proposal. Informal consultations allow the drafting team to gain insights into the lender's expectations, requirements, and preferences regarding the proposal. By engaging in open and constructive dialogue, the team can better align the proposal with the lender's specific needs and increase the likelihood of a successful outcome. These consultations typically involve discussions on various aspects of the proposal, such as project details, financial projections, risk mitigation strategies, and timelines. The drafting team can seek guidance from the lender regarding the preferred format, level of detail, and specific documentation that should be included in the proposal.

To ensure a smooth and efficient evaluation process, the proposal drafting team must anticipate the lenders' information requirements and address them comprehensively in the project plan. The anticipation should include providing relevant technical, financial, and operational details demonstrating the project's viability and potential for success.

5. DISCUSSION

To achieve the national geothermal target, Indonesia must focus on various prospect areas or WKP currently in the exploration stage. The importance of exploration projects can be seen from the target of adding an installed capacity of approximately 3,300 MW in 2030; more than 60% is expected to come from geothermal areas or WKPs in the exploration stage. With this understanding, all geothermal stakeholders in Indonesia need to work together to overcome the obstacles and complete all ongoing and future geothermal exploration projects.

This paper has discussed that one of the major challenges for geothermal exploration projects is the high upfront capital that must be allocated where the level of uncertainty on the economic geothermal resource's availability is still very high. The results of literature studies and interviews with various geothermal experts concluded that the funds that must be prepared for a geothermal exploration project in Indonesia range from USD 15-50 million, with deep well drilling activities being the largest cost component. Accurate project cost estimates required to achieve the agreed project objectives are crucial for the success of a project. They help communicate project expectations to stakeholders and ensure everyone is on the same page regarding budget constraints, project goals, and project outcomes.

Not all geothermal companies in Indonesia have or are willing to allocate their equity to finance geothermal exploration projects due to the high risk of losing all that equity if it turns out that the results of exploration are uneconomical. Therefore, it is important to have other funding options available for geothermal exploration activities besides using company equity.

This paper has discussed 3 (three) funding options currently available for geothermal exploration projects in Indonesia: own equity, government funds (PISP fund and APBN fund), and blended finance structure (combination of government funds and IFI funds, GEUDP and GREM). Although for GEUDP, the facility is not applicable for geothermal developers who already hold IPB licenses. This paper has also compared the pros and cons of the funding options. Of course, no option ultimately eliminates the risk of geothermal exploration. However, with the availability of several funding options, it is hoped that geothermal exploration projects in Indonesia can run at a higher pace. Therefore, geothermal developers need to understand the scheme, features, eligibility, requirements, application process, payment terms, funding amount, flexibility, cost, and timeframe of each available funding option for geothermal exploration projects in Indonesia to see suitability.

Understanding how to prepare technical documents properly becomes crucial for geothermal companies in Indonesia who wish to access funding facilities such as GREM. Considering that the application evaluation process will take 6-12 months, prospective borrowers need to understand the various

information/documents required by the lender. This paper has provided complete information on what must be available in the proposal documents submitted to lenders, including potential red flags, which will be the focus of the lenders' assessment team.

Understanding the importance of all exploration project plans written clearly in the document should already be in the minds of the proposal drafting team from the start when preparing the proposal package to lenders. Generally, Lenders will read a high-level summary before going into the details of every aspect of the proposed plan. Failure to include the level of detail requested by the lender will make the due diligence process longer and lead to the resubmission of the proposal.

In conclusion, providing critical information in a funding proposal is crucial as it helps lenders assess a project's viability and potential success. Accurate and comprehensive information helps to build trust and confidence with the lender and increases the chances of obtaining funding. Critical information includes, but is not limited to, the project's goals and objectives, technical details, expected outcomes, budget and cost estimates, project timeline, procurement plan, data gaps, uncertainties, risk assessment and mitigation plan. Information about the project's management team and their relevant experience, as well as the market demand and competition, is also important to provide. Providing all relevant information in a funding proposal can demonstrate the project's ability to deliver on its promises and repay the loan. It also helps to identify potential issues and address them proactively, which can improve the project's overall success.

Hopefully, this paper can provide essential guidance for stakeholders working on geothermal exploration projects in Indonesia. Of course, this paper has not touched on many aspects of submitting funding for geothermal exploration projects. Therefore, the authors plan to cover several additional aspects with a more focused discussion on the detail of various funding schemes to de-risk resource risk in the exploration stage in a separate publication.

REFERENCES

Adityatama, D. (2020). Mengenal Tahapan Proyek Panas Bumi di Indonesia. www.enerklaz.com

Apriani, D. N. I., Randle, J. B., & Paripurna, A. (2018). Government Drilling Program for Geothermal Exploration in Indonesia. 14–16.

Asian Development Bank (ADB), & The World Bank. (2015). Unlocking Indonesia's Geothermal Potential. ASIAN DEVELOPMENT BANK.

Asokawaty, R. F., Purba, D. P., Adityatama, D. W., Muhammad, F., & Umam, M. (2020). Indonesia's Geothermal Development Comp are to World Top Geothermal Producers. 45th Workshop on Geothermal Reservoir Engineering.

Darma, S. (2016). Indonesia: Vast geothermal potential, modest but growing exploitation. In Geothermal Power Generation: Developments and Innovation (pp. 609–643). Elsevier Inc. https://doi.org/10.1016/B978-0-08-100337-4.00021-8

Direktorat Panas Bumi. (2022). Buku Pintar Umum Panas Bumi.

GeothermEx (2010). An assessment of geothermal resource risks in Indonesia.

GGGI (2023). A Guideline to Differentiate Cost Type in Geothermal Development Project in Indonesia: Blawan-Ijen Geothermal Prospect Area Case. Global Green Growth Institute report to PT SMI (unpublished).

Ibrahim, R. F., & Fauzi, A., Suryadarma. (2005). The progress of geothermal energy resources activities in Indonesia. Paper presented at the Proceeding World Geothermal Congress 2005, 1-7.

IGA. (2014). Best practices guide for geothermal exploration. Bochum, Germany: International Geothermal Association.

Jacobs, & PT SMI. (2022). GREM Evaluation Framework Criteria.

Kristianto, B. (2018). Discussion on 3G surveys cost and duration in geothermal exploration in Indonesia. Personal communication.

PT SMI. (2022a). Indonesia Geothermal Resource Risk Mitigation Project Developer Manual. https://ptsmi.co.id/strategiccooperation/grem

PT SMI. (2022b). De-risking of Geothermal Exploration from Lender's Perspective.

Purba, D.P (2018).: Energy 785 Research Project Report: Investigation on Geothermal Resource Assessment Methods in Reducing Exploration Risk in Indonesia Geothermal System. The University of Auckland, New Zealand. Unpublished manuscript.

Purba, D.P., Adityatama, D.W., Umam, M.F., and Muhammad, F. (2019). Key Considerations in Developing Strategy for Geothermal Exploration Drilling Project in Indonesia, Proceedings, 44th Workshop on Geothermal Reservoir Engineering, Stanford University, Stanford, California, United States.

Purba, D.P., Adityatama, D.W., Agustino, V., Fininda, F., Alamsyah, D., and Muhammad, F. (2020). Geothermal Drilling Cost Optimization in Indonesia: A Discussion of Various Factors, Proceedings, 45th Workshop on Geothermal Reservoir Engineering, Stanford University, Stanford, California, United States.

Purba, D.P., Adityatama, D.W., Nugraha, R. P., Ayuningtyas, R. R., Chandra1, V. R., Al-Hassan, M. A., Ramadhan, R. F., Rizqy, M. M. (2021). Resource Assessment Methods Selection for Geothermal Exploration Project in Indonesia: What Are the Considerations? Proceedings, 46th Workshop on Geothermal Reservoir Engineering, Stanford University, Stanford, California, United States.

Poernomo, A. S. (2015). An overview of Indonesia Geothermal Development – Current Status and Its Challenges. Pp. 1 – 11. In: Proceedings of World Geothermal Congress, Melbourne, Australia.

Purwanto, E. H., Suwarno, E., Lukman, R. F., and Herdiyanto, B. (2018). Geothermal Drilling in Indonesia: A Review of Drilling Operation, Evaluation of Well Cost and Well Capacity, Proceedings, 6th Indonesia International Geothermal Convention & Exhibition, Jakarta, Indonesia (2018).

ThinkGeoEnergy. (2023, January 11). Top 10 Geothermal Countries 2022 – Power Generation Capacity (MW). https://Www.Thinkgeoenergy.Com/Thinkgeoenergys-Top-10-Geothermal-Countries-2022-Power-Generation-Capacity-Mw/Amp/.

Türkiye Kalkınma ve Yatırım Bankası (TKYB), & The World Bank. (2021). RSM Geothermal Resource Validation - Beneficiary Manual 2.0. https://rpmjeoturkiye.com/en/homepage/

Umam, M., Adityatama, D., & Purba, D. (2018): Tantangan Pengembangan Energi Panas Bumi Dalam Perannya terhadap Ketahanan Energi di Indonesia. Swara Patra, 8(3), 48-65.

Utami, P. (2010). High-temperature Geothermal Area and its Challenges for Civil Engineering Works. PERTEMUAN ILMIAH TAHUNAN XIV HATTI. Indonesia.

Looking back into Galunggung Geothermal Field through geoscience study

Triwening Larasati[1,2], Jessica Ivana[2], Alya Dhiya Oktaviani[2],
Ferdino R Fadhillah[1,2], Dyah Nindita Sahdarani[2], and Tri Rani Pujiastuti[2]

[1]PT Geoenergi Solusi Indonesia, Cibis Nine 11th Floor, Jakarta Selatan 12560, Indonesia
[2]Geology Study Program, FMIPA, Universitas Indonesia, Depok 16424, Indonesia

t.larasati@geoenergis.com

Keywords: Galunggung, geothermal system, geothermal geoscience, preliminary exploration

ABSTRACT

Galunggung volcano located on the southern side of Karaha-Bodas geothermal field also holds the potential for hosting geothermal prospect. Geoscience study has been previously carried out. Here, additional field observation had been conducted which included geological observation and thermal manifestation. The still active Galunggung volcano potentially supplies the heat to the system according to the geology analysis and gravity data which needs to be confirmed by direct subsurface data. Only a small number of manifestations exist in this area. The situation differs significantly from the Karaha-Bodas field where the condition of manifestations is rather impressive. The manifestations are concentrated within the volcanic cone area, some are widely separated in the far southern area. The manifestations have quite distinct characteristics in both areas, where steam-heated springs with well-developed travertine deposits dominated the northern area manifestations, and peripheral chloride-bicarbonate springs with travertine deposits dominated the southern manifestations. The limited number of manifestations within the area makes it difficult to interpret the geohydrology and subsurface condition of the geothermal system. Additional extensive geophysics survey and analysis are needed up to the southern manifestation to accommodate unanswered questions of the extent of the system along with direct subsurface data afterward. The present study favors the possibility of clustered reservoir existing in the geothermal area with the heat source situated in Mt. Galunggung and possibly near the southern area, and outflow represented by the thermal manifestation existence both in the north and south.

1. INTRODUCTION

Galunggung volcano located mainly in Tasikmalaya, West Java, holds the potential for hosting geothermal prospect. According to Van Bemmelen (1949), Galunggung area is physiographically situated in the boundary between Quaternary Volcanoes Zone (northern side) and South Mountain Zone (southern side). The volcano itself is of Quaternary age and is still active.

To the north of Mt. Galunggung, Karaha-Bodas geothermal prospect with its impressive geothermal signature is already in the exploitation stage. Meanwhile, no further exploration and development process has been made in Galunggung prospect up until the present time. However, Galunggung prospect is already included in the potential list of National Electricity Business Plan (RUPTL) 2021-2030 and could serve as additional capacity for electricity support considering there is at least 290 MW of additional energy needed from geothermal plant in Jawa-Bali area (1949). Therefore, further study of this prospect is considered necessary, and any findings must be taken into account to understand the nature of the geothermal system in this area.

In this paper, a look back into the surface thermal manifestations in Galunggung prospect is done. Direct observation on the thermal manifestation was done to further confirm the manifestation observed in the previous study. Previous geochemistry study from open-source materials will also be incorporated here to understand the geochemical process that occurred in this field. Additional lithology and geological structure study were also done to comprehend the geological nature of the system.

2. PREVIOUS STUDY OF GALUNGGUNG GEOTHERMAL AREA

The geology of Galunggung volcano has been comprehensively explained in Bronto (1989) for both pre-1983 eruption and post-eruption. Though not specifically for geothermal exploration purposes, the study briefly mentioned the occurrence of thermal manifestation in the area.

Galunggung geothermal area has been previously explored by PT Energi Kinan Internasional (abbreviated into EKI for the next utterance) for preliminary survey according to the Decree of Minister of Energy and Mineral Resources No. 2491 K/30/MEM/2013 and currently is in Geothermal Working Area (GWA) tender stage. Through the survey, geoscience study comprised of surface geology, water geochemistry, soil geochemistry (Hg and CO_2), gravity, geomagnetic, and MT survey has been conducted. EKI highlighted the possibility of heat source/upflow coming from Mt. Galunggung or Mt. Kencana. Three separated clusters of reservoirs are identified in this conceptual model. The fluid is flowing to the south manifestation of Cigunung (ESDM, 2017). Similar interpretation is also expressed in Pratama, et al. (2015) where the latter modelled it into a 3D conceptual model. The conceptual model is presented in Figure 1.

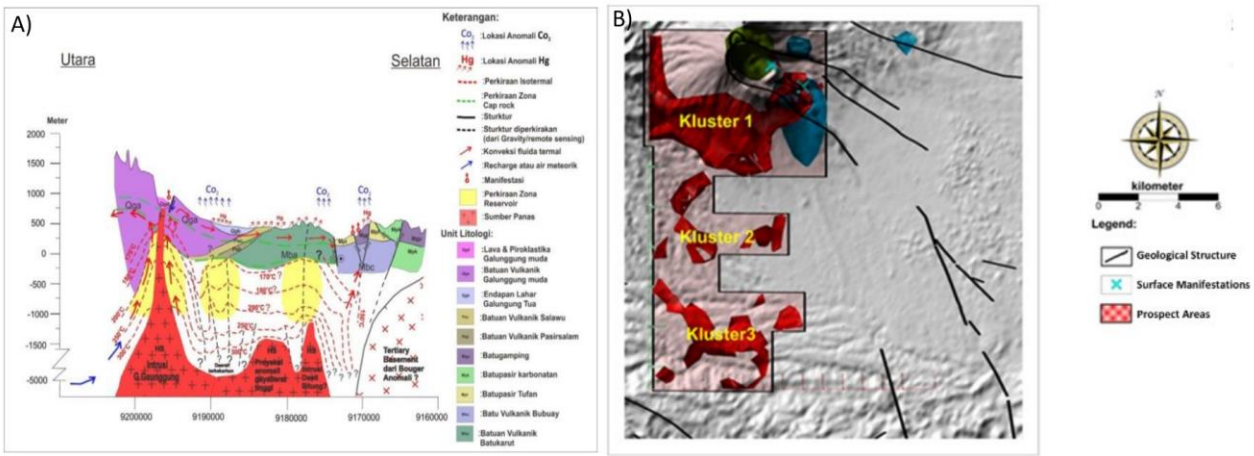


Figure 1: Conceptual model and resource area from PSPE study. A) Conceptual model in a cross section from north to south, showing three probable reservoir prospects (EKI, 2013 in ESDM, 2017). B) Three proposed prospect area in map view (Pratama, et al., 2015).

In Prabowo (2020), geophysics study through gravity analysis resulted in the interpretation of heat sourced from magma chamber of Mt. Galunggung and possibly connected to the heat source of Karaha-Bodas field in the north at about -3000 m depth (Figure 2). The subsurface geology interpretation in Figure 2 is very general because it only used the sampling density value of the closest field for reference, so the geology interpretation from EKI (2013) in ESDM (2017) is more considered. Normal fault is inferred in the summit area of Mt. Galunggung and possibly serves as a permeable pathway of the manifestation. The study also mentioned the possibility of manifestation in the southeast to be the outflow of the system.

Up to the present time, no exploration drilling activity has been conducted in Galunggung area. The interpretation of geothermal resources in this area is only dependent on geoscience data previously surveyed by EKI. In this paper, no well data has been added to the interpretation of the geothermal resource and the interpretation is also highly relied on geoscience data.

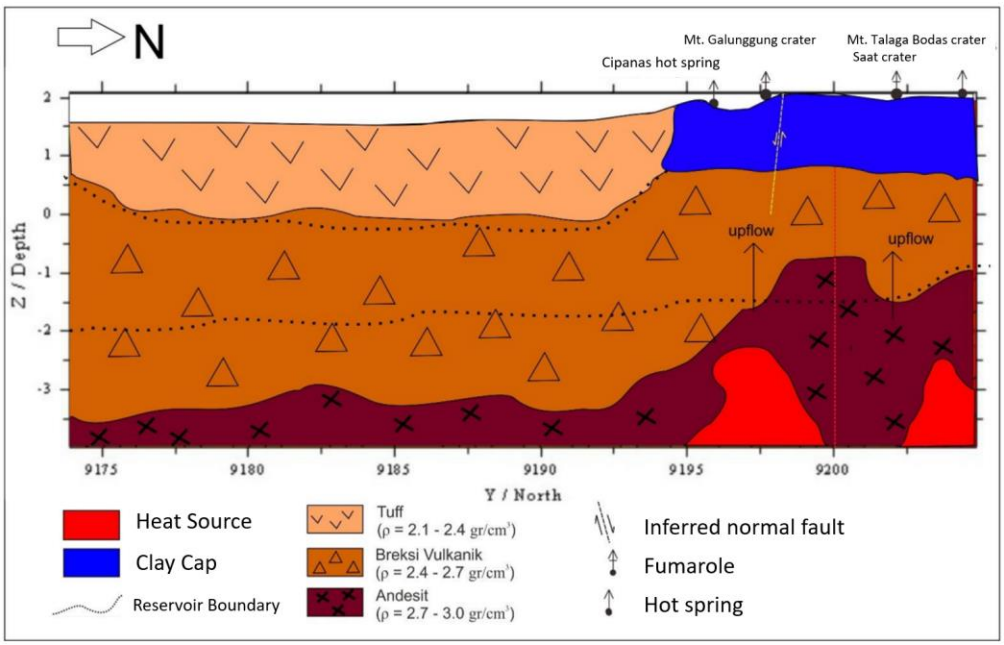


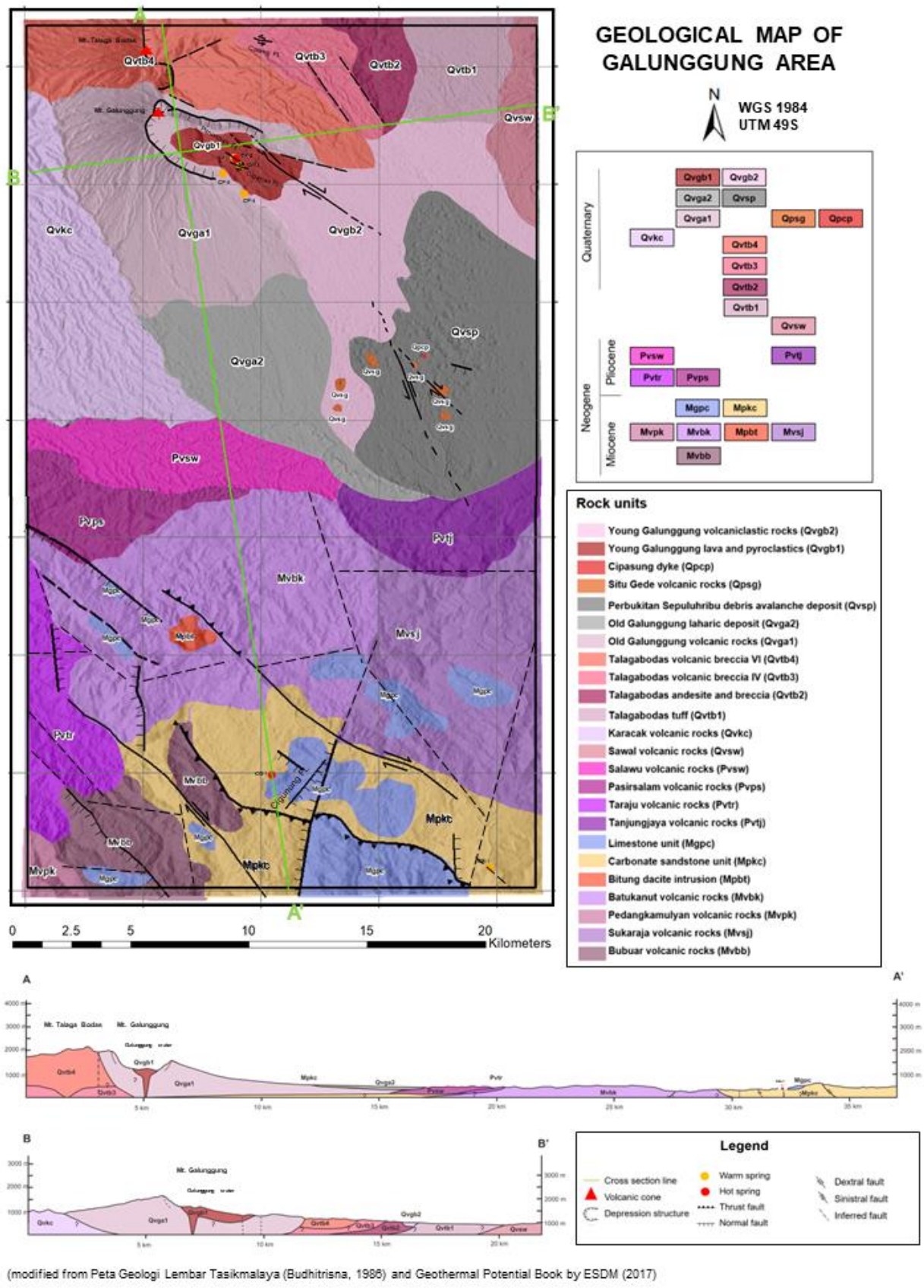
Figure 2: Geological model from gravity analysis in Prabowo (2020) showing a possibility of heat source connectivity between Galunggung area and Karaha-Bodas area at depth.

3. GEOTHERMAL SYSTEM OF GALUNGGUNG AREA

3.1 Geology of Galunggung Geothermal Area

The Galunggung area is predominantly composed of volcanic products with some distribution of sedimentary lithologies. Using DEM and ridge alignment, also highly referencing geological survey results in Pratama (2015) and EKI (2013) in ESDM (2017), volcanostratigraphy analysis according to Marti, et al. (2018) was done to delineate the geology of the Galunggung area which results in a total of 24 units presented in Figure 3. The 24 units are Bubuar volcanic rocks (Mvbb), Sukaraja volcanic rocks (Mvsj), Pedangkamulyan volcanic rocks (Mvpk), Batukanut volcanic rocks (Mvbk), Bitung dacite intrusion (Mpbt), carbonate sandstone unit (Mpkc), limestone unit (Mgpc), Tanjungjaya volcanic rocks (Pvtj), Taraju volcanic rocks (Pvtr), Pasirsalam volcanic rocks (Pvps), Salawu volcanic rocks (Pvsw), Sawal volcanic rocks (Qvsw), Karacak volcanic rocks (Qvkc), Talagabodas tuff (Qvtb1), Talagabodas andesite and breccia (Qvtb2), Talagabodas volcanic breccia IV (Qvtb3), Talagabodas volcanic breccia VI (Qvtb4), old Galunggung volcanic rocks (Qvga1), old Galunggung laharic deposit (Qvga2), Perbukitan Sepuluhribu debris avalanche deposit (Qvsp), Situ Gede volcanic rocks (Qpsg), Cipasung dyke (Qpcp), young Galunggung lava and pyroclastics (Qvgb1), and young Galunggung volcaniclastic rocks (Qvgb2) from the oldest to the youngest.

Figure 3 shows Geological map of Galunggung area modified from EKI (2013) in ESDM (2017). Some modifications that have been made include additional lineament analysis, confirmation of several faults through field survey, boundary of several geological unit, and cross section modification.



(modified from Peta Geologi Lembar Tasikmalaya (Budhitrisna, 1986) and Geothermal Potential Book by ESDM (2017)

Figure 3: Geological map of Galunggung area modified from EKI (2013) in ESDM (2017).

Lineament analysis was performed with context to the regional structural trends of the area. A high density of lineaments can be identified around the southern area where intense deformation seems to take place. It is hard to identify the lineament related to structural geology around Galunggung volcano as some lineaments are possibly related to lava ridge and younger deposits obscure the geologic structure traces. The contrast of lineament intensity coincides with the boundary between the two physiography zones previously mentioned. The lineament analysis, ground truthing, and literature study results are then incorporated into constructing a geological map in Figure 3. Both DEM-generated lineament and field measurements of structures display a similar trend of predominantly NW-SE pattern. Additionally, synthetic orientations of NNW-SSE and antithetic orientations, such as NE-SW, NNE-SSW, and N-S are also featured minorly in the lineament and structural data.

The reservoir of Galunggung prospect is predicted to be controlled by geological structure as well as lithological contact (EKI, 2013 in ESDM, 2017). Cipanas fault and Catang fault are two NW-SE oriented structures with oblique normal regimes according to field measurements. However, limited field measurements can be acquired in the field, thus a regional assessment was used as an approach to the regimes of fault orientations. The Meratus (NW-SE) and Indo-Australia (N-S) subduction events are the main tectonic events that form the regional structures in West Java. Fauzi, et al. (2015) identified surface compressional structures are mainly oriented NNE-SSW, while subsurface structures may vary between N-W, NE-SW, and N-S. A Riedel shear fault system model indicates the main NW-SE subsurface structure is the dextral primary deformation zone which induced the synthetic (R') NNW-SSE and antithetic (R') NNE-SSW structures on the surface (Figure 4). Therefore, NE-SW and NNE-SSW fault trends are more likely to provide secondary permeability.

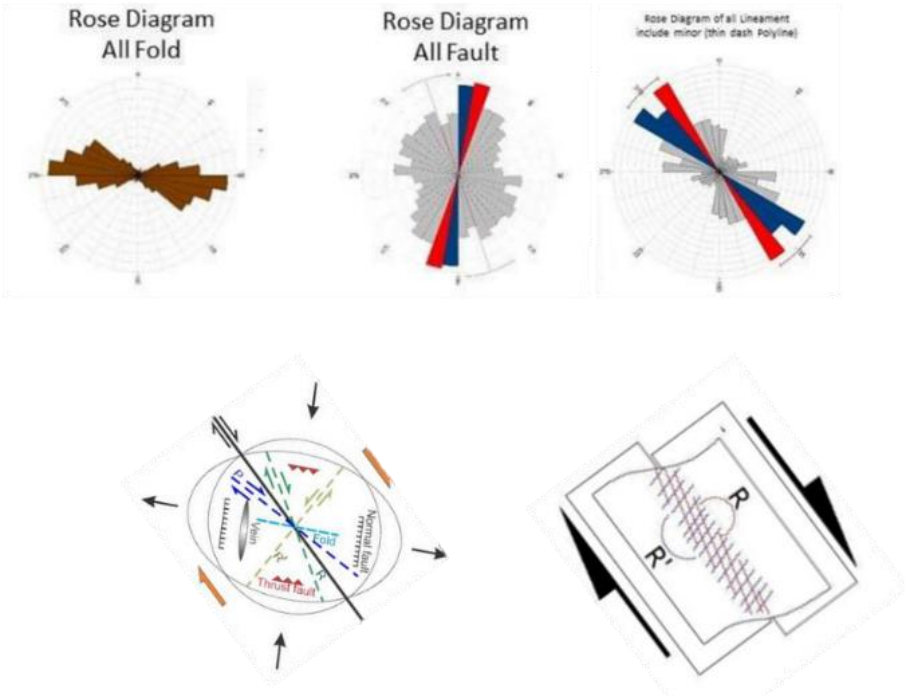


Figure 4: The rose diagram of surface-subsurface structures with a Riedel shear model that emphasizes the possible correlation between deep structures (NW-SE) with surface structure orientation that has NNE-SSW as the main orientation (modified from Fauzi et al., 2015).

The Galunggung volcano is located southeast of the Karaha-Bodas active geothermal field, evidence of the migration of volcanism from north to south. The Karaha-Bodas field also features similar structural trends of NW-SE and NNE-SSW, where NNE-SSW acting as permeability control as well as volcanic axis and intrusion pathway (Danakusumah & Suryantini, 2020). Whether the extent of the NNE-SSW reaches Galunggung further south is unclear as the recent deposit covers most of the surface outcropping of the structure. The interconnection between the hydrology is also unclear. However, the heat source

of the two systems is expected to be interconnected based on high-density anomaly under the Galunggung crater and Karaha-Bodas system in the three-dimensional gravity inversion model section profile of the two (Prabowo, 2020).

3.2 Thermal Manifestation of Galunggung Geothermal Area

Previous studies have mentioned several hot springs and warm springs manifested in Galunggung area. Field-checking result on the spatial distribution of thermal manifestations is concordant with previous studies. In general, thermal manifestation in Galunggung area consists of hot springs and warm springs with the distribution centered within Mt. Galunggung volcanic cone (northern area) also Cigunung and Cibalong area (southern area). The distance between manifestation in the northern area and the southern area is considered to be pretty far where it can reach about 25-30 km. All manifestations have a neutral pH (6-7) with temperatures ranging from 32℃ to 59℃ (Table 1).

Table 1: Encountered manifestations in Galunggung area with its temperature, pH level, identified deposits, and surrounding lithology.

Location	Code	T (℃)	pH	Deposit	Surrounding lithology
Northern, Mt. Galunggung	CP-1	32	6	Travertine nearby	Andesite lava, andesite lava breccia, pyroclastic deposit
	CP-2	59	6-7	Travertine along fluid path	Andesite lava, andesite lava breccia, pyroclastic deposit
	CP-3	41	7	Travertine in fault plane	Andesite lava, andesite lava breccia, pyroclastic deposit
	CP-4	50	7.5	Travertine terrace	Andesite lava, andesite lava breccia, pyroclastic deposit
	CP-5	39	7.8	Travertine along the fluid path	Andesite lava, andesite lava breccia, pyroclastic deposit
Southern, Cigunung	CG-1	55	7.5	Trace of travertine in the pool	Interbedded carbonate sandstone and siltstone with intercalation of limestone
Southeastern, Cibalong	CB-1	48	6	Travertine along the fluid path	Interbedded carbonate sandstone and siltstone with intercalation of limestone

Encountered manifestations in the northern area are mostly flowing through seepages of sloping land. The manifestations are situated inside Mt. Galunggung depression. The temperature varies from the lowest of 32℃ to the highest of 59℃. Well-developed travertine deposits are spotted in several springs as shown in Figure 5. Travertine was also identified at several spots near CP-1 and CP-2 without thermal spring spotted, indicating previous geothermal fluid activity nearby.

Figure 5: Several thermal springs in Mt. Galunggung (northern area). In CP-2, the travertine is formed along the main fluid pathway (A) and in the river lane (B). In CP-3 (C and D), fault with travertine deposit is identified. Terrace forming travertine is shown in E and F.

Manifestations in the southern area are only identified in Cigunung, 25 km to the south of Mt. Galunggung, and in Cibalong, about 30 km to the southeast. Manifestations in the southern area are mostly flowing vertically with gas discharge identified in the pool of both manifestations, though it is not too intense. Although not as well-developed as northern manifestations, traces of travertine deposits are also identified in both manifestations (Figure 4). Both Cigunung and Cibalong manifestations coincide with the identified lineament or fault as shown in Figure 3.

The thermal manifestation general distribution encountered at present is similar with the previous PSPE study, thus this paper will use previously conducted geochemistry analysis for subsurface study. According to the survey result of EKI in ESDM (2017) also Pratama, et al. (2015), thermal springs in northern area are categorized as neutral steam-heated water where the water is sourced mixing of condensed steam with meteoric water near surface. Travertine deposits developed around the manifestations show a strong influence of HCO_3 on the manifestation. Though having a higher ratio of SO_4/HCO_3 than southern manifestations, the northern manifestations might not directly indicate an upflow zone looking into the characteristic of the water (neutral pH, SO_4/Cl ratio is very high, no manifestations showing near boiling temperature). The upflow zone might be located in the crater area where it is closest to the eruption center of Mt. Galunggung, and where fumarole activity was previously reported in Bronto (1989). Additionally, isotope analysis ($\delta^{18}O$ and Deuterium) isotope analysis shows the fluid is derived from meteoric water without any mixing signature of magmatic input. Further, these manifestations are plotted as immature water, showing high input of Mg. The fluid possibly comes from steam-heated groundwater or water from condensed steam mixed with groundwater.

Figure 6: Thermal springs to the south of Mt. Galunggung: Cigunung (A and B) spring with its travertine deposit (gas discharge is not visible in the picture), and Cibalong spring with gas discharge shown in red dashed box.

The southern manifestations are categorized as peripheral water with higher Cl composition than northern manifestations, manifested as the result of lateral flow. The hot spring in Cigunung area has reached partial equilibrium state while the Cibalong spring is close to that state, indicating the possibility that the manifestation came from the reservoir and diluted with meteoric water. Similar with the northern manifestation, travertine is also deposited around the manifestation as a sign of strong HCO_3 production from rock-water interaction.

The lack of thermal manifestation in Galunggung area is contrasted with the condition of its neighboring Karaha-Bodas field where the spatial distribution of thermal manifestations and its characteristics are quite impressive. Therefore, it is hard to clearly determine the hydrology characteristics from geochemistry data and it needs to be assisted with other data, preferably direct subsurface data.

3.3 View on Geothermal System Condition in Galunggung Area

The geothermal system condition in Galunggung area still remains ambiguous. It is hard to conclude whether the area from Mt. Galunggung to Cigunung and Cibalong belongs to one extensive geothermal system or not. As for its connectivity to Karaha-Bodas field, it is possible to say they come from a different system separated by the inferred structure in between both fields. Their heat sources are possibly connected at depth (Prabowo, 2020). The heat source in Galunggung prospect itself very likely comes from the Quaternary Mt. Galunggung indicated by steam-heated water of the northern manifestation although it does not really represent the upflow characteristics of a common geothermal system.

Previous studies mentioned the existence of three clustered reservoirs primarily through the interpretation of 2D MT data with the upflow located in Mt. Galunggung. The MT survey coverage however does not reach the southern manifestations area. Furthermore, the published result does not really show the decency of the data, hence the hesitancy to rely on the MT data. Still, the published MT data is giving out the existence of conductive layer information which might indicate the existence of clay cap in this area. The hypothesis of clustered reservoirs is, however, reasonable considering the distance between one manifestation to others. Previous conceptual model mentioned the southern cluster to be the outflow of the system might correspond with the characteristics of thermal manifestations in the southern area which indicates an outflow characteristic. However, there is no geochemistry evidence of the northern and southern manifestations coming from the same reservoir. The Cl/B ratio shown in Pratama (2015) only indicates all manifestations in the northern area coming from the same source. Moreover, those manifestations do not exhibit acidic gaseous characteristics of the geothermal system upflow and might be considered to be manifested as nearby outflow as well. In the 3D gravity model of Prabowo (2020), high-density body is identified in Mt. Galunggung and several high-density bodies are also identified in the surrounding area, including to the south of Mt. Galunggung. Though the model does not reach the southern manifestations, it is possible that high-density body is also present near the area, supplying the heat to the fluid which later manifested in Cigunung and Cibalong through faults. Moreover, intrusion activity is also identified about 7 km in the northwest of Cigunung manifestation, indicating the possibility of intrusion activity significant to the southern manifestations. This analysis is still very much speculative, but additional MT surveys within this area might help to answer the subsurface condition between northern manifestations and southern manifestations.

The previous study used Na-K geothermometer and it showed an overestimation value due to samples categorized as immature water. The northern manifestations do show immature water chemistry in Na-K-Mg analysis (see section 3.2), hence the use of southern partially equilibrated manifestations is preferred for geothermometer calculation. Additionally, the existence of travertine around the manifestations shows high Ca^{2+} condition of the geothermal fluid under surface discharge conditions. This should be considered when estimating the reservoir temperature with a geothermometer to avoid falsely high-temperature estimation due to calcite precipitation affecting the calculation. The use of Na-K-Ca geothermometry method is preferred for this condition of the fluid with several factors to be considered. These new considerations to the manifestations and methods used for geothermometry calculations might yield different and more precise results to the real conditions of the reservoir.

4. CONCLUSION

At the moment, several preliminary geoscience studies have been conducted in Galunggung geothermal area. Surface geological study is looking robust already and needs to be confirmed with subsurface data. The lack of thermal manifestations within the area making it difficult to interpret the geohydrology and subsurface condition of the geothermal system. Although geophysics survey and analysis have been carried out, a more extensive additional survey is needed up to the southern manifestation to accommodate unanswered questions about the extent of the system. Direct subsurface data would also play a great part in assisting the interpretation if carried out. The present study favors the possibility of clustered reservoirs existing in the geothermal area with the heat source situated in Mt. Galunggung and possibly near the southern area, and outflow represented by the thermal manifestation existence both in the north and south.

REFERENCES

Bronto, S..: Volcanic Geology of Galunggung, West Java, Indonesia. University of Canterbury (1989).

Danakusumah, G. & Suryantini.: Integration of the Lineament Study in the Karaha-Bodas Geothermal Field, West Java. *IOP Conf. Series: Earth and Environmental Science*, 417, (2020).

ESDM: Potensi Panas Bumi Indonesia Jilid 1, **s.l.**: s.n. (2017).

Fauzi, A., Permana, H., Indarto, S. & Gaffar, E. Z.: Regional Structure Control on Geothermal Systems in West Java, Indonesia. *Proceedings World Geothermal Congress 2015* (2015).

Marti, J., Groppelli, G. & da Silveira, A.: Volcanic stratigraphy: A review. *Journal of Volcanology and Geothermal Research*, 357, (2018), 68-91.

PLN: Rencana Usaha Penyediaan Tenaga Listrik (RUPTL) 2021-2030, s.l.: s.n (2021).

Prabowo, L. A.: Identifikasi Struktur Permeabel dan Sumber Panas di Wilayah Kerja Panas Bumi Gunung Galunggung dan Konektivitas Sumber Panasnya Terhadap WKP Karaha-Cakrabuana dengan Menggunakan Data Gravitasi, s.l.: Universitas Gadjah Mada (2020).

Pratama, A. B., Srigutomo, W. & Suryantini.: 3D Conceptual Modeling Based on Geophysical and Geological Information for Targeting Geothermal Prospect Area in Hidden Geothermal System. *Proceedings*, 40th Workshop on Geothermal Reservoir Engineering (2015).

Van Bemmelen, R. W.: The Geology of Indonesia. The Hague: Government Printing Office (1949).

Geothermal Manifestation Identification using Multispectral UAV

Firmansyah Maulana Azhali[1], Mauliate Agustinus Sihotang[2], Indra Agoes Nugroho[2], Herwin Azis[2], and Agung Budi Cahyono[3]

[1]Terra Drone Indonesia, Bandung, Indonesia
[2]Supreme Energy Muara Laboh, Jakarta, Indonesia
[3]Institut Teknologi Sepuluh Nopember, Surabaya, Indonesia

firmansyah@terra-drone.co.id

Keywords: Geothermal Manifestation, UAV, Multispectral Sensor, Weighted Overlay

ABSTRACT

Identifying geothermal manifestations is very important for exploring and developing geothermal energy sources. Especially in Indonesia which has a wealth of natural resources ranging from water, sea, land, and geothermal energy. Traditional mapping methods for geothermal exploration are time-consuming, expensive, lower resolution, and may have limitations in identifying surface manifestations. In recent years, unmanned aerial vehicles (UAVs) and multispectral sensors have become promising tools for geothermal exploration. This study presents the use of UAVs equipped with multispectral sensors to identify the characteristics of geothermal manifestations and then use these characteristics to determine other potential geothermal manifestations around the site. The study area is located in Muara Laboh geothermal field, West Sumatra, Indonesia. The UAV was flown at a low altitude to capture high-resolution multispectral images of the study area. Images are processed using a variety of image processing techniques to create digital terrain models, including single-band orthomosaics and multispectral index orthomosaics such as NDVI, NDRE, OSAVI, Iron Oxide, and Land Surface Emissivity. To identify the characteristics of geothermal manifestations, there are nine geothermal manifestations around the site area, but only three will be used to identify geothermal characteristics, and the rest will be used to check the accuracy of the model. The analysis used to identify potential geothermal manifestations is weighted overlay analysis. The method used is to assign a value, weight, or score to the multispectral index raster that has been classified, all these rasters will be combined with their weight values to produce a distribution of potential manifestation locations. The classification used for weighting is divided into 5 classes: vegetation index, mineral index, emissivity, terrain, and true color composite. The results showed that the two potential geothermal manifestation areas have characteristics similar to the existing ones. Based on the accuracy test, five existing geothermal manifestations can be detected using the model, and the rest cannot be detected using the model because some of the locations of the existing geothermal manifestations are covered by vegetation. This study provides important insights into the use of UAVs and multispectral sensors for geothermal exploration, which can significantly reduce exploration time and costs while increasing the accuracy and reliability of geothermal resource identification.

1. INTRODUCTION

Geothermal energy is a renewable resource that derives its heat from the earth [1]. The world's largest producer of geothermal energy is Indonesia. This is demonstrated by the fact that 13% of all volcanoes in the globe are located in Indonesia, with an estimated 80% of them having the capacity to produce geothermal energy. According to estimates, Indonesia has 28.617 terawatt-hours of geothermal energy potential or nearly 40% of the global total [2]. Geothermal energy has excellent potential for future development and is a renewable source of energy. An environmentally preferable and perhaps superior replacement for fossil fuels is geothermal energy [3].

In Indonesia, there are about 265 geothermal areas that are currently in operation, with 138 of those locations (52.07%) still in the preliminary investigation stage to inventory their potential resource class and 24 other locations (9.05%) still in the introduction investigation stage to the potential of the resource

class hypothetical. With a total installed capacity of 1189 MW, just seven geothermal facilities, or 2.64%, are actively used to generate power.

The local community frequently uses undeveloped geothermal sites for tourism, heating, mushroom cultivation, fertilizer production, agriculture, and fish farming. However, geothermal energy hasn't generally been produced for direct usage in Indonesia [4].

This work focuses on using multispectral sensors to image surface geothermal manifestations and identify their properties. To finish this project, the Birdie Terra Wing UAV is equipped with two interchangeable camera sensors: the Micasense RedEdge-M for multispectral data collection and the Sony Alpha 6000 for RGB image data collection.

It is feasible to recognize the traits of the ground and vegetation conditions surrounding geothermal manifestations using the method for processing the spatial resolution of the sensors described below utilizing multispectral images. High-resolution RGB cameras mounted on UAVs can more precisely visualize the topographical situation in addition to multispectral sensors.

UAV image acquisition is becoming more and more important around the world right now. In this work, the researcher uses the UAV to collect multispectral and RGB data in a portion of the study region. In this study, a multispectral camera is used to identify the geothermal manifestations condition based on the vegetation condition surrounding the manifestation area, as opposed to some researchers who used thermal imaging to identify the geothermal manifestations condition by monitoring the hydrothermal and geothermal vegetation growing conditions [5].

Table 1: Type of aerial imagery and their use for vegetation monitoring.

Type of Aerial Imagery	Use in Vegetation Monitoring
Color Aerial Photo	Long-term vegetation change
Near-Infrared Imagery	Monitoring vegetation condition and phenology
Thermal Infrared Imagery	Monitoring hydrothermal and geothermal vegetation growing conditions
LiDAR	3-D information regarding vegetation structure

This study aims to determine the characteristics of geothermal manifestations using RGB and multispectral imagery. In addition, this study aims to find the location of other geothermal manifestations that have similar characteristics to the existing geothermal manifestations. This research can be used as a reference to help geothermal-based companies to explore new geothermal manifestations around their work areas.

2. MATERIAL AND METHODS

2.1. Study Area

The area photo mapping location or referred to as Area of Interest (AOI) is in Padang, West Sumatera. The area to be mapped using a multispectral camera and RGB camera is ± 3900.

The orthophoto mosaic obtained from RGB camera data acquisition has a spatial resolution (GSD) of 5 cm/pix and 13 cm/pix for multispectral data. The geometric correction that is used to correct the position of the RGB orthophoto mosaic is post-processing kinematic with additional 7 GCPs used to enhance the accuracy of orthophoto mosaic, while multispectral orthophoto mosaic use orthorectifies to the corrected RGB orthophoto mosaic. To calculate the accuracy of the orthophoto mosaic model and digital field, 3 points are pre-marked and measured using Trimble R8s for later use as ICP

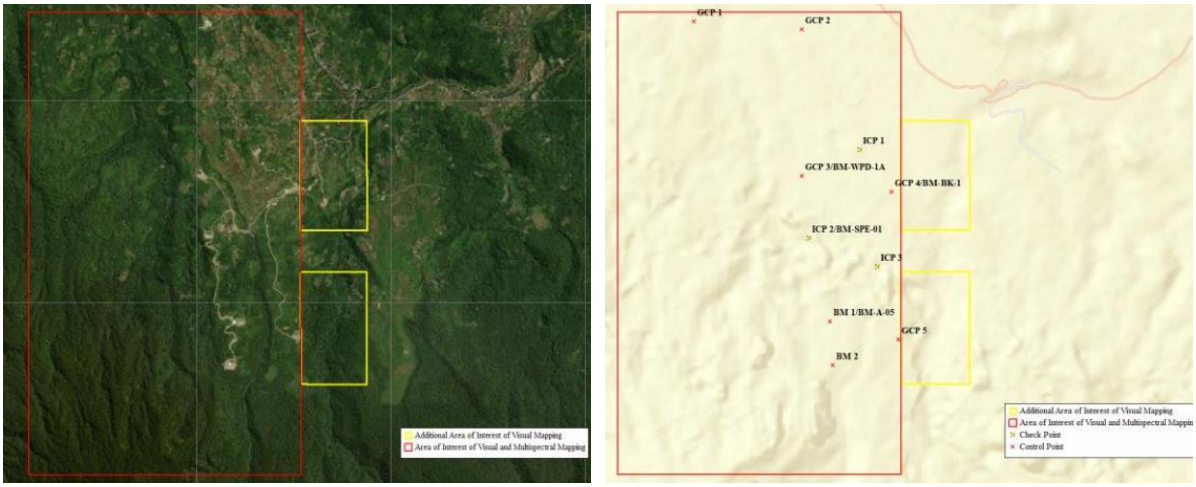


Figure 1: The research area of interest (left) and distribution of ground control point and independent checkpoint (right).

2.2. Data Acquisition

To analyze the geothermal features at Muara Laboh manifestation, the researchers used UAVs that carry RGB and multispectral camera sensors. The drone used in this study is a Birdie Terra Wing UAV with a weight of 2.5 kg and a coverage range of up to 4 km and a maximum flight time of 30 minutes per battery. It is equipped with an RGB Camera of Sony Alpha 6000 with a 24-megapixel resolution capable of taking photos and videos. Each image is tagged with a GPS, which provides information such as its latitude and longitude as well as the altitude at which it was taken. This GPS allows us to process the data in post-processing kinematic mode.

To obtain multispectral data, the Micasense RedEdge-M camera was integrated into Birdie Terra Wing UAV with multiple sensors to capture data in various spectral bands simultaneously. The RedEdge-M captures data in five spectral bands such as blue, green, red, red-edge, and near-infrared. Each band has its own dedicated sensor. The resolution and wavelength (nm) for each of these sensors are as follows:

Table 2: Sensor center wavelength and resolution

Bands	Center Wavelength	Sensor Resolution
Blue	475 nm ± 20 nm	1280 x 960 pix
Green	560 nm ± 20 nm	1280 x 960 pix
Red	668 nm ± 10 nm	1280 x 960 pix
Red Edge	717 nm ± 10 nm	1280 x 960 pix
Near-Infrared	840 nm ± 40 nm	1280 x 960 pix

Micasense RedEdge-M can capture multispectral images with a resolution of 8.2 cm/pixel (per band) at 120 m AGL. Multispectral data from Micasense RedEdge-M was used to calculate several multispectral indices such as the Normalized Difference Vegetation Index (NDVI), Normalized Difference RedEdge Index (NDRE), Optimized Soil Adjusted Vegetation Index (OSAVI), Soil Adjusted Vegetation Index (SAVI), Land Surface Emissivity Index (LSE), Iron Oxide Index.

2.3. Vegetation Index

Normalized Difference Vegetation Index (NDVI) is a multispectral index that can be used to identify the vegetation condition by reviewing the greenness level or chlorophyll content. NDVI is a mathematical combination between the red band and the near-infrared band. The NDVI calculation basically has the principle that green plants grow more effectively by absorbing radiation from visible light (PAR or Photosynthetically Active Radiation), which green plants reflect with strong infrared radiation [6]. This equation is commonly used for satellite image data as shown in Eq. (1):

$$NDVI = (\rho NIR - \rho RED) \; / \; \rho NIR + \rho RED) \quad (1)$$

Where ρNIR is the reflectance of the near-infrared band and ρRED is the reflectance of the red band. The Normalized Difference Vegetation Index (NDVI) has a value range of -1 to 1 where the higher the value of the vegetation index, the higher the chlorophyll level in vegetation. Besides identifying the leaf condition based on chlorophyll level, the Normalized Difference RedEdge Index (NDRE) was used to identify the leaf variability. This equation is only possible if the red edge band is available in its sensors. NDRE has a similar concept to NDVI, but NDRE can identify the leaf condition more clearly. This is because chlorophyll has maximum absorption in the red band and therefore red light is not able to penetrate too far through the layers of the leaf. On the other hand, light in the red edge (RE) and green bands can penetrate the leaves deeper than the red and blue bands, so the red edge band will be more sensitive to moderate to high levels of chlorophyll [7], which can be expressed mathematically in Eq. (2):

$$NDRE = (\rho NIR - \rho RED\ EDGE) \ / \ (\rho NIR + \rho RED\ EDGE\ ) \quad (2)$$

Where ρNIR is the reflectance of the near-infrared band and $\rho RED\ EDGE$ is the reflectance of the red edge band. The Normalized Difference Red Edge Index (NDRE) also has a value range of -1 to 1 where the higher the value of the vegetation index, the higher the chlorophyll level in vegetation.

Optimized Soil Adjusted Vegetation Index (OSAVI) is an optional equation that can be used to identify the chlorophyll content of the leaf. This index is best used in areas with relatively sparse vegetation where the soil is visible through the canopy and where the NDVI is Saturated (high plant density). OSAVI is a special case of the Soil Adjusted Vegetation Index (SAVI). OSAVI is developed by Rondeau et al in 1996 using reflectance of the near-infrared band and a red band with a soil adjustment coefficient of 016. Like the normalized difference index, OSAVI values can range from -1 to 1. High OSAVI values indicate denser and healthier vegetation while lower values indicate lower vigor [8]. Based on this concept, a mathematical model is created as shown in Eq. (3):

$$OSAVI = (\ 1.5\ x\ (\rho NIR - \rho RED)) \ / \ (\rho NIR + \rho RED + 0.5) \quad (3)$$

Where ρNIR is the reflectance of the near-infrared band and ρRED is the reflectance of the red band. In addition to calculating vegetation that shows stress due to temperature anomalies in geothermal areas, the NDVI value is needed to calculate the proportion of vegetation (PV), defined as the ratio of the vertical projection over the vegetation canopy in each pixel as follows in Eq (4):

$$Pv = ((\ NDVI - NDVIs) \ / \ (NDVIv - NDVIs))^2 \quad (4)$$

Where NDVIs is response value on vacant land, and NDVIv is response value on the densely-vegetated area. Then from the data of vegetation propagation, the parameter of land surface emissivity (LSE) is calculated, which is the ratio of radiation energy emitted by the ground surface to radiation emitted by black bodies at the same temperature. Meanwhile, according to Sobrino & Raissouni (2000), the NDVIs coefficient has a value of 0.2 and the NDVIv coefficient has a value of 0.5[9]. Orthophoto mosaic Pv is then used to calculate LSE, which can be expressed mathematically in Eq (5):

$$LSE\ (\varepsilon\lambda) = \varepsilon v\lambda\ Pv\ \varepsilon s\lambda(1 - Pv) + C\lambda \quad (5)$$

Where $\varepsilon v\lambda$ is the emissivity of vegetation object, $\varepsilon s\lambda$ is emissivity of soil object, and $C\lambda$ is 0.005 (constant). Emissivity value of the

soil pixel (NDVI < NDVIs) is 0.96 (Pv = 0 and $C\lambda$ = 0, so $\varepsilon\lambda = \varepsilon s\lambda$ = 0.96) and the emissivity value of the vegetation object (NDVI > NDVIv) is 0.99 (Pv = 1 and $C\lambda$ = 0.005, so $\varepsilon\lambda = \varepsilon v\lambda + C\lambda$ = 0.99). Multispectral data also can be used to identify mineral resources such as clay and iron oxide.

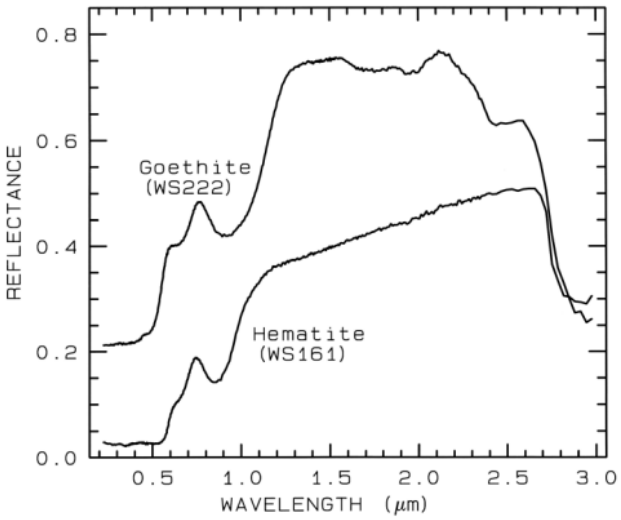


Figure 2: Spectral features of iron oxide.

Figure 2 shows the reflectance spectral for iron oxide (goethite and hematite). The vertical axis shows the percentage of indecent sunlight reflected by the materials. The horizontal axis shows wavelengths of energy for the visible spectral region (0.45 to 0.52 nm) and the reflected portion (0.63 to 0.69 nm) of the infrared region. Reflected infrared energy consists largely of solar energy reflected from the earth at wavelengths longer than the sensitivity range of the eye. The spectral reflectance curve shows that the maximum reflectance of iron oxide occurs in the red band and that the reflectance is considerably lower in the blue band. The method that can be used to calculate the ratio of the red band and the blue band is the band ratio. Band ratio is a technique that has been used for many years in remote sensing to display spectral variations effectively. It is based on highlighting the spectral differences that are unique to the materials being mapped. Based on this concept, a mathematical model is created as shown in Eq. (6):

$$Iron\ Oxide\ Index\ I = (\ \rho RED\ /\ \rho BLUE) \quad (6)$$

Where ρRED is the reflectance of the red band and $\rho BLUE$ is the reflectance of the blue band. In addition to gathering a better view of iron oxide variability, the green band was used to substitute the blue band from Eq. (6). This is because the green band has a little higher reflectance rather than the blue band. Based on this concept, a mathematical model is created as shown in Eq. (7):

$$Iron\ Oxide\ Index\ II = (\ \rho RED\ /\ \rho GREEN) \quad (7)$$

Where ρRED is the reflectance of the red band and $\rho Green$ is the reflectance of the green band.

3. RESULT AND DISCUSSIONS

3.1. Orthophoto Mosaic Results

The orthophoto results obtained from RGB data acquisition has a spatial resolution (GSD) of ± 5 cm/pix and the orthophoto result from Multispectral data has a spatial resolution (GSD) of 13 cm/pix. Data generated from the Micasense RedEdge-M is classified into 3 types of classification based on the object identification, which are:

1. Band Composite Classification
    a. True Color Composite
2. Vegetation Index Classification
    a. Normalized Difference Vegetation Index (NDVI)
    b. Normalized Difference Red Edge Index (NDRE)

c. Optimized Soil Adjusted Vegetation Index (OSAVI)

d. Land Surface Emissivity (LSE)

3. Mineral Resource Index Classification

a. Iron Oxide I Index

b. Iron Oxide II Index

The following are orthophoto results of RGB map and multispectral map that obtained from data processing.

Figure 3: RGB map (left) and True Color Composite map (right).

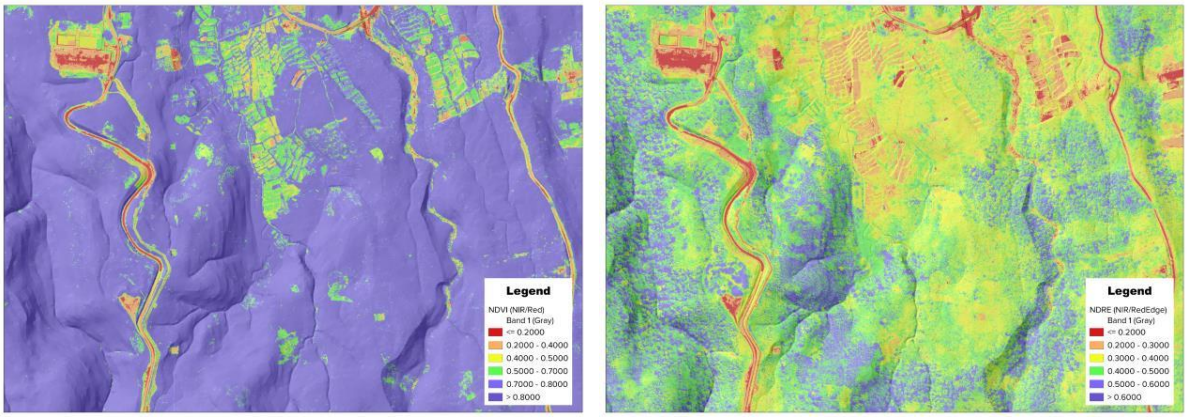


Figure 4: Normalized Difference Vegetation Index map (left) and Normalized Difference RedEdge map (right).

Figure 4 shows that the normalized difference vegetation index is classified into 6 class which is: less than 0.2, 0.2 to 0.4, 0.4 to 0.5, 0.5 to 0.7, 0.7 to 0.8, and more than 0.8. The majority of the area has an NDVI value of 0.83, which means some of the vegetation areas have a good chlorophyll content. The normalized difference red edge index as shown in Figure 8b has a less vegetation index value than the normalized difference vegetation index. The normalized difference red edge index has an average index value of 0.45 which means some of the vegetation areas still has a good chlorophyll content.

The optimized soil adjusted vegetation index has a similar result to the NDVI orthophoto mosaic which has an average vegetation index value of 0.83. The land surface emissivity is used to define the emissivity of an object above the surface. The land surface emissivity found some anomalies, which is there are some areas that has more than one emissivity value where the maximum emissivity value of an object is one. These anomalies usually happen when a noise such as a hole in the false color multispectral image. The land surface emissivity map shows that the majority of the area has an emissivity value of 0.99 and the minimum emissivity value of 0.986.

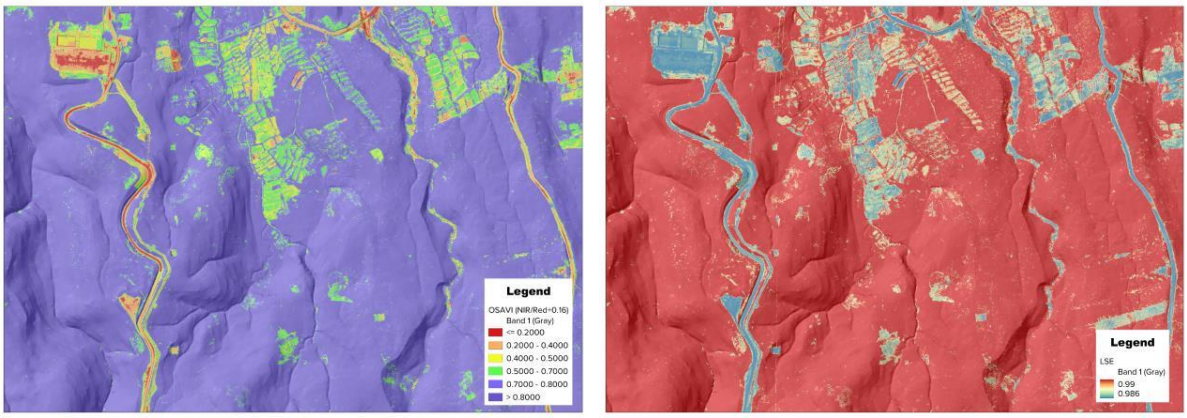


Figure 5: Optimized Soil Adjusted Vegetation Index map (left) and Land Surface Emissivity map (right).

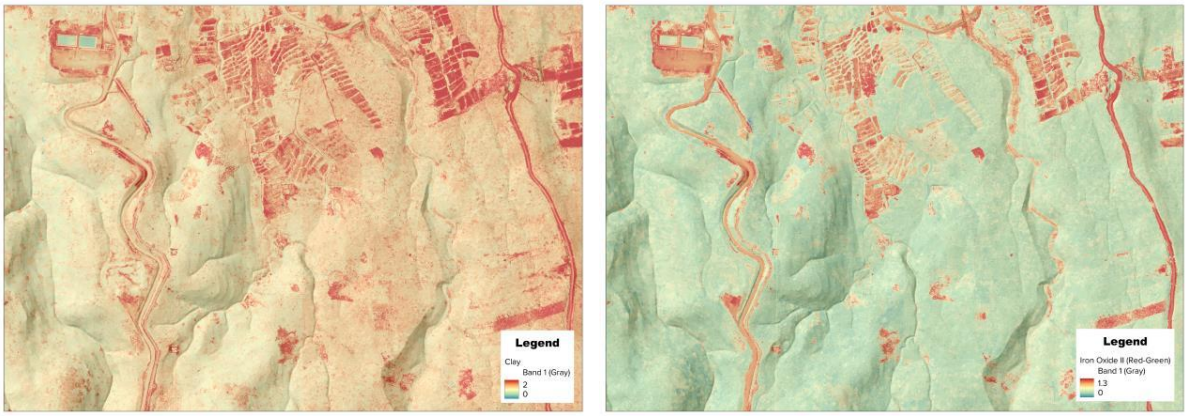


Figure 6: Iron Oxide I map (left) and Iron Oxide II map (right).

3.2. Manifestation Geothermal Identification

In this study, multispectral data was used to create the Normalized Difference Vegetation Index (NDVI), Normalized Difference Red Edge (NDRE) index, and Optimized Soil Adjusted Vegetation Index (OSAVI). The index is useful for knowing the level of chlorophyll or the greenness of the leaves of vegetation. NDVI utilizes the red (R) and near-infrared (NIR) channels because green objects (vegetation) reflect NIR electromagnetic waves well. Meanwhile, NDRE utilizes the near red channel (RedEdge) and NIR as a formula to obtain information on the chlorophyll content of vegetation. NDRE is considered better than NDVI because the RedEdge channel has a longer wavelength than the R channel so chlorophyll variations will be more visible using NDRE than using NDVI. OSAVI utilizes the red (R) and near-infrared (NIR) channels as with NDVI, but sometimes the condition of the NDVI index experiences a saturation period so that the vegetation index on the soil features around the plant becomes high. In an effort to mitigate this condition, OSAVI is also prepared as the output of this work.

Identification of geothermal manifestations condition was conducted to determine the conditions around the geothermal manifestation area using multispectral index data. The conditions that want to be known are the effect of geothermal steam on vegetation conditions around the manifestation area, soil conditions around the manifestation area, and predicting the location of geothermal manifestations using parameters similar to the current geothermal manifestation area.

The number of samples that want to be analyzed for the condition of the vegetation index is 8 samples with specifications of 4 samples at the location of the soil around the manifestation and 4 samples on vegetation exposed to hot steam. The following is the result of the identification of multispectral conditions at the location of IM manifestations.

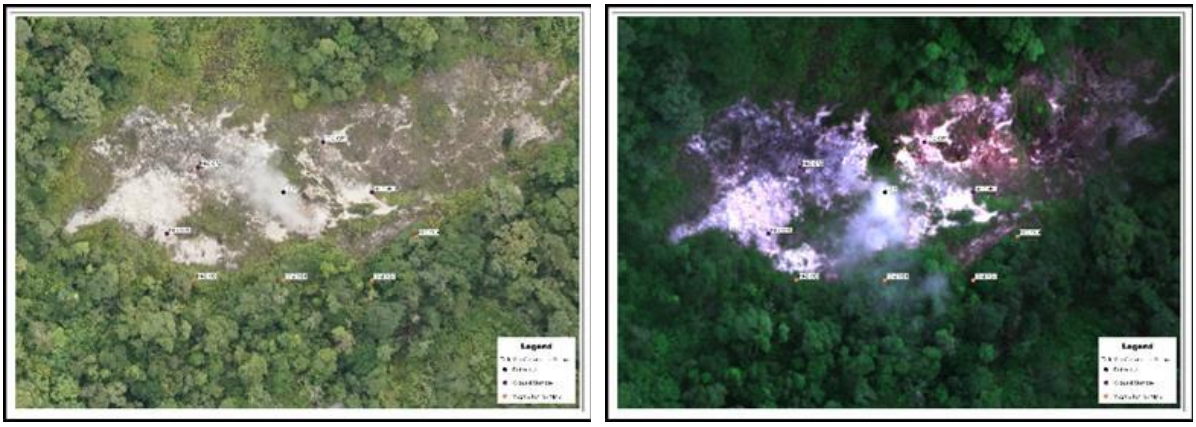


Figure 7: Sample distribution on IM manifestations shown on RGB map (left) and true color composite map (right).

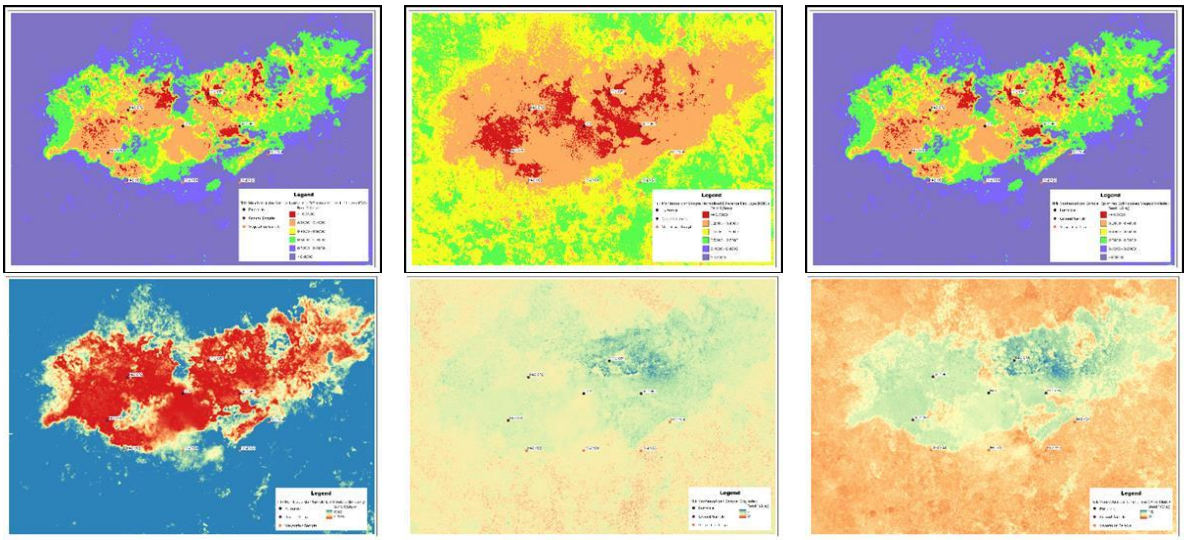


Figure 8: Sample distribution on IM IM-2 manifestations shown on NDVI map (a), NDRE map (b), OSAVI map (c) and LSE map (d), Iron Oxide I map (e), Iron Oxide map (f).

Figure 8a-c show that the value of the vegetation index at the manifestation point has very low value. This is because the object identified at the point of manifestation is hot steam coming out of the ground. In addition, there is a pattern that is always the same in the three samples of the identified manifestation points, namely the vegetation index value from the manifestation point to the nearest vegetation has a low index value. This is because there is empty land around the manifestation point. It is possible that the soil around the manifestation has a higher temperature than other areas, causing plants to not grow around the manifestation point. However, to support this statement, field checks are needed around the point of manifestation. Figure 8d-e show that both mineral index equations have high values in the manifestation area. Iron oxide II is able to distinguish objects of soil, vegetation, and point of manifestation in contrast. The hypothesis drawn from this analysis is that the green band is more sensitive to identifying artificial/mineral objects than the Near Infrared (NIR) and blue bands. Figure 8f show that the emissivity value around the manifestation point has a shallow value. This is because the point of manifestation object and the ground are able to reflect light better than the vegetation object.

3.3. Correlation Test

A correlation test was conducted to determine the correlation of vegetation and mineral indices at the location of geothermal manifestations. This is done to look for potential locations for other geothermal manifestations around the area where geothermal manifestations are located. In this study, 27 samples were used which were obtained at 3 manifestation locations where 1 sample was at the manifestation point, 4 samples were on the soil around the manifestation and 4 samples were in the vegetation around the manifestation. Because the number of samples is 27, the R-value of the product moment for sample

27 (f=27) is 0.381. This value is used as a reference for the lower limit of the strength of the relationship between variables. Meanwhile, to determine the significance between variables if the probability value of the relationship between variables is less than 0.05 (<0.05). The results of the correlation test are then presented in the form of a table to make it easier to find out the relationship between variables.

Table 3: Correlation Result.

No.	Correlation	Correlation Coef.	R Product Moment (f = 27)	Probability Value
1	NDRE-NDVI	0.796	0.381	0.0000 < 0.05
2	NDRE-OSAVI	0.796	0.381	0.0000 < 0.05
3	NDRE-Iron Oxide I	-0.304	0.381	0.1226 > 0.05
4	NDRE-Iron Oxide II	-0.438	0.381	0.0222 < 0.05
5	NDRE-LSE	0.641	0.381	0.0003 < 0.05
6	NDVI-OSAVI	1.000	0.381	0.0000 < 0.05
7	NDVI-Iron Oxide I	-0.050	0.381	0.8058 > 0.05
8	NDVI-Iron Oxide II	-0.845	0.381	0.0000 < 0.05
9	NDVI-LSE	0.916	0.381	0.0000 < 0.05
10	OSAVI-Iron Oxide	-0.050	0.381	0.8059 > 0.05
11	OSAVI-Iron Oxide II	-0.845	0.381	0.0000 < 0.05
12	OSAVI-LSE	0.916	0.381	0.0000 < 0.05
13	Iron Oxide I-Iron Oxide II	0.080	0.381	0.6922 > 0.05
14	Iron Oxide I-LSE	-0.616	0.381	0.0006 < 0.05
15	Iron Oxide II-LSE	-0.904	0.381	0.0000 < 0.05

From the table above, it can be seen that several variables have a good linear correlation because the bands used are still similar (NIR/RE/RE) such as NDVI, NDRE, OSAVI, LSE and Iron Oxide I & II. For other variables that do not have A good linear correlation means that the sample taken to determine the relationship between variables is lacking, or the relationship between variables is not linear.

3.4. Weighted Overlay Model

Weighted overlay analysis was conducted to identify potential locations as manifestations based on the characteristics of the multispectral index at the known manifestation locations. This analysis was carried out using ArcGIS software. The method used is to assign a value/weight/score to the classified multispectral index raster, then all the rasters will be combined with their weight values so as to produce a distribution of potential manifestation locations.

The percent influence value or the amount of weight to be given is uneven where the four parameters of vegetation indices, mineral indices, emissivity indices, and terrain indices have the same weight portion of 13.33% while the TCC index has the largest weight of 50%. The determination of this weight is based on the presence of steam at the mandatory manifestation point so that only the blue band false color index is able to properly describe the vapor. Another alternative is if there is thermal infrared index data (TIR), then the TCC index is no longer needed.

Figure 9 describes the results of the orthophoto mosaic from the weighted overlay analysis. From these results, there are 4 class categories, namely high potential, moderate potential, low potential, and non-manifestation.

Table 4: Percent influence value.

Classification	Purpose	Multispectral Indices	Percent Influence
Vegetation Indices	to define vegetation condition around manifestation area	NDRE, NDVI, OSAVI	13.33%
Mineral Indices	to define mineral condition around manifestation area	Iron Oxide I and II	13.34%
Emissivity	to define surface emissivity condition around manifestation area	Land Surface Emissivity	13.33%
True Color Composite (RGB)	to define steam around manifestation area	Blue Band	50.00%
		Total	100.00%

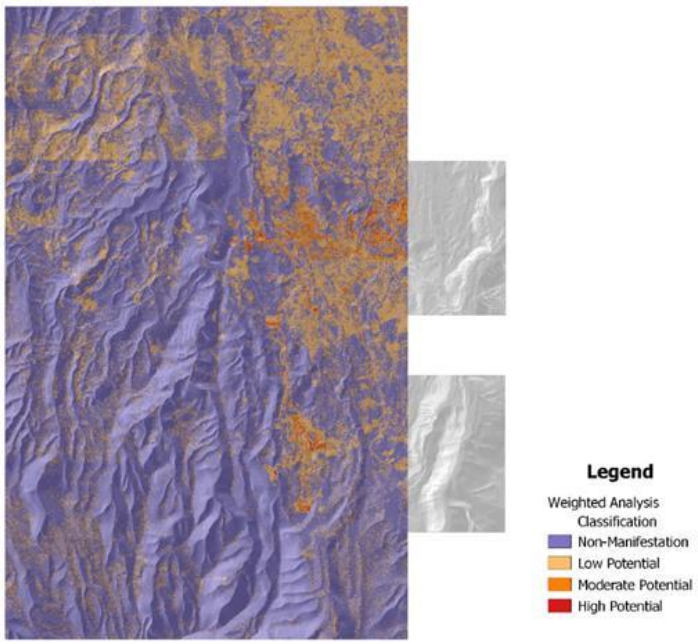


Figure 9: Manifestation model map.

3.5. Validity Test

To test the validity of the identification results, another manifestation point is were used as a reference for the location of the geothermal manifestation area. The following are the results of the validity test on all samples of manifestation points at the Muara Laboh site:

Table 5: Validity test on all samples of manifestation at Muara Laboh site.

No	Code	Type	Detection Result	Remark
1	RT-D	Hot spring	Not detected	Under vegetation
2	SMA	Hot spring	Detected	High potential
3	SMA-F	Streaming ground	Detected	High potential
4	BK	Hot spring	Detected	Moderate potential
5	PK	Hot spring	Not detected	No manifestation pattern
6	BKH	Hot spring	Not detected	Under vegetation
7	IM	Fumarole	Detected	High potential
8	IM-A	Steaming ground	Not detected	No manifestation pattern
9	IM-B	Hot spring	Detected	High potential

4. CONCLUSION

Drone technology has proven to be a relevant tool to provide data and information to identify manifestation conditions and characteristics. The analysis carried out aims to identify the spectral characteristics in the manifestation area using a multispectral camera sensor so that with the same idea it can be used to detect the location of other potential manifestations at the muara laboh site. The multispectral indexes used such as NDVI, NDRE, OSAVI, Iron Oxide Index, Land Surface Emissivity, Slope map, and blue band false color. The manifestation points used as reference or control points for this analysis are the IM manifestation points and SM. The correlation test method used is Pearson Correlation because it can be used to determine whether there is a relationship between 2 variables. From the results of the correlation test, it can be concluded that 53% of the variables have a positive correlation while 47% of the variables have a negative correlation.

REFERENCES

Bina, S. M., Jalilinasrabady, S., Fujiii, H., & Pambudi, N. A. (2018, October). Classification of geothermal resources in Indonesia by applying exergy concept. *Renewable and Sustainable Energy Reviews*, 93(ISSN 1364-0321), 499-506. https://doi.org/10.1016/j.rser.2018.05.018

Boriarskii, B., & Hideo, H. (2019). Comparison of NDVI and NDRE Indices to Detect Differences in Vegetation and Chlorophyll Content. *International Conference on Applied Science, Technology and Engineering J. Mech. Cont. Math. Sci., Special Issue*, 4, 20-29. https://doi.org/10.26782/jmcms.spl.4/2019.11.00003

Indriawati, J. K. (2012). Prediksi Daya Listrik Geothermal Power Plant Berdasarkan Metode Weighted Moving Average. *Jurnal Teknis POMITS*, 1(1), 1-6.

Jose, S., & Juan, J. C. (2010). A Single-Channel Algorithm for Land-Surface Temperature Retrieval from ASTER Data. *IEEE Geoscience and Remote Sensing Letters*, 7(1), 176-179. http://dx.doi.org/10.1109/LGRS.2009.2029534

Maryanto, S., Dewi, C. N., Syahra, V., Rachmansyah, A., Foster, J., Nadhir, A., & Santoso, D. R. (2017). Magnetotelluric-Geochemistry Investigations of Blawan Geothermal Field, East Java, Indonesia. *Geosciences*, 7(2), 41. https://doi.org/10.3390/geosciences7020041

Nasruddin, M., I. A., Yunus, D., Arief, S., Agus, S., B., A. H., & M.I., M. T. (2016). The potential of geothermal energy for electricity generation in Indonesia: A review. *Renewable and Sustainable Energy Reviews*, 53(C), 733-740. https://doi.org/10.1016/j.rser.2015.09.032

Nishar, A. (2017). Understanding warming effects on vegetation through geothermal hotspots: A case study of the Wairakei - Tauhara geothermal field, Taupo, New Zealand. 20.

Rondeaux, G., Steven, M., & Beret, F. (1996). Optimization of soil-adjusted vegetation indices. *Remote Sensing of Environment*, 55(2), 95-107. https://doi.org/10.1016/0034-4257(95)00186-7

Rouse, J. J.W., H., H. R., A, S. J., & W., D. D. (1974). Monitoring vegetation systems in the Great Plains with ERTS. NASA. *Goddard Space Flight Center 3d ERTS-1 Symp.*, 1(A).

Evaluation of Cisolok-Cisukarame Geothermal System using Gravity Inversion

Fanzly Togap Zisochi Lase[1], Dandi Baskoro Soebakir[2], Tony Rahadinata[1,3], and Ahmad Zarkasyi[3]

[1]Geothermal Engineering, FTTM ITB
[2]Department of Physics, Faculty of Mathematics and Natural Science, University of Indonesia
[3]Pusat Sumber Daya Mineral Batubara dan Panasbumi

22621012@mahasiswa.itb.ac.id

Keywords: Cisolok-Cisukarame, geothermal, gravity, inversion, conceptual model

ABSTRACT

The Cisolok-Cisukarame geothermal field is located on western Java Island, administratively located in Cisolok Village, Cisolok Sub-district, Sukabumi District, West Java Province, Indonesia. Pre-feasibility studies have been conducted covering geology, geochemistry, and geophysics. In this study, the evaluation of the geothermal system was conducted using gravity inversion to describe the subsurface geological model and geothermal conceptual model system of the Cisolok-Cisukarame geothermal field. The Complete Bouguer Anomaly (CBA) map has a positive anomaly in the Cisolok area, while Cisukarame is between positive and negative anomalies. Geothermal manifestations in the form of hot springs and spouting springs are controlled by geological structures that are oriented NE-SW, N-S, and NW-SE, as evidenced by the contrast of the gravity anomaly with positive local anomaly values and maximum Horizontal Gradient (HG) values. Gravity inversion results show that positive anomalies are associated with the presence of intrusive rocks in the form of dacite, while negative anomalies are associated with the presence of volcanic breccia rocks. The middle-to-high anomaly is indicated as a reservoir rock, which is thought to be a mixture of sedimentary and limestone rocks. A conceptual geological model based on inversion modeling of the Gravity data provides clear and comprehensive information about the geothermal system in Cisolok-Cisukarame.

1. INTRODUCTION

The Cisolok-Cisukarame geothermal field is located in the western part of Java Island, administratively located in Cisolok village, Cisolok sub-district, Sukabumi district, West Java province, Indonesia. The field is indicated to have subsurface hydrothermal activity characterized by the appearance of surface manifestation features, namely hot springs and spouting springs with high temperatures and relatively neutral pH with flow rates of around 10 L/m. In addition, there are deposits of travertine and silica sinter associated with alteration zones (Herdianita & Mandradewi, 2010). With these indications, a pre-feasibility study was conducted in 1970 by conducting a detailed 3G (geological, geochemical, and geophysical) survey.

Geologically, the Cisolok-Cisukarame geothermal field is dominated by Quaternary rocks in the form of andesitic, basaltic, and pyroclastic lavas from Mount Halimun. In addition, there are sedimentary rocks in the form of limestone (Sujatmiko & Santosa, 1992). The geological structures that developed in the research area are north-south, and northeast-southwest, formed during the Plio-Pleistocene period and have been covered by Quaternary volcanic deposits (Sujatmiko & Santosa, 1992; Herdianita & Mandradewi, 2010).

The geothermal manifestation is divided into two areas, namely the Cisolok and Cisukarame manifestations. In the Cisolok area, there are manifestations of hot springs and spouting springs with temperatures (90 - 100°C) with a relatively neutral pH of around 8. (Suryantini, 2009; Herdianita & Wulandari, 2010; Haty & Nugroho, 2013; Abdidallah et al., 2017). Manifestations in the Cisolok area have relatively high sulfate and bicarbonate fluid types which are thought to be influenced by limestone as evidenced by the evolution of travertine deposits in the area (Sintawati, 2014; Kurniawan et al., 2018). While the Cisukarame area has hot springs with temperatures around (54 - 99°C) with a relatively neutral pH of around 6.8 - 8.2 (Haty & Nugroho, 2013). Manifestations in the Cisolok area have a sodium chloride fluid type that reflects the reservoir fluid (Sintawati, 2014). Therefore, it is suspected

that the Cisolok and Cisukarame areas are characterized by different geothermal systems as evidenced by the manifestation temperatures of the two areas reaching the boiling point. The Cisolok-Cisukarame reservoir temperature using a Na-K geothermometer based on empirical equations derived by Fournier (1979) and Giggenbach (1988) ranges from 185 - 212°C) (Kurniawan et al., 2018).

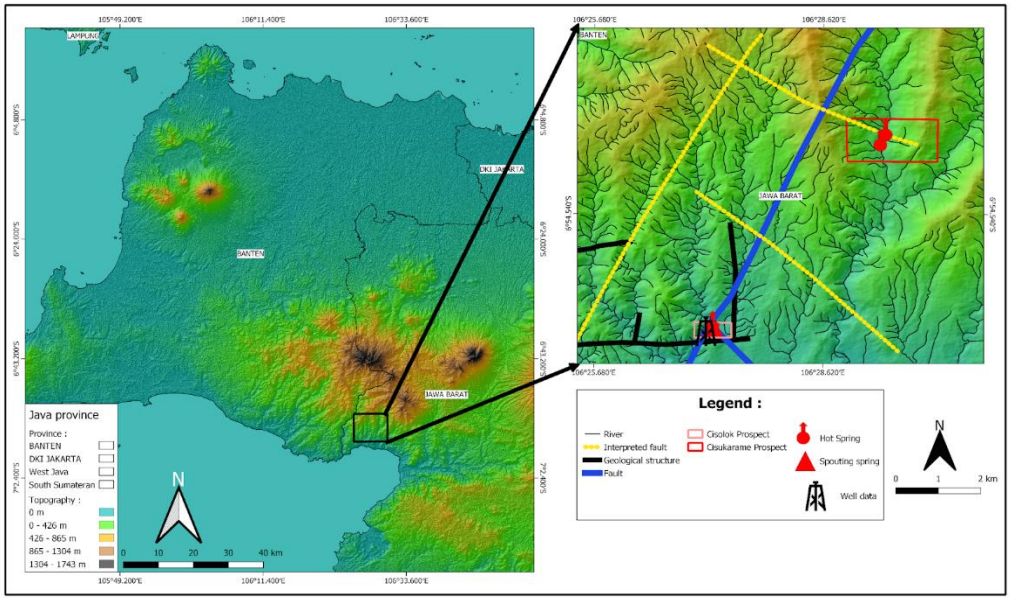


Figure 1: The Location of Cisolok-Cisukarame Geothermal Field (modified from West Japan Engineering Consultants, 1976; Divisi Geothermal Pertamina Pusat, 1986; Sujatmiko S., 1992; Suryantini and Hendrasto F, 2009).

The geophysical survey was conducted using DC Resistivity, Magnetotelluric (MT), and Gravity methods, from which the first drilling well (CSL-01) with a depth of 1477 meters was conducted. However, the CSL-01 well was only utilized as a publication study of the research area. DC Resistivity surveys in 1-D and 2-D were conducted in two periods, namely in 1976 and 1982 by West Japan Engineering Consultants and Pertamina with a total of 150 measurement points, only 69 points were used in analysis and interpretation while the rest had poor data quality (Alhamid, 1982; Hochstein, 1988). From these studies, it can be concluded that there is a low resistivity anomaly (<10 ohm.m) in the Cisukarame area. The zone is open to the south which reflects as the center of the geothermal system in the area associated as an upflow zone while the Cisolok area is associated with the outflow zone. Based on the research of Kurniawan et al. (2018) it can be concluded that the MT results show the existence of a low resistivity anomaly zone under the Cisolok-Cisukarame area which forms a pattern heading northeast-southwest in the eastern part. The low anomaly zone is associated with the clay cap zone of Cisolok-Cisukarame and the estimated presence of heat sources in the northeast of the Cisolok-Cisukarame area. And from the research of Lase & Soebakir (2022), it can be concluded that from the low residual anomaly, there is a controlling structure as evidenced by the appearance of hot spring manifestations and spouting springs that have NE-SW, N-S, and NW-SE orientations. Therefore, this study will use gravity inversion to evaluate a clear and comprehensive condition of the Cisolok-Cisukarame geothermal system.

2. REGIONAL GEOLOGY

The Cisolok-Cisukarame geothermal field is located southeast of Mount Bayah which is a large dome, the Bayah Dome, and several mountains of the upper Pleistocene age. The field is dominated by volcanic products of the Quaternary age with a relatively steep morphology of 150-900 masl (Abdillah et al., 2017). In general, the lithology of the Cisolok-Cisukarame area mainly consists of three types of rocks, namely sedimentary rocks (Early Miocene-Pliocene), acid intrusive rocks (Miocene), and andesite rocks (Pleistocene). Pleistocene andesite rocks as the youngest volcanic product in the area.

Based on Figure 2, consisting of 12 rock units, the Cikotok Formation is the oldest formation composed of volcanic breccia, tuff, and lava. The Citarete Formation is composed of limestone and tuff while the Cimapag Formation is dominated by breccia and conglomerate (Sujatmiko & Santosa, 1992). Dacite can be found in the south while in the west there is granite covered by lava and pyroclastic deposits (Sujatmiko & Santosa, 1992). The Citorek Formation is composed of marine sedimentary material and volcanic products deposited on top of the Cikotok, Citarete, and Cimapag formations. Volcanic products of the Quaternary age are andesite and basaltic rocks which are products of Mount Halimun (Sujatmiko & Santosa, 1992). The alluvium is the youngest product in the area and is distributed around Cimaja and Pelabuhan Ratu in the south (KESDM, 2017). Structures developed in the study area have N-S, NE-SW, and NW-SE orientations around the caldera. The geological structure of the study area acts as a controlling medium for the emergence of manifestations in the form of hot springs and spouting springs associated with high permeability zones.

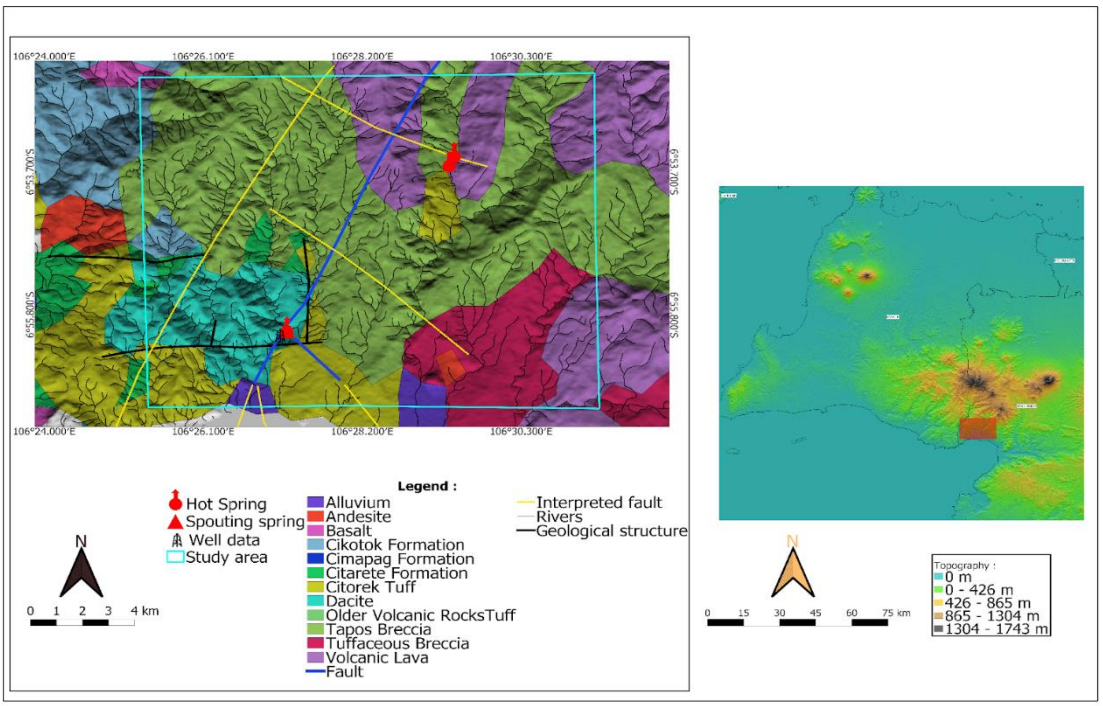


Figure 2: Regional Geology Cisolok-Cisukarame Geothermal (modified from West Japan Engineering Consultants, 1976; Divisi Geothermal Pertamina Pusat, 1986; Sujatmiko S., 1992; Efendi A.C. et al., 1998; Suryantini and Hendrasto F, 2009).

3. METHODOLOGY

The gravity survey was conducted by PVMBG. Gravity measurement points were distributed in the Cisolok and Cisukarame areas with a total of 75 measurement points. The gravity data has been processed by making corrections to the gravity data to reduce the effects on the gravity of the research area. The average density value of the Cisolok-Cisukarame area is 2.35 g/cm3 using the Parasnis method. In separating regional and local anomalies using the 1st order polynomial method with Oasis Montaj software. This research uses filters to detect the presence of geological structures and sources of gravity anomalies using Horizontal Gradient (HG) derived from the Complete Bouguer Anomaly (CBA) anomaly. Inversion of gravity data is used to determine the density distribution of subsurface rocks to identify the presence of geological structures and the potential presence of heat sources in Cisolok-Cisukarame.

4. RESULT AND DISCUSSION

4.1 Complete Bouguer Anomaly (CBA)

The CBA map of the Cisolok-Cisukarame geothermal field can be seen in Figure 3. Based on the results of the CBA map shows a range of CBA anomaly values around 119 to 151 mGal which provides combined information between regional and local anomalies. High anomalies (135 to 151 mGal) characterized by pink color in the southwest or Cisolok area can be interpreted as the presence of relatively older rocks, namely dacite. The medium anomaly (124 to 130 mGal) is found in the middle or in the Cisukarame area, where the zone can be interpreted as a flow of volcanic material, namely pyroclastics, and tuff. The low anomaly (119 to 121 mGal) is characterized by blue color in the east and can be interpreted as volcanic breccia rock. The Cisukarame area is at the boundary between the high and medium anomalies, so it is suspected that a structure controls the occurrence of hot spring manifestations in Cisukarame. The contrast of the CBA anomalies is associated with the geological structure of the study area which has N-S, NE-SW, and NW-SE directions.

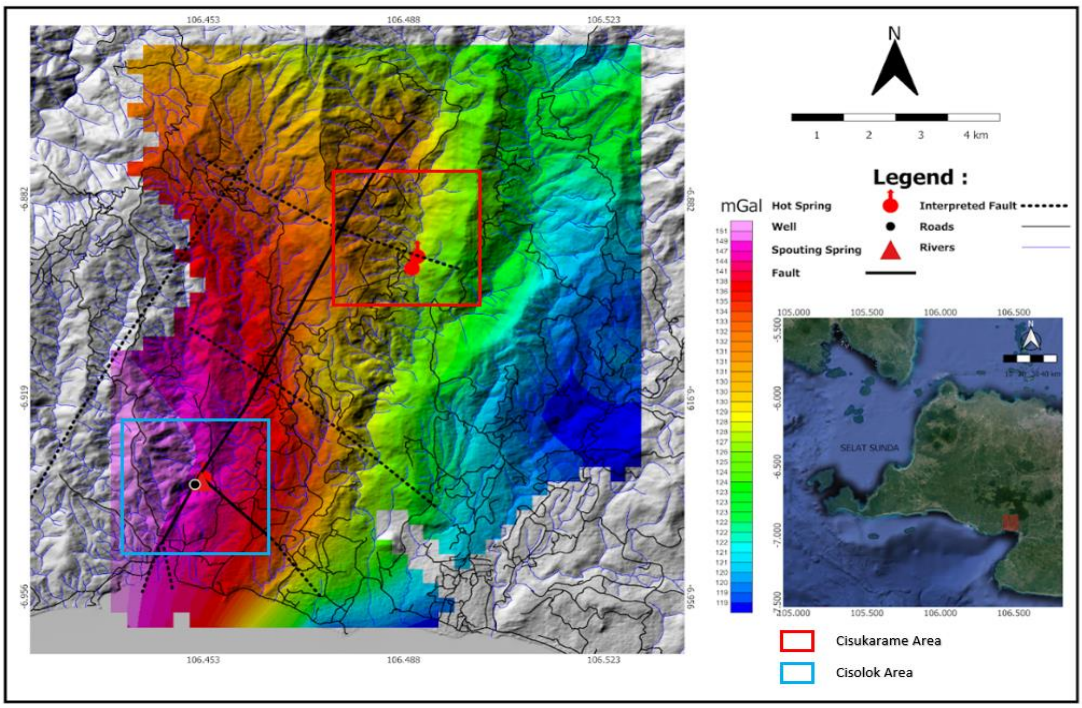


Figure 3: CBA Map of Cisolok-Cisukarame Geothermal Field.

4.2 Local Anomaly

The local anomaly map of the Cisolok-Cisukarame geothermal field can be seen in Figure 4. Based on the results of the local anomaly map shows the range of local anomaly values is around -11.7 to 15.9 mGal associated with anomalies at shallow depths. In separating the local anomalies in this study using the first-order polynomial method, where the results show representative results with field conditions. High anomalies (7.2 to 15.9 mGal) characterized by pink color in the southwest or Cisolok area can be interpreted as the presence of relatively older rocks, namely dacite. In addition to the southwest, the north is characterized by a high anomaly associated with volcanic lava. The medium anomaly (-6.6 to 6.7 mGal) is found in the central part or in the Cisukarame area, where the zone can be interpreted as a flow of volcanic material, namely pyroclastic and tuff. The low anomaly (-11.7 to -7.4 mGal) is characterized by blue color in the east and can be interpreted as volcanic breccia rock. The Cisukarame area is at the boundary between the high and medium anomalies, so it is suspected that a structure controls the occurrence of hot spring manifestations in Cisukarame. The existence of this boundary is supported by the presence of geological structures that develop in the study area in NW-SE direction.

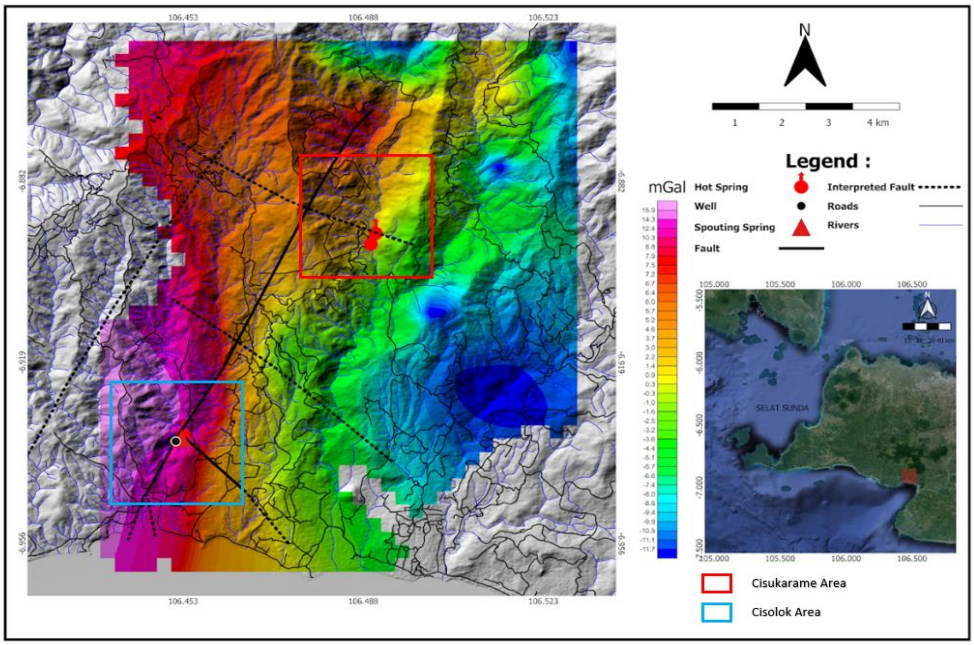


Figure 4: Local Anomaly Map of Cisolok-Cisukarame Geothermal Field.

4.3 Horizontal Gradient (HG)

The HG anomaly map of the Cisolok-Cisukarame geothermal field can be seen in Figure 5. HG is based on the CBA anomaly which is used to identify the presence of boundaries/contacts associated with geological structures. The presence of geological structures is characterized by the maximum value of HG. Based on the results of the HG anomaly map, it is positively correlated with geological data, namely showing the maximum HG pattern in the N-S, NW-SE, and NE-SW directions supported by the appearance of hot springs and spouting spring manifestations. Four structures were identified based on the results of the HG anomaly which showed results that correlated positively with the results of the geological interpretation that there was a structure that was oriented NE-SW as evidenced by the manifestation features of spouting springs and hot springs along the structure (Lase and Soebakir, 2022).

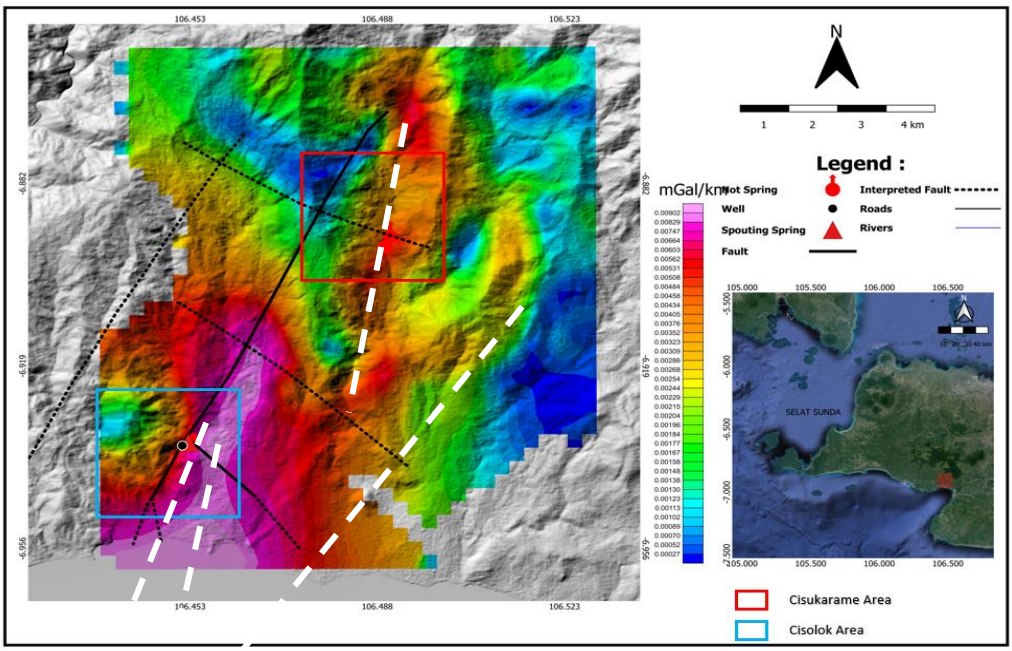


Figure 5: HG Anomaly Map of Cisolok-Cisukarame Geothermal Field.

4.4 Inversion Model

The results of the inversion of the research area were caried out by inversion of the local anomaly map with a depth of ± 6000 m by ignoring topography. Data processing using ZondGM2D and ZondGM3D includes slicing 1 pass SW-NE evaluating Cisolok-Cisukarame geothermal system. Iteration using Levenberg-Marquardt for 40 times with a 0.002% error.

The Cisolok area has a high anomaly characterized by a pink color associated with intrusive rocks, namely granodiorite (0.06 g/cc). In the CSL-1 well with a total depth of 1477.36 meters, granodiorite was found at a depth of 1400 meters (Suryantini & Hendrasto, 2009). In addition, there are extrusive rocks in the form of dacite (0 to 0.03 g/cc) found at relatively greater depths. In the YZ slicing results of the Cisolok area, there is an updome feature that indicates the presence of a plutonic body that acts as a heat conductor through a geological structure that runs NW-SE (Cisolok Fault) in the subsurface as evidenced by the spouting spring manifestation.

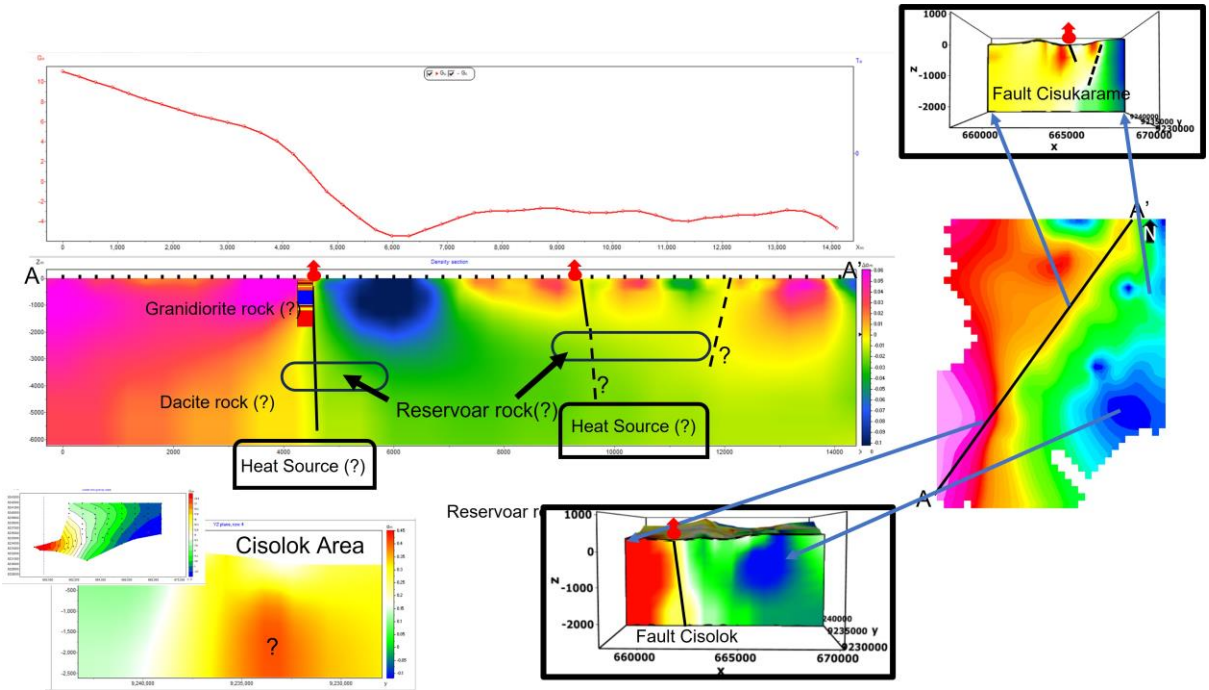


Figure 6: Inversion Model of Cisolok-Cisukarame Geothermal Field.

The Cisukarame area has a low anomaly marked in blue which is associated with volcanic breccia rocks (-0.07 to -0.1 g/cc). While high anomalies are marked with pink color associated with basaltic andesite (0 to 0.4 g/cc) found at the surface to a shallow depth. In addition, the presence of low anomalies at greater depths is thought to be associated with the presence of potential heat sources from Mount Halimun, which is relatively younger than Cisolok. The existence of a potential heat source in Cisukarame is evidenced by the appearance of hot spring manifestations through the Cisukarame Fault with a N – S and NE-SW direction.

In our gravity inversion interpretation, we found that at a depth of 1000 m from the maximum depth of well CSL-1, it is suspected to be a reservoir rock in the Cisolok geothermal system that has a medium-low density value. The caprock layer is visible above the geothermal reservoir layer with a distribution of low- and high-density contrast in the NW-SE direction, while the geothermal source rock is estimated to be at a depth of more than 5 km.

4.5 Conceptual Model

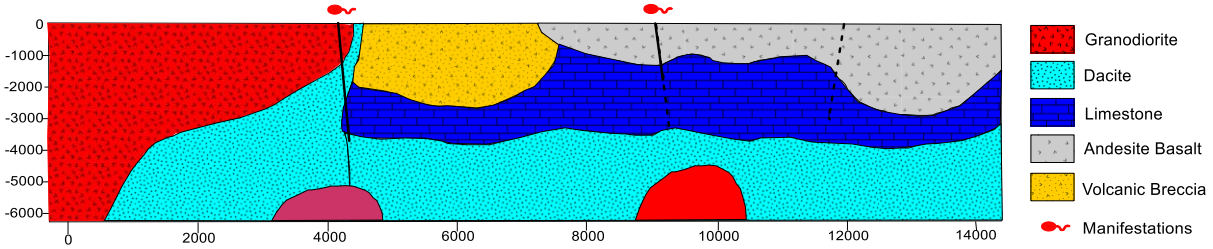


Figure 7: Conceptual Model of Cisolok-Cisukarame Geothermal Field.

According to the availability of information and supporting data, a three-dimensional conceptual model has been constructed as an integrated and comprehensive picture as shown in Figure 7. This model is the development of an initial conceptual model given the result of the MT method (Anshari, 2022) and the lithology of exploration wells (Suryanti & Hendrasto, 2009). The Cisolok-Cisukarame geothermal system is thought to have different potential heat sources due to the difference in high density between the Cisolok area and the Cisukarame area, which has medium-low density. This is also evidenced by MT slicing measurements (Anshari, 2022) that show a boundary between these two systems. We interpret that the Cisolok field is associated with relatively old rocks and cooling plutons and has a considerable depth, while the Cisukarame area is associated with magmatism activity from Mount Halimun. Cimaja and Citirus formations that are dominated by sedimentary rocks and the intersection of tuff and andesite are interpreted as reservoir rocks (Sintawati, 2014). The caprock layer is caused by rocks that have undergone changes due to hydrothermal activity that occurs below the surface and are made of volcanic breccia rocks. Permeability occurs due to the CSK-CSL geological structure in the form of N-S, NW-SSE and NE-SSE and the absorption area is estimated from the Cisukarame and Cisolok areas with low topography. From the results of the exploration well, the maximum temperature obtained is 103°C at a depth of 1333 m, so it is interpreted that at a depth of 2500–3000 m, high enthalpy temperatures are obtained.

5. CONCLUSION

The application of gravity inversion modeling offers detailed findings for the study of the subsurface model of the geothermal system in Cisolok-Cisukarame, West Java, Indonesia. In general, the distribution of the gravity anomalies provides consistent results with the existing studies conducted in the study area. Geothermal manifestations in the form of hot springs are generally located in the NW-SE and N-S-oriented gravity anomalies of the alteration zone. The caprock layer of the Cisolok-Cisukarame geothermal system at depths of up to 300 m to 600 m in Cisukarame and 800 m to 1000 m in Cisolok is thought to be associated with volcanic lava rocks of Halimun product and Granodiorite intrusion. The reservoir layer as a source of geothermal fluid deposition is estimated to be at a depth of 700–1200 m in Cisukarame and for Cisolok at a depth of 2500 m, consisting of a mixture of limestone and sedimentary rocks, which is the Citarate formation. The geothermal heat source is estimated in Cisukarame as magmatic activity from Mount Haimun, and in Cisolok, it is a cooling pluton and has a deeper depth than Cisukarame.

ACKNOWLEDGMENTS

The authors would like to thank the Center for Volcanology and Geological Hazard Mitigation for granting permission to use gravity data and providing additional data. The author is very grateful to Tony Rahadinata as a friend of Geothermal Master ITB and a friend of the struggle in the use of data permits.

REFERENCES

Abdillah, M.R. et al., 2017. Hidrogeokimia air manifestasi panas bumi di daerah Cisolok – Cisukarame, Kabupaten Sukabumi, Provinsi Jawa Barat. Padjadjaran Geoscience Journal, 1(3).

Alhamid, I. 1982. *Resistivity Survey of the Cisolok-Cisukarame Geothermal Area, West Java, Indonesia*. UNU Geothermal Training Programme National Energy Authority.

Anshari, A. 2022. *Rekonstruksi Model Konseptual Geothermal di Daerah Cisolok-Cisukarame Menggunakan Data Gravitasi Satelit GGMPlus dan Magnetotellurik*. Skripsi. Universitas Indonesia.

Divisi Geothermal Pertamina Pusat, 1986, Laporan Akhir Pemboran Sumur CSL-1, Pasir Pamengpeuk-Cisolok, Jawa Barat.

Fournier, R.O.: A revised equation for the Na/K geothermometer. Geothermal Resources Council Transactions, 3, (1979).

Giggenbach, W.F.: Geothermal solute equilibria. Derivation of Na-Mg-Ca geoindicator, Geochimica et Cosmochimica Acta, 52, (1988)

Haty, I. P. and Nugroho, A. N. (2013), "Geothermometer dan Heat Loss Dalam Eksplorasi Geokimia Lapangan Panasbumi Daerah Cisukarame, Kabupaten Sukabumi, Propinsi Jawa Barat".

Herdianita, N.R., et al. 2010. *Evolution of Cisolok-Cisukarame Geothermal System, West Java-Indonesia, Based on Its Surface Manifestation*. Proceedings of the World Geothermal Congress. Bali.

Hochstein, M.P. 1988. *Assessment and Modelling of Geothermal Reservoirs (Small Utilization Schemes)*. Geothermics.

KESDM 2017 *Potensi Panasbumi Indonesia* Direktorat Jenderal Energi Baru Terbarukan dan Konservasi Energi Kementerian Energi dan Sumber Daya Mineral.

Kurniawan et al. 2020. *Updating the Conceptual Model of Cisolok-Cisukarame Geothermal Field, West Java, Indonesia*. IOP Conference Series: Earth and Environmental Science, Vol.417. ITB International Geothermal Workshop.

Lase and Soebakir. 2022. *Investigation of Permeable Zone Using Magnetic and GGMPlus Gravity Data in Cisolok-Cisukarame Geothermal Field*. Proceedings the 8th Indonesia International Geothermal Convention & Exhibition (IIGCE) 2022.

Perusahaan Pertambangan Minyak dan Gas Bumi Negara, West Japan Engineering Consultants, Inc., 1976: General Report on Cisolok Geothermal Survey (Part 1)

Sintawati, F. 2014. *Analisis Prospek Panasbumi Cisolok Cisukarame Menggunakan Data Magnetotellurik dan Gravitasi*. Skripsi. Universitas Indonesia.

Sujatmiko dan Santosa, S., 1992, Geologi lembar Leuwidamar, Jawa (lembar : 1109-3), skala 1:100.000.

Suryantini and Hendrasto F. 2009.*Geothermal excursion* Geothermal Magister Program Institut Teknlogi Bandung

The Study of Supercritical Geothermal Potential in Indonesia from Geoscience Perspective

Astri Indra Mustika[1], Triwening Larasati[1], Aulia Rizky Pratama[2], M. Ghassan Jazmi[1], Ferdino R.F[1], and Serina A.P[1]

[1]PT Geoenergi Solusi Indonesia, Cibis Nine 11th Floor, Jakarta Selatan 12560, Indonesia
[2]Directorate of Geothermal, Ministry of Energy and Mineral Resources, Jakarta, Indonesia

astri.indra@geoenergis.com

Keywords: supercritical, unconventional, geothermal, Indonesia

ABSTRACT

Indonesia has set the target by 2060 anticipate the geothermal energy able to supply approximately 22 GW of the country energy demand. Realizing the ambitious goal through the nowadays geothermal extraction method appears challenging. The nation's favourable geological positioning within a subduction zone has elevated temperature conditions and shallow intrusions, indicative of potential supercritical geothermal reservoirs. Supercritical geothermal systems, characterized by exceedingly high enthalpy and located near or below the brittle-ductile transition zone, offer notable promise, marked by distinct temperature, pressure, and fluid attributes. Due to their exceptional power output per well, supercritical geothermal systems exhibit enhanced economic competitiveness for geothermal power plant initiatives. Moreover, they hold potential as efficient sources for green hydrogen production. This study aims to explore the opportunities for developing supercritical geothermal systems in Indonesia from geoscience perspective. Several developed geothermal fields which show signs of high temperature will be investigated to seek possibilities for further development. The study will involve discussions with geothermal developers, capture signals and clues for supercritical geothermal systems, and identify the geological settings and magmatic environments of developed geothermal fields in Indonesia. Challenges, benefits, and business opportunities of supercritical geothermal projects will then be examined, from the technical aspects. The main results will present considerations in developing supercritical geothermal projects along with the candidates for pilot projects in Indonesia.

1. INTRODUCTION

Today's geothermal systems, which are known to be conventional geothermal systems, only constitute a small portion (around 2%) of the total geothermal potential in the world at 15 Gigawatts of power globally and are largely confined to regions where concentrated heat is located near the surface due to the tectonic setting of the region that causes a shallow intrusion zone. Regretfully, the existence of conventional geothermal systems is very limited due to the complexity of the geological condition of the region. To reach geothermal energy's global target, unconventional geothermal systems seek to emulate the current geothermal system production through some pilot projects, such as supercritical geothermal systems, hot dry rock, and hot sedimentary aquifer. Although the unconventional system will require another method of extraction, more advanced exploration technology, and deep research, it is worth considering to be an option. This study zooms in on the opportunities for developing supercritical geothermal systems in Indonesia by comparing the global data to the current geothermal development status in Indonesia.

Supercritical geothermal systems are very high-temperature geothermal systems located at depths near or below the brittle–ductile transition zone in the crust where the reservoir fluid is assumed to be in the supercritical state (Reinsch, et al., 2017). The critical point for pure water occurs at 374˚C and 22.2 MPa but is higher for solutions containing dissolved salts 405˚C and 30.2 MPa. Aqueous hydrothermal fluid in supercritical conditions with a temperature of 400˚C and a pressure of 25 MPa has more than five times the power-producing potential of liquid water at a temperature of 225˚C (Elders, et al., 2014; Stimac, et al., 2015).

Located in convergent subduction geological setting which leads to intense volcanism activities, Indonesia has a good chance to discover supercritical geothermal system. Several developed geothermal fields have showed high-temperature sign that possibly hold the potential for further development. The subsurface data from existing wells and fields will give more confident to explore the supercritical geothermal system. Furthermore, the existing geothermal license holders have obligation to conduct research, development, and innovation on their projects. Hence, supercritical system investigation on existing field will have more legal support compared to the greenfield areas.

2. GEOTHERMAL RESOURCES IN INDONESIA

Indonesia is located in a subduction zone that is known to have great potential for geothermal energy resources. The geological settings of Indonesia cause the occurrence of magmatism activities that generate shallow intrusion in the subsurface so that the volcanic arcs were formed, namely Sunda Arc, Banda Arc, and Sangihe Arc. Those volcanic arcs result in a high enthalpy geothermal system, which is commonly associated with and has been proven to generate electric power generation (Hochstein & Sudarman, 2008).

To avoid confusion between supercritical and superheated resources, no distinction is made in this study. In this regard, a supercritical geothermal system is defined as a very high-temperature (superheated) and very high-pressure (supercritical) geothermal system located somewhere deep in the subsurface, way deeper than the conventional resource (Scott, et al., 2015; Reinsch, et al., 2017). The fluid is expected to reach above the critical point of temperature and pressure. As a comparison, the critical point for pure water is around 374°C and 221 bars, while seawater is around 407°C and 298 bars (Procesi, 2015; Scott, et al., 2015).

The deep occurrence of this supercritical condition pertains to brittle-ductile transition (BDT) zone occurrence. In the model by Scott et al. (2015), supercritical water resource is predicted to be extensively developed if the brittle-ductile transition temperature (T_{BDT}) reaches at least 450°C and larger if the temperature is higher. Aside from T_{BDT} influence, host rock permeability and intrusion depth influence the resource. The convective flow of the fluid should be confined for the intrusion to heat the fluid sufficiently to reach a supercritical condition; in other words, a high permeability of host rock is not favorable. Additionally, the depth of intrusion could have an effect on the fluid pressure above the intrusion, and shallower intrusion could lead to a lower pressure of the fluid. Thus, the better resources are those that lie in the vicinity of deeper magmatic intrusion nearer to BDT with a low permeability of host rock.

A supercritical resource is considered to be rather beneficial if it is developed, given its enormous power-producing capability. Considering the very high temperature and pressure of the resource, the fluid viscosity will be decreased, and compressibility will increase, instead, making the fluid mobility to be more intense and causing higher mass flow rates (Jolie, et al., 2021). Thus, the produced enthalpy would be higher than conventional resources and be expected to reach even more than 5 times the conventional high-temperature resources (Procesi, 2015). Therefore, it can improve the ratio of drilling costs to a power output per well, making the resource economically competitive. Some comparisons between conventional resources and supercritical resources are listed in the following table.

3. OPPORTUNITY OF SUPERCRITICAL GEOTHERMAL SYSTEM IN INDONESIA

Indonesia, constructed by the convergence of several tectonic plates that lead to intense volcanism along the islands, is known to have considerably high geothermal potential with pretty much high-temperature resources. Several high-temperature fields in Indonesia are identified to exhibit the probable existence of even higher temperature resources if not as well as high pressure, possibly holding the potential of more critical resources that can be developed in the future. In Sumatra, many developed geothermal fields are located in the vicinity of the Great Sumatra Fault (GSF) zone. Silangkitang field is located in the margin of Sarulla graben with a high influence of GSF on the permeability and hydrology condition of the field. The heat source is associated with Quaternary Sarulla rhyolite dome (Gunderson, et al., 2000; Simatupang, et al., 2021). It is known that two of Silangkitang wells that were targeted directionally into the GSF found a very strong upflow in the vicinity of the fault. It is significantly

overpressured with respect to a normal hydrostatic gradient with fluid temperature excess 310°C (Gunderson, et al., 2000). While Silangkitang field condition is highly affected by GSF, Sorik Marapi field which is also located adjacent to GSF is more controlled by the Quaternary stratovolcano of Mt. Sorik Marapi that acts as the heat source. The permeable zones are mostly associated with fractures from GSF zone and/or sedimentary rock units. Drilling result of T-05 and T-09 with total depth of about 2100 mMD shows discovery of ~320°C temperature at -600 to -900 masl with pressure 80-90 barg, with drilling directed to the upflow zone. The wells encountered typical benign reservoir liquid originated from meteoric water with low concentration of NCG content (Hidayat, et al., 2021).

Table 1: Comparison between conventional geothermal systems and supercritical geothermal systems .

	Conventional	Supercritical
Exploration and extraction method	Exploration method includes remote sensing, field mapping of structural and alteration features, fluid chemistry, gravity, magnetics, electrical survey, and deep exploration drilling (3G Survey).	Supercritical temperature conditions are often found at the roots of high-temperature geothermal system (Reinsch, et al., 2017). If sufficient permeability and recharge are not present then hydrofracturing and injection could be viable options (Elders, et al., 2014).
Average drilling depth and technology	The average drilling depth is typically ~500-2000m for slim holes or ~2000-3000m for standard holes and big holes (Mackenzie K. M., et al., 2017).	It needs adapted drilling and completion technologies for extreme reservoir conditions (Muraoka, et al., 1998; Reinsch, et al., 2017; Jolie E. , et al., 2021).
Heat source, fluid, and permeability	Thermal fluids, heat source, and permeability occur naturally.	Heat source might occur naturally and need artificial fluids and enhanced permeability.
Enthalpy	Commonly, a high-temperature system reaching at least 200°C is preferred in reservoir shallower than 3,000 m (Moeck, et al., 2015).	To reach supercritical hydrous fluid conditions in natural geothermal systems requires deep drilling to a minimum depth of some 3.5–5 km where temperature conditions can be expected to range between 400 and 600°C (Friðleifsson & Elders, 2017).

In Java, the presence of deep well and/or high-temperature resources is identified in some fields i.e., Awibengkok field and Karaha-Bodas field. Awibengkok field is located on the southwestern side of Mt. Salak that acts as the main heat source of the system. The reservoir is liquid-dominated, having benign chemistry and low-moderate NCG content (Stimac, et al., 2008). Indication of deep permeability is detected at the southwestern portion of Awibengkok reservoir, confirmed in AWI 9.9 well at 3058 mMD. This corresponds to a reservoir pressure of 185 barg and a temperature of 321°C with upflowing conditions from the bottom feedzone. The well is one of the successfully drilled deepest well in Indonesia that encountered the resource. Micro-seismicity events suggests that permeability could extend to as deep as ~4000 m, in which the pressure can be expected to reach 257 barg, thus has a possibility of higher temperature and supercritical fluid (Libert, 2017). In Karaha-Bodas field which is located in the northern side of Galunggung volcano, the heat source comes from the Quarternary volcanic complex elongated from Karaha to Galunggung. Yet, the main source is the magmatic vapor plume beneath Talaga Bodas area. This field is partially vapor-dominated with steam zone formed above locally boiling fluid. About 350°C temperatures reaching ~140 bar pressure was measured at the bottom of TLG2-1 suggesting possible superheated conditions in the passively magmatic degassing area which is presumably a cooling intrusion (Allis, et al., 2000).

Aside from AWI 9.9 well, HLS-E1 well in Hululais field is also one of the deepest well drilled in Indonesia. The field is located near Barisan Range and GSF area, making the volcanism and structural permeability highly influenced by the GSF regime. The permeability comes from two dextral strike-slip faults which are also part of GSF segments. The heat source is associated with Suban Agung volcanism (Nurseto, et al., 2021). The deep well in this field reached the total of 3203 mMD and has been confirmed by pressure-temperature injection survey. The permeable zone is detected to be started from around 1900 mMD to the well bottom, identified from total loss circulation of 20 BPM with no gains of returns. Aerated drilling is successfully utilized in overcoming these challenges and possibly can also be applied for similar problem in the future (Toni, et al., 2016). Other well from the same wellpad, noted as HLS-EX reached total depth of 3280 mMD at -1355 masl. The reservoir temperature measured from this well is 258°C in the convective zone and reaching about 120 bar pressure with liquid phase (PT Pertamina Geothermal Energy, 2018 in Nusantara, 2022)

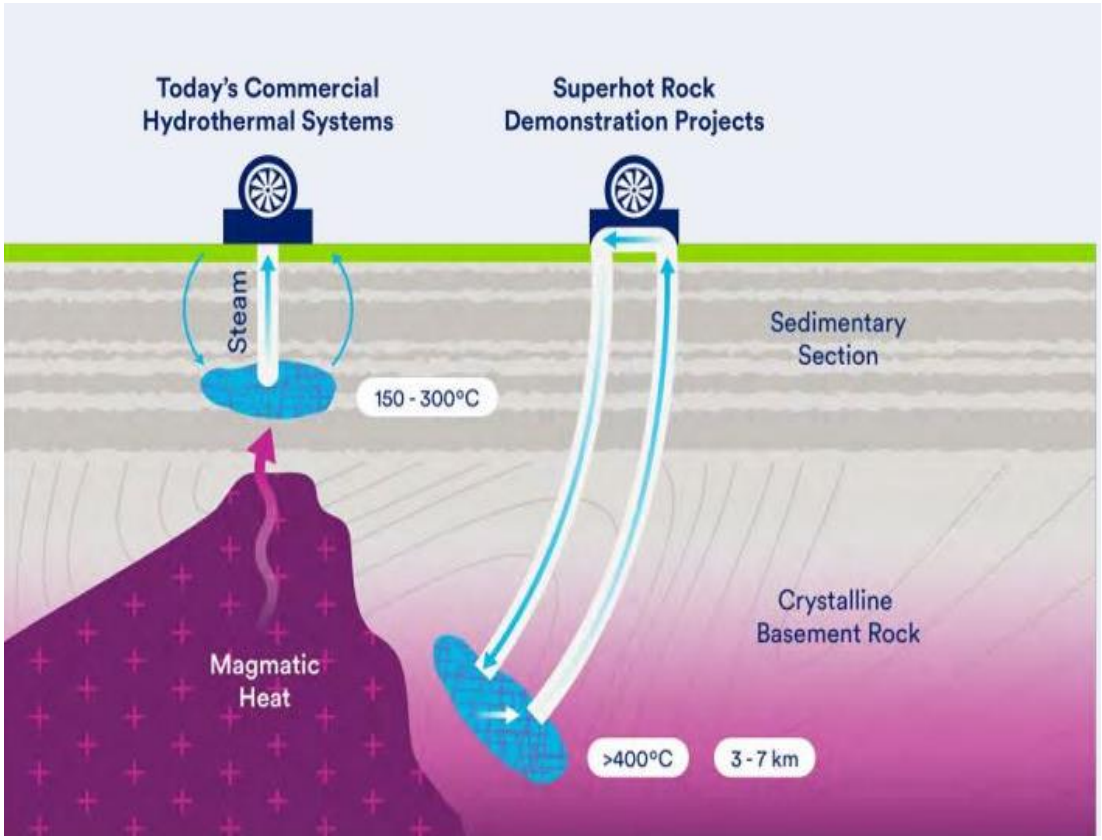


Figure 1: According to Hill (2022) the ideal pilot project to utilize the deep geothermal system is in volcanic region nearby the hydrothermal system that already proven due to the Currently available mechanical drilling methods can and are being used to drill to depths of 3-7 km to access relatively shallow superhot rock.

4. COMPARISON OF SUPERCRITICAL GEOTHERMAL POTENTIAL IN INDONESIA, NEW ZEALAND, ICELAND, AND JAPAN

Several countries have already started to show interest in supercritical resource. In Iceland, the Iceland Deep Drilling Project (IDDP) is meant to be a pilot project for exploring the deep unconventional supercritical resource after the discovery of >380°C temperature with very high pressure and inflow rates in Nesjavellir geothermal field (Steingrimsson, et al., 1990; Reinsch, et al., 2017). Up until today, there are three IDDP projects with one concluded project located in Krafla geothermal field, one on-progress completion project in Reykjanes geothermal field, and one planned project in Hengill (Friðleifsson, et al., 2019).

Research was also conducted in New Zealand, focusing on Taupo Volcanic Zone (TVZ) area. Deeper untapped resource is under study to be developed to meet the future electricity demand. Regional geophysical study had been conducted to understand the regional subsurface condition of the field, including the brittle-ductile transition zone and connection between shallow and deep resources (Bannister, et al., 2015; Newman, et al., 2015). There has been no attempt to drill the supercritical resource yet.

Japan also participated in the exploration of deeper geothermal reservoir, knowing the drilling in Kakkonda Geothermal Field resulting in a very high temperature fluid with probable BDT encountered. Japan Beyond Brittle Project (JBBP) is designed to explore the deep enhanced geothermal system (EGS) reaching almost the ductile zone. The considered extraction would be near the top of BDT or beyond BDT depending on the study result (Muraoka, et al., 2014). As the geological setting of Japan is similar to Indonesia, the study result is most likely closely relatable to the resource condition in Indonesia, thus some lessons should be noted. In Table 2, comparison between geological condition and probable and proven supercritical resources in the mentioned countries before is outlined.

Figure 2: Superhot potential project location with the development status (Hill, 2022).

Table 2: Comparison between regional conditions, resource characteristics, and development method of proven supercritical resources in Iceland and probable supercritical resources in New Zealand and Japan with conditions in Indonesia.

	IDDP Project, Iceland*	Taupo, New Zealand**	Kakkonda, Japan**	Indonesia**
Geology setting	Both Krafla field and Reykjanes field are located in magmatic rift setting. Shallow magmatic intrusion is present in this field with system hosted in basaltic rock (Elders, et al., 2014; Scott, et al., 2015; Friðleifsson & Elders, 2017). IDDP-1	Located in continental volcanic arc/extensional back-arc basin. Heat source is associated with volcanism (Bignall & Carey, 2011)	The field is located in the southern part of Hachimantai volcanic field. Kakkonda granite acts as the heat source of this field in which the drilling reached the granitic basement. Fractures	Convergent subduction setting generates intense volcanism that usually became the heat source of the geothermal system (Hall, 2009). Intense structural influence is also

	IDDP Project, Iceland*	Taupo, New Zealand**	Kakkonda, Japan**	Indonesia**
	project encountered magma at 2096 m depth (Pálsson, et al., 2014).		abruptly decrease below 2860 m in the Kakkonda granite (Muraoka, et al., 1998)	notable in some fields i.e., Silangkitang, Sorik Marapi and Hululais (Hidayat, et al., 2021; Nurseto, et al., 2021; Simatupang, et al., 2021)
Well depth	Final vertical depth of IDDP-1 is 2077 m. The well started as vertical well, but side tracking was made later on (Pálsson, et al., 2014) IDDP-2 well was drilled vertically down to 2750 m then directionally to the SW. The bottom of the well has a vertical depth of about 4500 m depth (Friðleifsson & Elders, 2017)	In Ngatamariki field, current deepest well depth reached 3398 mRF depth at NM6 vertical well and encountered greywacke basement (Bignall, 2009; Simpson & Bignall, 2016)	WD-1a's final depth reached 3729 m. The well is vertical to 800 m and drifted in various directions with a total of about 11 trajectory correction was made (Muraoka, et al., 1998)	Depth range of geothermal wells in Indonesia is 1200-2800 m depth (Purwanto, et al., 2021). The deepest well in Indonesia reached ~3000 m, i.e., AWI 9.9 in Awibengkok field and HLS-E1 and HLS-EX in Hululais field (Libert, 2017; Nurseto, et al., 2021; Nusantara, 2022)
Pressure and Temperature	IDDP-1 produced superheated steam at 452℃ (Friðleifsson & Elders, 2017) IDDP-2 bottom of well reached ~426℃ with 34 MPa pressure and good permeability (Friðleifsson & Elders, 2017)	Research efforts in New Zealand have included study of the deep (5-7 km) geothermal resource potential for the Taupo Volcanic Zone (Figure 3), which is estimated to have temperatures >400°C (Dobson et al, 2017). Deepest well (NM6) has ~260°C temperature (Bignall, 2009).	WD-1a exploration well encountered BHT of 500℃ at 3729 m total vertical depth. Fluid pressure near the bottom of well is unknown in a natural state. Pressure reached 24 MPa at a depth of 3100 m with 380℃ temperatures. Kakkonda conduction-dominated temperature gradient reached 32℃/100 m (Muraoka, et al., 1998; Muraoka, et al., 2014)	Temperature range in geothermal well is 200-300°C (Purwanto, et al., 2021) with some potential supercritical fields encountered temperature as high as 350°C, i.e., Karaha Bodas (Allis, et al., 2000)
Fluid characteristics	IDDP-1: acidic fluid is formed by condensation of sulphuric gas. The gas content is relatively low (Ármannsson, et al., 2014) IDDP-2: oceanic origin, a saline fluid system. The project affects the	Ngatamariki field has neutral chloride water condition (Boseley, et al., 2010). All fields in TVZ have neutral pH alkali chloride water	The well did not produce supercritical fluid and the bottom hole was dry (Elders, et al., 2014; Dobson, et al., 2017) The fluid at 3708 depth was hypersaline and contain high	Some fields (i.e., Sorik Marapi) shows benign fluid condition (Hidayat, et al., 2021), though it is a bit far from the heat source. Meanwhile, some well in several

	IDDP Project, Iceland*	Taupo, New Zealand**	Kakkonda, Japan**	Indonesia**
	surrounding shallow geothermal reservoir fluid where the salinity decreased temporarily, and influx of atmospheric gas increased (Friðleifsson, et al., 2019)	(Simpson & Bignall, 2016).	concentration of heavy metals (Muraoka, et al., 1998)	fields (i.e., Karaha) that tend to be closer to the upflow exhibits magmatic input with acidic fluid and high gas content encountered (Allis, et al., 2000)
Permeability	IDDP-1: transition from upper to lower reservoir has decreasing porosity and permeability. Main feed zone occurs at 2035 m depth (Mortensen, et al., 2014) IDDP-2: indications of good permeability at depth (Friðleifsson & Elders, 2017). Total loss circulation is encountered below 3.2 km to the bottom of well (Friðleifsson, et al., 2019)	Shallow-sourced EQ loci in southern TVZ show apparent cessation inferring 6-7 km depth BDT zone (Bibby, et al., 1995; Heise, et al., 2007). Total loss circulation was encountered from 2575 mrF down to the deepest depth of NM6 well. The greywacke basement has low matrix porosity (Bignall, 2009)	Brittle-ductile boundary is indicated at about 3100 m depth with temperature reached 380°C as farther depth shows lower fracture density (Muraoka, et al., 1998)	Some drilled wells that reached ~3000 m shows indicated permeability at depth, i.e., Awibengkok and Hululais (Libert, 2017; PT Pertamina Geothermal Energy, 2018 in Nusantara, 2022)
Method	IDDP-1: The acid gas in the steam is proven can be scrubbed off with alkaline water in an experiment (Hauksson, et al., 2014). The pre-drilling used 36”/26” underreamer. The cement is also slurry and fiberglass drill pipes was used to place cement plugs (Pálsson, et al., 2014) IDDP-2: cement plugging was unsuccessful to handle the loss zone, thus drilling was continued blindly (Friðleifsson, et al., 2019)	Conducting survey geophysics method: 3D MT modeling to provide evidence down to 10 km depth, a passive-seismic broadband survey of the region to elucidate changes in crustal velocity structure between 3 and 8 km depth with the goal to get an integrated image of the brittle-ductile transition zone and identify potential deep drilling targets (Dobson, et al., 2017)	Efficient borehole cooling technique was implemented by using top-drive system which allows mud to be continuously pumped while running the BHA with additional mud-cooler system (Muraoka, et al., 1998)	Total loss circulation of 20 BPM is detected in HLS-E1 and solved with aerated drilling (PT Pertamina Geothermal Energy, 2018 in Nusantara, 2022)

*) Drilling Project/Proven
**)Non-drilling Project/Not Proven

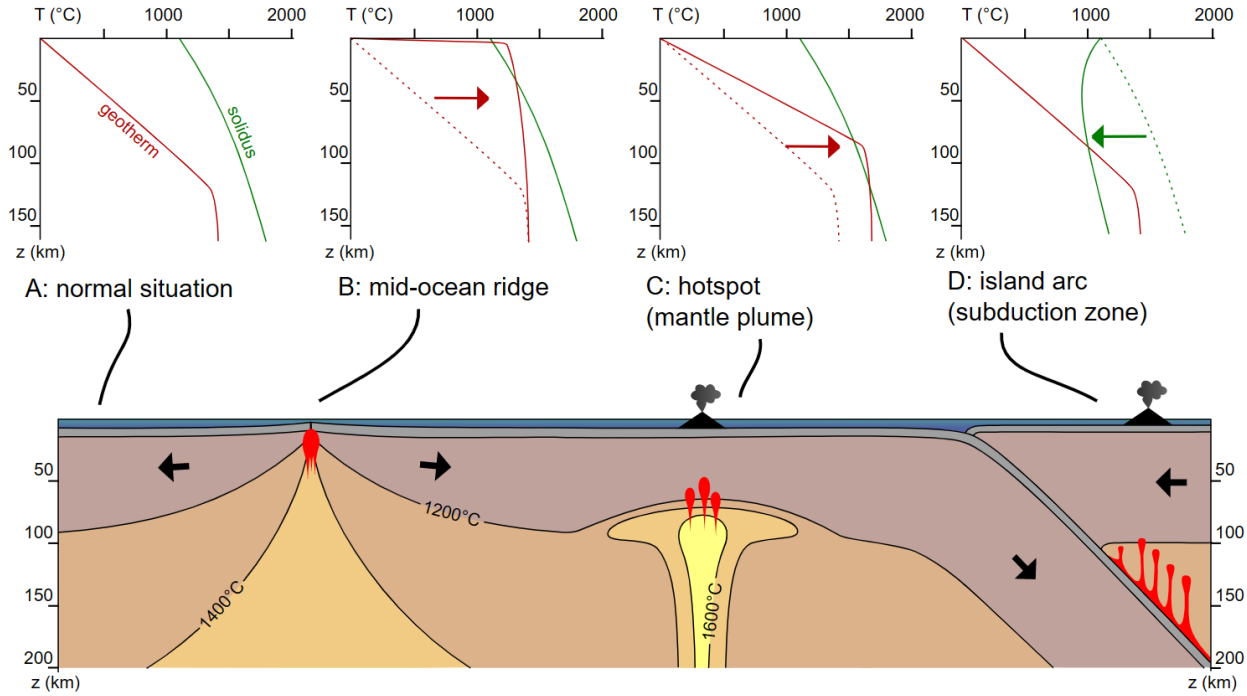


Figure 3: Diagram of physical processes in Earth's upper mantle that led to magma generation. A-D are different plate tectonic settings. The graphs show the geotherm in red (temperature curve inside the Earth) and the solidus in green (temperature where rock starts to melt). When the curves cross each other, partial melting of mantle rocks occurs Niu (2021) modified by Wouldper.

5. SURVEY AND EXPLORATION

Figure 4 shows the distribution map of unconventional geothermal system in Indonesia according to exploration report by geological agency some area showed the potential geothermal field that could be fit as supercritical pilot project. This information that provided by Geological Agency of Indonesia is the good start of initiation study even so the detailed and more comprehensive research should be conducted to get more information regarding the distribution (Mustika, et al., 2022).

Several specific challenges should also be considered since the geological setting of Indonesia is very different than the pilot projects (high relief might cause deeper heat source, magmatic input of different tectonic settings might influence the heat source, etc.). According to Dobson, et al. (2017) that already summarized several challenges in the supercritical pilot project such as Iceland and Japan, a number of serious issues were encountered while trying to successfully handle and utilize fluids from geothermal reservoirs at temperature and pressure conditions exceeding supercritical conditions of water. These issues need further in-depth investigation to get the lesson learned from previous projects.

Supercritical temperature conditions are often found at the roots of high-temperature geothermal system (Reinsch, et al., 2017) since this system is deeper than current commercial geothermal system that already produce, the approach and method in exploration to located the brittle-ductile transition whereas the supercritical condition will be found. Exploration method for better resource assessment such as advance geophysical exploration method to produce the integrated deeper image to find the brittle-ductile transition zone and identify potential deep drilling targets. Dobson, et al. (2007) mentioned that the integrated 3D MT modelling in New Zealand is possible to do modeling provide evidence down to 10 km depth, combine with passive-seismic survey to detect the changes in crustal velocity structure between 3-8 km depth.

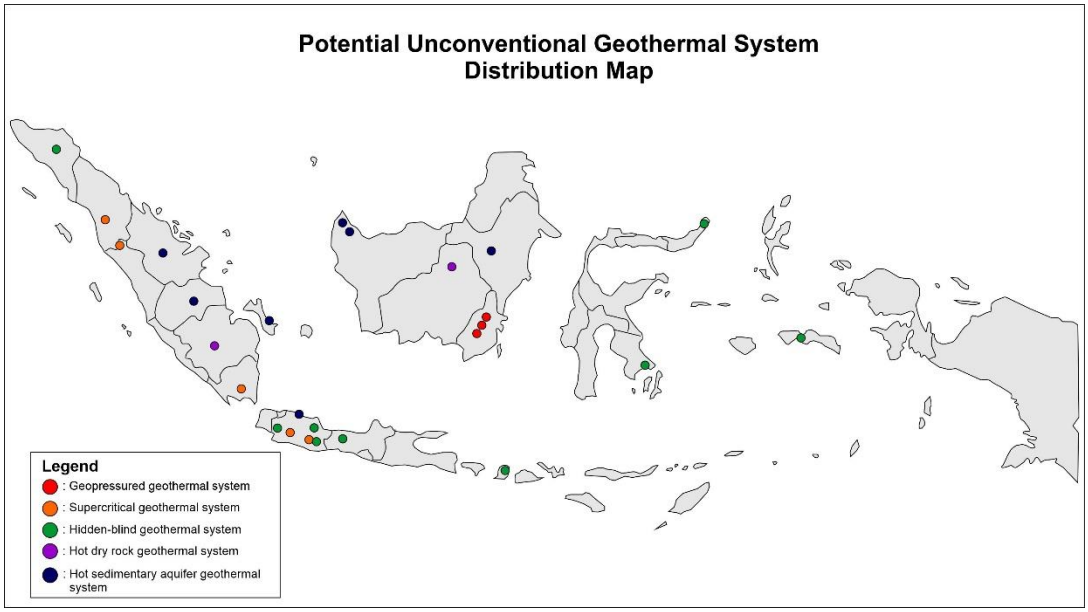


Figure 4: Potential Unconventional Geothermal System Distribution Map.

Laboratory simulation and modelling also needed for supercritical systems, this is also including geologic and geophysical modeling of the brittle–ductile transition zone. The laboratory measurement of rock and fluid properties work is needed as the calibration since the system will be dealing with very high temperature, pressure and commonly with magmatic fluid. Since the acid magmatic dominated fluids are found in the hotter plastic rock and hydrothermal fluids circulate through the overlying cooler brittle rock.

The other important thing also to identify the economically feasible resource such as the source of the funding the project and the continuity of the pilot project. This could also relate to geohazard prevention due to the system commonly associated with active volcanoes since most of volcanic area in Indonesia is a densely populated area. Therefore, the surface facility and strategy should be prepared since the beginning, due to dealing with supercritical fluids and corrosive gases could be endanger the populated area. Despite the fact that the map based on the initial data and to be further investigation, but it showed that the highest possibility to start the pilot project on the exist field has more chance than the green field. Based on that fact, it should be considered some of the challenge in development phase from existence field.

The supercritical fluid located in brittle-ductile transition that mean the permeability is considered low comparing to the commercial geothermal field nowadays, if sufficient permeability and recharge are not present then hydrofracturing and injection could be viable options (Elders, et al., 2014). The hydraulic fracturing and injection could be a challenge especially for the system above that already running. The risk of both methods could affect the reservoir temperature above more over creation of heat reservoirs in fracture systems in dry superhot rock while avoiding seismic risk (Hill, 2022).

Besides that, on the drilling process in supercritical condition, we need to adapt some deep drilling and completion technologies in supercritical condition (high T and P). Casing cementing methodology for the hot rock environment is needed to be learned. Stage cementing tools using rubber packers are not advisable in formation hotter than 300°C and reversed circulation should be considered to secure good cementing over long sections (Pálsson, et al., 2014).

Furthermore, to reach supercritical conditions in natural geothermal systems requires temperature range between 400◦C and 600 ◦C (Friðleifsson & Elders, 2017) to keep the sustainability of the supercritical condition should be considered. The idea to create more permeability in brittle-ductile condition may lead into creating the supercritical system promising yet the fact that supercritical condition need in low permeability environment to keep the condition sustain.

6. CONCLUSION

Supercritical geothermal systems have opened up new opportunities in utilization of geothermal energy. Due to its fluid characteristic and enthalpy, a supercritical system may produce energy output of more than five times the conventional hydrothermal system. Although its development is promising, the investigation of supercritical systems in Indonesia remains to be limited mostly because it is considered very expensive and high-risk. However, the opportunity to discover a supercritical geothermal system can lay beneath the existing conventional hydrothermal system. Thus, further research and investigation can be conducted on Sarulla, Sorik Marapi, Awibengkok, Karaha Bodas, and Hululais fields as they have indication for higher temperature systems and higher pressure.

It is imperative for the Indonesian to meticulously consider the potential of supercritical geothermal systems, taking into account their existence and associated opportunities. This entails the establishment of comprehensive safety protocols and methodologies for estimating resources specific to this unconventional geothermal approach. Furthermore, it is recommended that Indonesia embark on a pilot initiative for drilling a supercritical geothermal system, drawing valuable insights from the experiences of other nations. After all, more advanced development of geothermal energy will help reduce the energy sector's dependency on the fossil source of energy that dominated nowadays.

REFERENCES

Allis, R. et al.: Karaha-Telaga Bodas, Indonesia: A Partially Vapor-Dominated Geothermal System, *Geothermal Resources Council Transactions*, Volume 24, (2000)

Ármannsson, H. et al.: IDDP—The chemistry of the IDDP-01 well fluids in relation to the geochemistry of the Krafla geothermal system. *Geothermics*, Volume 49, (2014), pp. 66-75

Bannister, S., Bourguignon, S., Sherburn, S. & Bertrand, T.: 3-D seismic velocity and attenuation in the Central Taupo Volcanic Zone, New Zealand: imaging the roots of geothermal systems, *Proceedings World Geothermal Congress 2015*, (2015)

Bibby, H. M., Caldwell, T. G., Davey, F. J. & Webb, T. H.: Geophysical evidence on the structure of the Taupo Volcanic Zone and its hydrothermal circulation, *Journal of Volcanology and Geothermal Research*, Volume 68, (1995), pp. 29-58.

Bignall, G.: *Ngatamariki Geothermal Field Geoscience Overview*, s.l.: GNS Science, (2009)

Bignall, G. & Carey, B.: A DEEP (5 km?) GEOTHERMAL SCIENCE DRILLING PROJECT FOR THE TAUPO VOLCANIC ZONE - WHO WANTS IN?. *Proceedings New Zealand Geothermal Workshop 2011*, (2011)

Boseley, C. et al.: A Resource Conceptual Model for the Ngatamariki Geothermal Field Based on Recent Exploration Well Drilling and 3D MT Resistivity Imaging, *Proceedings World Geothermal Congress 2010*, (2010)

Dobson, P. et al.: Supercritical Geothermal System - A Review of Past Studies and Ongoing Research Activities, *Proceedings 41st Workshop on Geothermal Reservoir Engineering*, (2017)

Elders, W. A., Friðleifssonb, G. Ó. & Albertsson, A.: Drilling into magma and the implications of the Iceland Deep Drilling Project (IDDP) for high-temperature geothermal systems worldwide, *Geothermics*, Volume 49, (2014), pp. 111-118

Friðleifsson, G. Ó. et al.: The Reykjanes DEEPEGS Demonstration Well – IDDP-2, *European Geothermal Congress 2019*, (2019)

Friðleifsson, G. Ó. & Elders, W. A.: Successful Drilling for Supercritical Geothermal Resources at Reykjanes in SW Iceland, *GRC Transactions*, Volume 41, (2017)

Geological Agency: *Indonesia Geothermal Resource Map*, s.l.: s.n. (2021)

Gunderson, R. et al.: Exploration results in the Sarulla block, North Sumatra, Indonesia, *Proceedings World Geothermal Congress 2000*, (2000)

Hall, R.: Indonesia, Geology, In: *Encyclopedia of Islands*. s.l.: University of California Press, (2009), pp. 454-460

Hauksson, T. et al.: Pilot testing of handling the fluids from the IDDP-1 exploratory geothermal well, Krafla, N.E. Iceland, *Geothermics*, Volume 49, (2014), pp. 76-82

Heise, W. et al., 2007. Melt distribution beneath a young continental rift: The Taupo Volcanic Zone, New Zealand. *Geophysical Research Letters*, Volume 34.

Hidayat, R. et al.: The Characteristics of 320℃ Geothermal Wells at Sorik Marapi Geothermal Field, *Proceedings The 2nd Digital Indonesia International Geothermal Convention (DIIGC)*, (2021)

Hill, L. B.: *Superhot Rock Energy*, s.l.: Clean Air Task Force, (2022)

Hochstein, M. P. & Sudarman, S.: History of geothermal exploration in Indonesia from 1970 to 2000, *Geothermics*, Volume 37, (2008), pp. 220-266

Jolie, E. et al.: Geological controls on geothermal resources for power generation, *Nature Reviews*, Volume 2, (2021), pp. 324-339

Libert, F. T.: Evaluation of the Deepest Production Well in Salak Geothermal Field, Indonesia, *5th Indonesia International Geothermal Convention & Exhibition*, (2017)

Mackenzie, K. M. et al.: Use of Deep Slimhole Drilling for Geothermal Exploration, *Proceedings The 5th Indonesia International Geothermal Convention & Exhibition*, (2017)

MEMR: *Net Zero Emission Road Map - Energy Sector*, s.l.: s.n, (2022)

Moeck, I. S., Beardsmore, G., Harvey, C.: Cataloging Worldwide Developed Geothermal Systems by Geothermal Play Type, *Proceedings World Geothermal Congress*, (2015)

MoEF: *Indonesia Long-Term Strategy for Low Carbon and Climate Resilience 2050*, s.l.: s.n, (2021)

MoEF: *Enhanced Nationally Determined Contribution, Republic of Indonesia*, s.l.: s.n, (2022)

Mortensen, A. K. et al.: Stratigraphy, alteration mineralogy, permeability and temperature conditions of well IDDP-1, Krafla, NE-Iceland, *Geothermics*, Volume 49, (2014), pp. 31-41

Muraoka, H. et al.: The Japan Beyond-Brittle Project, *Scientific Drilling*, Volume 17, (2014), pp. 51-59

Muraoka, H. et al.: DEEP GEOTHERMAL RESOURCES SURVEY PROGRAM: IGNEOUS, METAMORPHIC AND HYDROTHERMAL PROCESSES IN A WELL ENCOUNTERING 499DEGC AT 2618 m DEPTH, KAKKONDA, JAPAN, *Geothermics*, 27(5/6), (1998), pp. 507-534

Mustika, A. I. et al.: Discovering the Potential of Unconventional Geothermal Systems in Indonesia. *The 8th Indonesia International Geothermal Convention & Exhibition*, (2022)

Newman, G. et al.: The importance of full impedance tensor analysis for 3D magnetotelluric imaging the roots of high temperature geothermal systems: application to the Taupo Volcanic Zone, New Zealand, *Proceedings World Geothermal Congress 2015*, (2015)

Niu, Y.: Lithosphere thickness controls the extent of mantle melting, depth of melt extraction and basalt compositions in all tectonic settings on Earth – A review and new perspectives, *Earth-Science Reviews*, Volume 217, (2021)

Nurseto, S. T. et al.: Structural Geology and Volcanism in Hululais Geothermal Area, Bengkulu, Indonesia, *ITB International Geothermal Workshop 2020*, (2021)

Nusantara, V. D. M.: *Borehole geology of Well HLS-EX Hululais geothermal field, Sumatra Island, Indonesia*, s.l.: University of Iceland, (2022)

Pálsson, B. et al.: Drilling of the well IDDP-1, *Geothermics*, Volume 49, (2014), pp. 23-30

Procesi, M.: The Unconventional Geothermal Resources : Features and Current Uses, *Energy Science and Technology*, Volume 9, (2015)

Purwanto, E. H. et al.: An Updated Statistic Evaluation of Drilling Performance, Drilling Cost and Well Capacity of Geothermal FIelds in Indonesia, *Proceedings World Geothermal Congress 2021*, (2021)

Reinsch, T. et al.: Utilizing supercritical geothermal systems: a review of past ventures and ongoing research activities., *Geothermal Energy* 5(16), (2017)

Scott, S., Driesner, T. & Weis, P.: Geologic controls on supercritical geothermal resources above magmatic intrusions, *Nature Communications*, Volume 6:7873, (2015)

Simatupang, C., Matsuda, K. & Astra, D.: The Initial State Geochemical Model and Reservoir Response of 2 Years Production at Silangkitang, a Fault-Controlled Geothermal System along the Great Sumatera Fault. *Proceedings World Geothermal Congress 2021*, (2021)

Simpson, M. P. & Bignall, G.: Undeveloped high-enthalpy geothermal fields of the Taupo Volcanic Zone, New Zealand, Geothermics, Volume 59, (2016), pp. 325-346

Steingrimsson, B., Gudmundsson, A., Franzson, H. & Gunnlaugsson, E.: EVIDENCE OF A SUPERCRITICAL FLUID AT DEPTH IN THE NESJAVELLIR FIELD, *15th Workshop on Geothermal Reservoir Engineering*, (1990), pp. 81-88

Stimac, J., Goff, F. & Goff, C. J.: Intrusion-related geothermal systems, In: *Encyclopedia of Volcanoes*. s.l.:Academic Press, (2015), pp. 799-822

Stimac, J., Nordquist, G., Aquardi, S. & Lutfhie, S.-A.: An Overview of the Awibengkok Geothermal System, Indonesia, *Geothermics*, Volume 37, (2008), pp. 300-331

Sumardi, J. A. et al.: Indonesia Geothermal Drilling History: What We Can Learn from It?, *Proceedings 47th Workshop on Geothermal Reservoir Engineering*, (2022)

Toni, A., Pratama, R. A., Prasetyo, I. M. & Saputra, M. B.: The Deepest Geothermal Well in Indonesia: A Success Story of Aerated Drilling Utilization, *GRC Transactions*, Volume 40, (2016), pp. 263-270

This page is intentionally left blank

Part 2:
Engineering

Geothermal Power Plants and Energy Transition Mechanism, Unleashed a challenge Under Just Energy Transition Partnership (JETP)

Sugeng Triyono, F. Xaverius Guwowijoyo, and Tarwaji Warsokusumo

PT. PLN Indonesia Power
Indonesia Power Building Fl.7, Jln. Jendral Gatot Subtoto, Kav 18 Jakarta, Indonesia

sugeng@plnindonesiapower.co.id, Guwowijoyo@plnindonesiapower.co.id, arwaji@plnindonesiapower.co.id

Keywords: Keywords: JETP, Energy, transition, CO2, coal, geothermal

ABSTRACT

In lining with the government policy on energy transition mechanism, the international partnership program gives an opportunity to finance renewable energy sector from the Just Energy Transition Partnership (JETP) between Indonesia and its international partners. The target is renewable energy "RE" production to comprise 34% of Indonesia's power generation by 2030, higher than the current RUPTL set up of 25% by 2030. The 34% renewable target is equivalent about 20.000 MWe, that would be coming from additional new RE power plants or cofiring with renewables feed stock on the existing thermal power plants. In 2022 renewable energy contribution is about 13% that equivalent to about 8000 MWe. The JETP mechanism is promised of spending capital of an initial US$20 billion in the financing, that consist of US$10 billion will come from public sector pledges and US$10 billion will be mobilized from private sector financial institutions. The JETP's objectives among others are to cap power sector emissions at 290 megatons of CO2 in 2030, and further to reach net zero emissions in the power sector by 2060. The program is also to accelerate the early retirement of coal-fired power plants, and restriction of new development of coal-fired power plants.

Potential resource of about 28 GW energy from geothermal in Indonesia, should be a low hanging fruit to increase new capacity power plants, utilizing medium enthalpy through more binary power plants. Geothermal is only renewable energy that can provide base loader power plants that like coal power plants, and geothermal has much lower greenhouse gas emissions. Intermittencies energy source of solar PV and wind turbines require a high size and capital cost energy storage during peak hours. Part of the higher upfront costs, infrastructure cost, social cost, and geologic formation of geothermal are solved through providing an incentive, leveraging international partnerships on conducting detailed resource assessments. Further, geothermal energy is a localized site-specific source of a non-tradeable commodity, increases local economy growth, less dependance from volatility international energy market, once power plant is in operation. Though, the geothermal sector could play a greater role on energy transition mechanism towards extending net-zero emissions by 2060.

1. INTRODUCTION

The earth's natural mechanisms to maintain temperature within the range of supporting the habitable life is the accumulation of CO2, CH4, N2O gases in the atmosphere, which act as if a blanket from the sun's heat. This phenomenon is known as the greenhouse gas effect. The greenhouse gases absorb the sun's heat and retain it from reflecting into outer space. The smaller gas blanket is the colder earth's surface temperature, and vice versa. Nowadays gas blanket is too much leading to trigger a climate change, that give more on negative impacts, for example flooding in one areas but doughtiness in different areas, rising sea levels due to sea water expansion, and melting of ice from the earth poles, and occasionally experience extreme heat waves, ecosystem disruption and some of it goes to extinct.

The long lead historically energy supplied including the electricity sector, have been dominated by cheap price coal-fired power plants. Fortunately, this energy is successful driving the economy and people's welfare, especially in the developed countries. The high electricity consumption per capita is a yard stick for the prosperity economic level of the countries. The better prosperity the more electricity being consumed, but the more CO2 emission is released, see Figure 1. Climate change impacts on a global scale. The CO2 emissions in the southern hemisphere will slowly bring a similar negative climate

impact in the northern hemisphere, and vice versa. The meaning is responsible to reduce CO2 actions should be in the hands of all people around the globe.

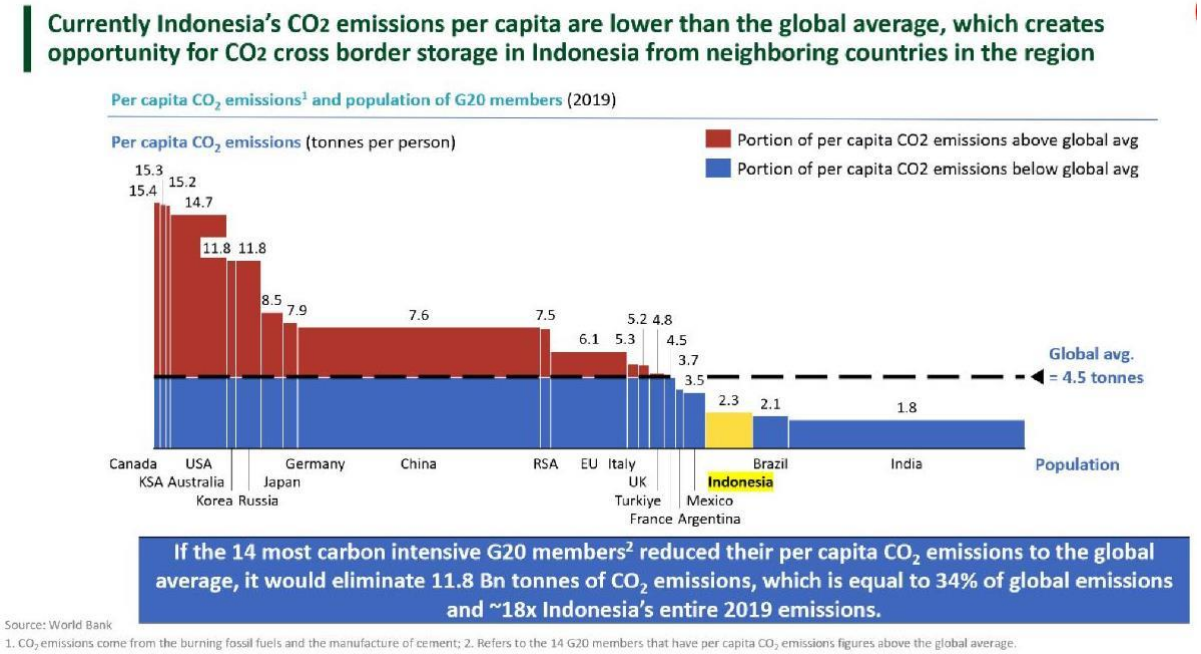


Figure 1: Emission of CO2 per capita in 2019 for different countries.

Business utility companies such as PLN group also embarks for study on potential nuclear power plants to substitute the base loader existing coal fired power plant, that no longer allowed for new coal power plants construction as well as no permit for power plant extension. Introducing CO2 emission tax policy, CO2 emission trading among coal power plants is positive sound to a greener energy sector. Similarly untapped of more than 25 GW geothermal power plants should take the momentum to increase its capacity, as part of solution of a long list construction delayed from geothermal power plants under PLN RUPTL 2021 - 2030.

2. ENERGY TRANSITION MECHANISHM "ETM"

2.1 Implementation Constraints of ETM

The Energy Transition Mechanism "ETM" is a national strategic policy to reduce CO2 emissions, by mutual funding collaboration with developed countries, and optimizing internal funding to move from coal-based energy source to become cleaner renewable and new energy sources. Natural gas fuel will be an intermediary source of fuel before coal is completely avoided.

The first implementation constrain on ETM, is related to the readiness of supply of fuel sources. Unlike fossil energy is available in abundance, renewable energy sources are available small in amount and scattered in locations. Biomass should be planted or biomass waste from plantation, solar energy required a lot amount of land used, as well as wind turbine respectively. sun which can only be harvested during the day while the need for electricity is more at night, as well as wind energy which is very dependent on variations in wind availability.

The second constraint is firming energy to be dispatched anytime the grid needs. Sun energy and wind energy and electricity consumer demand are not always on the same timing, hence energy storage required during night electricity demand, or during the day disruption of in sufficient energy from sun energy during shedding and wind energy requires a significant cost for backup power plants.

The third constraint is transmission infrastructure, which is technically vulnerable to disrupt if the imbalance between electricity supply and consumer demands. Grid frequency is maintained in 50 Hz

should be in the range of 49 – 51 Hz. High penetration of solar PV, especially during short period of shed cloudy area, or a sudden increase / loss wind energy can impact the grid frequency less than 49 Hz, especially on the small grid capacity. Grid failure led to black out on the entire electricity system.

Another business constraint related to providing biomass is maturity biomass business chain. Cofiring and conversion of coal power plant to become completely green biomass steam power plants, offer an advantage of no capital investment up to 5%, utilizing the existing facilities and infrastructure of coal power plants, resulting electricity tariff increase is less in comparison with construction of new renewable power plants. Geothermal construction cost currently is about 3 – 4.5 M USD/MW, that needs 5 – 10 years to in development. In contrast, cofiring is ready to drive whenever supplying biomass available. Nevertheless, geothermal power plants have their own advantages such as locally non tradeable energy, long term sustainability energy business and mostly very stable from volatility global energy market.

2.2 JETP (Just Energy Transition Partnership)

During the G20 summit in Bali in 2022, concluded an agreement on funding commitment to provide financial assistance to Indonesia to participate in reducing CO2 emissions towards NZE 2060 through JETP. The energy transition funding to combat the climate change through partnerships from G7 countries plus Norway and Denmark, include on the various scopes of electric vehicles, technology, and the early shutdown of coal-fired power plants in Indonesia. The financial allocation is about US$20 billion under the JETP framework.

As a reference, visiting delegations from South African and Vietnam to Pelabuhan Ratu coal power plants, at the end of June 2022, the delegates shared their activities and experiences in related to the JETP implementation program. South Africa receives funding from JETP, is in accordance with the 26th Conference of the Parties (COP) in Glasgow, England, in 2021, the financing assistance worth of USA 8.5 million for a period of 3-5 years. The funding went to ESKOM, a utility company in South Africa to reduce CO2 emissions from their coal power plants, through repurposing old coal power to installation of solar PV power plants and providing location for BESS at the previously coal power plants area. Unfortunately, the mismatch between demand - supply capacity needs to anticipate the demand growing loads, and the delay in the development of renewable energy power plants, plus to do an early retired of the coal-fired power plants has an impact on a power balance deficit, that caused regularly rotating blackouts in South Africa. While development of solar PV in Vietnam seem to be more aggressive therefore have a potential risk on resiliency of the electricity grid due to the sun shed on their intermittency solar PV.

The two funding partnership model between JETP in South Africa and JETP Vietnam could be a reference model for JETP's implementation in Indonesia, see table 1.

- JETP South Africa, at the 26th COP in Glasgow, England, in 2021 ago, the Government of South Africa together with the Governments of France, Germany, United Kingdom, United States of America and the European Union, which is also referred to as the International Partners Group (IPG), announced a partnership to mobilize USD 8.5 million over the next 3–5 years to help South Africa decarbonize.

- JETP Vietnam, on 14 December 2022, Vietnam together with the G7 countries plus Denmark and Norway issued a joint declaration to form the Just Energy Transition Partnership This non-binding agreement aims to mobilize at least 15.5 billion USD over the next 3 to 5 years, consisting of 50% sourced from private financial funds and 50% sourced from public sector finance.

- JETP Indonesia, concurrent with the G20 Summit in Bali last November 2022, it was announced that JETP would allocate funding of USD 20 billion, while ETM would allocate USD 500 million in the form of soft funding (Ministry of Finance of the Republic of Indonesia, 2022). JETP's USD 20 billion funding commitment will be mobilized in two ways: USD 10 billion will be mobilized by members of the International Partnership Group (IPG), while

another USD 10 billion will be committed by the Glasgow Financial Alliance for Net Zero (GFANZ) Working Group in collaboration with the Government of Indonesia and IPG.

Table 1: Comparison of JETP in South Africa, Vietnam and Indonesia.

Subject'	South Afrika [1)]	Vietnam[2)]	Indonesia[3)]
Peak CO2 emission	373 MtCO2-eq in 2030	170 MtCO2-eq in 2030	290 MtCO2-eq in 2030
% renewable energy		47% by 2030	34% by 2030
JETP funding commitment	USD 8,5 billion (3–5 years)	15,5 billion USD (3 – 5) years	USD 20 billion (3 – 5) years.
Demand Peak MW	34.660 MW on July 23	45.700 MW on 2022	29.160 MW on June 23

- ✓ [3)] Reach the target of net zero emissions in the power generation sector in 2050, 10 years faster if there is no funding from JETP.
- ✓ [1,2,3)] Acceleration for efficiency programs
- ✓ [1,2,3)] Acceleration of termination of CFSPP operations (early retirement of coal-fired power plants).
- ✓ [1,2,3)] Limiting the construction of new power plants for their own use (captive power).
- ✓ [1,2,3)] Using old coal power plant for other needs, for example as a synchronous condenser, location for BESS, repowering boilers with Nuclear power plants, etc.

2.3 Government of Indonesia / PLN on Energy Transition

CO2 reduction program is also carried out in the very early step, by cancellation for the construction planning of new coal power plants from the list of PLN's RUPTL 2021 – 2030 or before, amounting to 8,770 MW which is equivalent to an estimated of GHG emission reduction equivalent to 64.5 million tones of CO2/year (Wanhar, 2022), figure 6 attachment.

Further CO2 reduction program through retirement of the existing coal power plants, both normal retirement and accelerated retirement of coal power plants, with a certain terms and conditions applied. The CFSPP age under current operation has mostly been extended in accordance with PLN's asset revaluation policy 2015 up to 40 years in operation. The private coal power plants for their own use (Private Power Utility, PPU) have a maximum lifetime of 30 years, life extension is not allowed. IPP (Independent Power Producer) coal power plants, where electricity is sold to PLN for 25-30 years operation permit according to PPA (Power Purchase Agreement) signed. The CFSPP capacity profile (GW) versus year for normal retirement is shown in Figure 2.

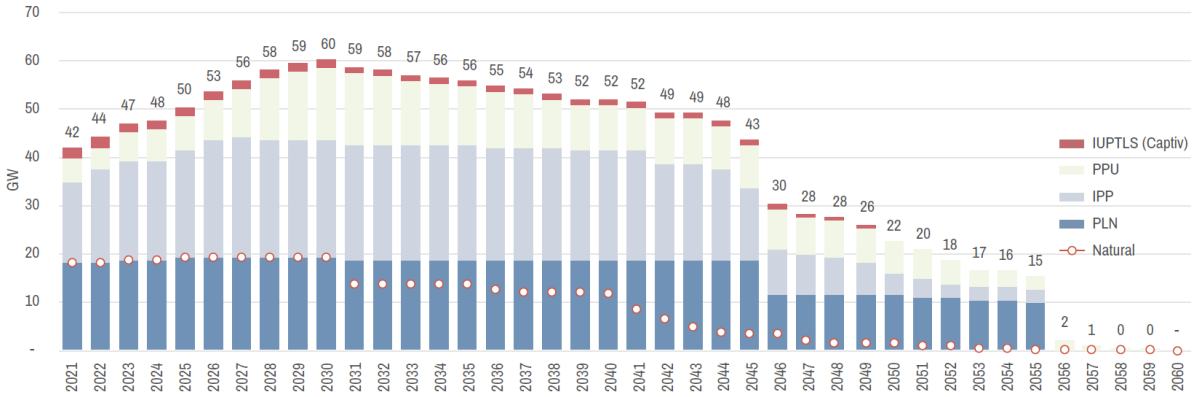


Figure 2: Capacity profiles of CFSPP up to 2060 to achieve NZE 2060.

As an energy substitute due to CFSPP's are no longer operational, the future electricity production is depending on the acceleration development of renewable energy sources power plants and new energy from nuclear power plants. Strategies are as follows.

- The development of intermittent solar power plants and wind power plants will be added with a BESS energy storage system which functions at a minimum as firming capacity to maintain frequency volatility on the grid, and power reserves at night. Massive development of intermittent solar PV and BESS will be built starting in 2030, see figure 7.
- Geothermal power plants are developed in stages to be maximized to achieve the target capacity maximum of about 22 GW, through the development of the Advance Geothermal System and the development of other non-conventional geothermal systems;
- Hydroelectric power plants, where currently most of the availability of water is far from the grid, for example in North Kalimantan and Papua, will be optimized through the construction of transmission to load centers, hydropower operations with reservoirs can function as a balance for the operation of solar PV and wind turbine; see figure 8.
- Large-scale nuclear power plants (NPP) will operate in stages starting in 2039, while SMR (small medium reactor) technology can operate more quickly. Large-scale nuclear power plants as base load bearers are estimated to reach 31 GW in 2060., figure 7

2.4 Java – Bali grid CO2 Emission Record 2011 – 2019

The Java-Bali grid is the largest electricity grid in Indonesia, serving the densely populated islands of Java and Bali. Within the period of 2011 to 2019, the national economic growth of 5% - 7% per year, electricity elasticity is between 1.1 – 1.3, then the electricity growth about of 5.5 – 9.1 % per year. Peak load capacity in 2011 and 2019 was 19.7 GW, and 27.6 GW respectively, that correspond to CO2 emission of about 94.3 million ton and 134.3 million ton per year.

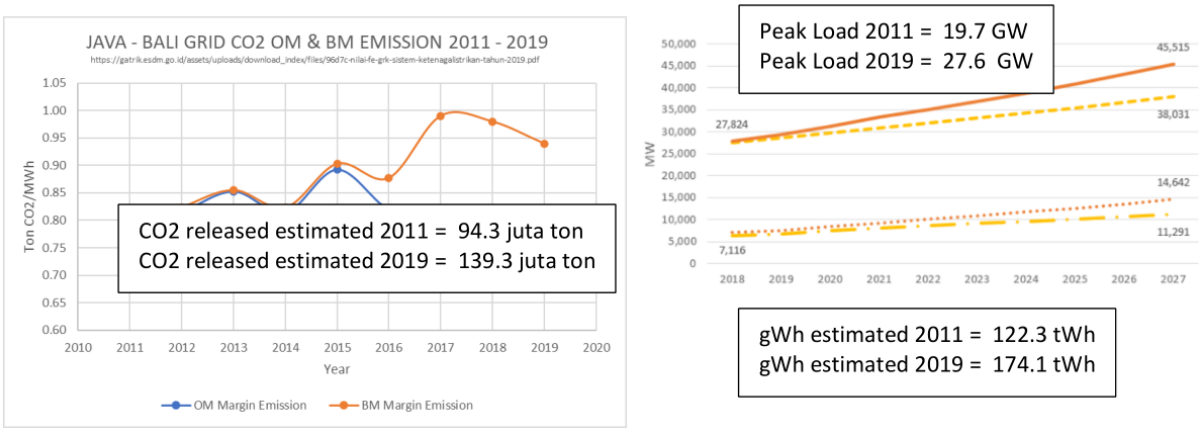


Figure 3: OM & BM CO2 emission margin recorded within period of 2011 – 2019.

Within the period of 2016 to 2019, it is recorded that EM CO2 margin and BM CO2 margin start to be more divers, and expectedly continue onward up to 2035. This is because the available published data during the period of 2011 – 2015 about CO2 emission only based on the calculation of fossil fuel install capacity in the Java Bali grid. The published electricity dispatch data started available since 2016, then the detailed calculation of CO2 emission can be more detailed calculation based on operation of fossil fuel rather than CO2 emission calculated based install capacity, see figure 3. In 2015, the OM and BM CO2 emission margin is about 0.9 ton CO2/kWh, and 2019 of 0.8 ton CO2/kWh for OM margin and 0.95 ton CO2/kWh for BM margin respectively.

To secure the capacity demand, the Government of Indonesia (GoI) announced of a first Fast Track Program (FTP I) in 2006 for developing of 10,000 MW of coal-based power generation, finished in 2014. In 2010 again the GoI announced the second 10,000 MW Fast Track Program (FTP II) that was

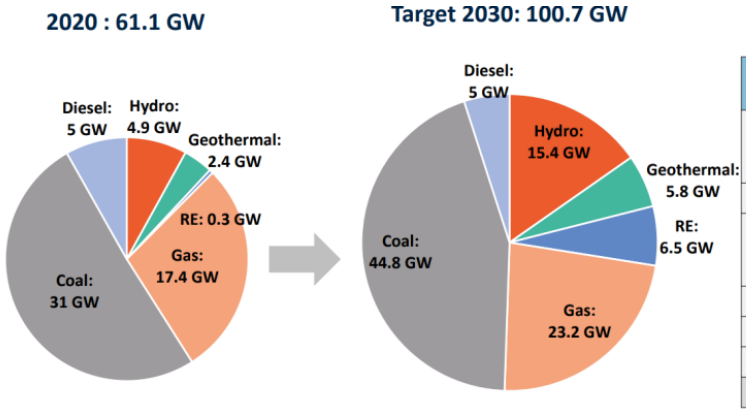
predominantly made up of renewable energy, with geothermal making up 40 percent of the target in 2020. New power plants under FTP-II, is 10.047 MW total capacity consist of Geothermal 4.900 MW, hydro 1.753 MW, and coal and gas power plant of about 5000 MW. The new install capacity of geothermal power plants finished was much less than 1000 MW or 20% from capacity targeted, mostly due to require further detailed on geothermal resource confirmation. The costly and risky financing to drill at a minimum of 3 exploration wells. Similarly, the problem with hydropower plants, the capacity lacks due to delayed of social impact assessment and its permit, and water resource availability.

2.5 Java – Bali grid CO2 Emission Based on PLN RUPTL 2019 – 2028 & 2021 - 2030

The Java-Bali grid's CO2 emissions estimation based on PLN RUPTL (Electricity Supply Business Plan) 2019 – 2028 & 2021, indicates a promising shift towards reducing carbon emissions. The new capacity development from renewable energy within period of 2021 – 2030 is 21 GW, see table 2. The new green power plant will from geothermal of 3,354 MW, hydro of 9,272 MW and solar PV of 4,680 MW. Appendix – 1, shown the geothermal project listed in the PLN's RUPTL that need to more detailed on the resource confirmation goes to 98 locations, while issues on hydro power plants to meeting the target is required new 150 KV transmission, since those hydro resource located far away from load center, and solar PV will have an intermittency issues.

Nevertheless, to achieve these goals, the PLN's RUPTL has sets forth several keys' initiatives, including development of not only land base solar PV but also combination operation of solar PV installed on the hydro dam. The water is stored in the dam during the day, solar PV will fill the area leave by electricity generated from water, then during the night the hydro dam will serve on the load frequency control, as well as during the day when cloud shed on the PV solar panel. Thus, combination of floating solar PV in the hydro dam gives benefit for additional power generation and grid stability at the same time. The RE for base load as per PLN's RUPTL is the meaning of combined intermittency solar PV with battery energy storage, despite the current cost of grid energy storage being considered expensive.

The very promising initiative of CO2 reduction in a fast way is cofiring biomass on coal power plants. The capital required for cofiring is minimal, study shown that up to 5% cofiring biomass to the existing coal power plants will have no impact on operation and maintenance. The current coal install capacity as per 2020 data is 31 GWh, then 5% is about 1500 MW. It will contribute to reducing CO2 emission significantly. In the long term, by converting the existing coal power plants to become green biomass steam power plants, will both utilizing the existing assets and infrastructure to meet NZE 2060, see figure 4.



Technology	RUPTL 2019 – 2028 targets	RUPTL 2021 – 2030 targets	difference
Hydro (and pump storage)	14.5	15.4	6%
Geothermal	5.2	5.8	12%
RE (PV, wind, biomass)	2.6	6.5	145%
Gas	28.8	23.2	-20%
Coal	56	44.8	-20%
Diesel	5	5	-
Total	112.1	100.7	-10%

Figure 4: Planning Profiles of strengthening electricity grid to support the development of RE power plants.

Table 2: New capacity development of renewable energy under PLN'RUPTL 2021-2030.

No	RE – Power Plants	Unit	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030	Total, MW
1	Geothermal	MW	136	108	190	141	870	290	123	450	240	808	3.355
2	Hydro	MW	400	53	132	87	2.478	327	456	1.611	1.778	1.950	9.272
3	Mini Hydro	MW	144	154	277	289	189	43	-	2	13	6	1.118
4	Solar PV	MWp	60	287	1.308	624	1.631	127	148	165	172	157	4.680
5	Wind	MW	-	2	33	337	155	70	-	-	-	-	597
6	Biomass / Waste Power Plant	MW	12	43	88	191	221	20	-	15	-	-	590
7	RE – Base Load	MW	-	-	-	-	-	100	265	215	280	150	1.010
8	RE – Peaker	MW	-	-	-	-	-	-	-	-	-	300	300
Total, MW		MW	752	648	2.028	1.670	5.544	978	991	2.458	2.484	3.370	20.923

3. GEOTHERMAL OPPORTUNITY AND CHALLENGE TO ACHIEVE THE NEW DEVELOPMENT CAPACITY OF ABOUT 3.5 GW ON 2030

3.1 Clean and Base Loader Geothermal Power Plant

The Word bank reported on geothermal clean energy investment (2019), that Indonesia had difficulties in mobilizing financing for the ambitious geothermal development target both globally and within the country, given the challenging investment climate at the time of appraisal. The barriers to investments in geothermal developments included (a) insufficient policy and regulatory support, (b) inadequate incentives and pricing mechanisms that fail to enable investors to secure a return commensurate with higher risks in developing unexplored geothermal fields (that is, green fields), (c) limited institutional capability, and (d) weak domestic capacity in geothermal resource monitoring and assessment and equipment manufacturing. Consequently, geothermal generation capacity was only 1,189 MW at the time of appraisal (2019 see figure 5) which was well below the 4,000 MW short-term FTP II target. Figure 5 shows that geothermal generation capacity expanded only marginally at appraisal.

Figure 5: Geothermal capacity MW gap of 300 – 400 MW in 2022 between target and the current install capacity.

As of December 2022, see table 3, Indonesia is a significant player of harnessing its geothermal capacity, with total capacity stands at approximately 2,344 megawatts (MW). Despite the progress made, there is still 98 geothermal projects under PLN's RUPTL 2021 – 2030 that not able to be meeting the schedule of COD (commercial operation date). see Appendix.

Table 3: the current geothermal power plants in operation as of December 2022.

No.	Area	Steam field Operator	Power Plant Operator	No. of units	Size @ MW	Total , MW
1	Sibayak	PT. Pertamina Geothemal Energy	PT. Pertamina Geothemal Energy	1	10	10
2	Sarula	KKOB Sarula	KKOB Sarula	3	110	330
3	Sorik Merapi	KS Orka	KS Orka	1	42.5	42.5
4	Muara Laboh	PT. Supreme Energy	PT. Supreme Energy	1	85	85
5	Rantau Dadap	PT. Supreme Energy	PT. Supreme Energy	1	98	98
6	Lumut Balai	PT. Pertamina Geothemal Energy	PT. Pertamina Geothemal Energy	1	55	55
7	Ulubelu	PT. Pertamina Geothemal Energy	PT. Pertamina Geothemal Energy	4	55	220
8	Gn. Salak	KKOB Star Energy	PT. PLN Indonesia Power	3	60	180
9	Kamojang	PT. Pertamina Geothemal Energy	PT. PLN Indonesia Power	1	30	30
		PT. Pertamina Geothemal Energy	PT. PLN Indonesia Power	2	55	110
		PT. Pertamina Geothemal Energy	PT. Pertamina Geothemal Energy	1	60	60
		PT. Pertamina Geothemal Energy	PT. Pertamina Geothemal Energy	1	35	35
10	Darajat	KKOB Star Energy	PT. PLN Indonesia Power	1	55	55
		KKOB Star Energy	KKOB Star Energy	1	94	94
		KKOB Star Energy	KKOB Star Energy	1	121	121
		KKOB Star Energy	KKOB Star Energy	3	65	195
11	Wayang Windu	KKOB Star Energy	KKOB Star Energy	1	110	110
		KKOB Star Energy	KKOB Star Energy	1	117	117
12	Patuha	PT Geodipa Energy	PT Geodipa Energy	1	65	65
13	Karaha	PT. Pertamina Geothemal Energy	PT. Pertamina Geothemal Energy	1	30	30
14	Dieng	PT Geodipa Energy	PT Geodipa Energy	1	60	60
		PT. Pertamina Geothemal Energy	PT. Pertamina Geothemal Energy	2	1	2
15	Lahendong	PT. Pertamina Geothemal Energy	PT. PLN (Persero)	4	20	80
		PT. Pertamina Geothemal Energy	PT. Pertamina Geothemal Energy	2	20	40
		PT. Pertamina Geothemal Energy	PT. Pertamina Geothemal Energy	1	0.5	0.5
16	Mataloko	PT. PLN (Persero)	PT. PLN (Persero)	1	2.5	2.5
17	Ulumbu	PT. PLN (Persero)	PT. PLN (Persero)	2	2.5	5
		PT. PLN (Persero)	PT. PLN (Persero)	2	2.5	5
		KS Orka	KS Orka	2	50	100
18	Sokoria	KS Orka	KS Orka	2	3.3	6.6
				34	999.3	2344.1

The untapped geothermal potential is still high in the order of 40 GW, remains beauty to be developed. Achieving this target will require sustained investments, technological advancements, and regulatory reforms to overcome challenges such as project financing, land acquisition, and resource exploration.

Geothermal power plants are naturally base loader power plants because of stiffness operational constraint on managing steam output from wells. Coal power plants are base loader power plants because of a cheaper fuel cost. Even though solar PV and wind turbine is no fuel cost, but these power plants not allowed for base loader operation due to its intermittencies and not firming capacity. When coal power capacity is reduced, following early retirement strategy, changing with renewable energy, then geothermal energy could fill in the slot capacity. Since the MW capacity sizing of geothermal power plants are much smaller than the sizing of coal power plants, this opportunity could be filled in by nuclear power plants. If the base loader capacity gap is fully occupied by nuclear power plants, then geothermal power plants need to be capable of operation in base loader and medium load regime as free governor mode in operation. These necessary modifications will allow long line steam piping system functioning as a steam line energy pack and likewise to install control system facilities at the geothermal wellheads to allow power plant on more adaptive on load variation demand. Success story goes on Darajat 55 MW geothermal power plant, that able operation under free governor requirement since 2021.

3.2 Geothermal Electricity Tariff

The complexity of geothermal resource exploration, including high upfront costs and geological uncertainties, makes it challenging to determine a tariff that adequately reflects these factors. The substantial drilling activities can be risky and costly, which affects the overall project economics and its financing securities. The risk of encountering dry holes on exploration drilling, resulting in the

company not able to pay the loan. Thus, ensuring a fair and attractive tariff that covers these risks and costs while providing a reasonable return on investment is a delicate balance of it.

The Ministry of Energy and Mineral Resources through Regulation No. 17 of 2014 on the Utilization of Geothermal Energy for Power Generation, the ceiling of geothermal tariff is not based on capital investments and O & M cost, but tariff determination is depending on the electricity production cost applied on the region. In consequence, the geothermal tariff will vary on the year of the COD, and grid from aggregate production cost composition of the power plants. For instance, new geothermal power plants located in Java – Bali connect to 150 KV has ceiling tariff in 2014 and 2020 of 11.8 US cent/kwh and 13.8 US cent/kWh. In 2020 electricity production cost in Java Bali is 6.23 US cent/kwh, and as comparison ceiling geothermal tariff is 13.8 cent/kwh. Tariff negotiation under PPA for new geothermal will difficult to meet the mutual benefit between PLN as off taker and geothermal developer, see figure 9.

To avoid a lengthy price negotiation, the government through PLN to do an open tender for new geothermal power plants. The lowest price bidder is not always the preferred bidder, but mostly the lowest price tariff will continue to have tariff approval from the ministry, stated on the PPA. Though, as per RUPTL 2021 – 2030 mostly the geothermal area, about 98 area are not yet ready for geothermal bid, to meet the geothermal target.

4. GEOTHERMAL FINANCING OPPORTUNITY AND CHALLENGE

Geothermal energy financing opportunity in Indonesia, that abundance untapped geothermal resources require a big capital investment opportunity. Assuming total geothermal is close to 25 GW, the current geothermal capacity is 2500 MW, meaning remain of 90% equivalent to 22.5 GW capacity silent on geothermal fields. Assuming 3 – 4 million USD / MW installed, then financing opportunity is 60 – 90 billion USD. Geothermal projects offer long-term, stable returns on investment due to the reliable and consistent nature of geothermal power generation, locally energy used and very stable low influences of the international tradeable volatility energy commodities.

Geothermal de-risking is an approach to mitigate geothermal risk by international cooperation and partnerships with development banks and multilateral institutions in providing financial support and expertise to overcome financing barriers. These strategies in providing fiscal incentives of free imported tax for geothermal capital goods, both during exploration and construction, as well as streamlining regulatory procedures, are a mechanism to mitigate the risks associated with geothermal development

Several financing options and opportunities exist to support geothermal projects in Indonesia:

- Domestic and International Commercial Banks: Commercial banks, both domestic and international, can provide project financing for geothermal developments. These banks offer various financial instruments such as loans, lines of credit, and project finance structures. They assess project viability, risks, and potential returns to determine the financing terms.

- Government Support: The Indonesian government plays a vital role in supporting geothermal development through financial incentives, grants, and guarantees. Government-owned financial institutions, such as PT Sarana Multi Infrastructure (SMI), offer financing and guarantees specifically tailored for renewable energy projects, including geothermal.

- Multilateral and Development Banks: International financial institutions like the Asian Development Bank (ADB), World Bank, and International Finance Corporation (IFC) provide financial support and expertise for geothermal projects. They offer project financing, guarantees, and technical assistance to bridge funding gaps and mitigate risks.

- Public-Private Partnerships (PPPs): Public-Private Partnerships involve collaboration between the government and private sector entities. In Indonesia, the government has implemented PPP schemes to attract private sector investment in geothermal projects. These partnerships can provide access to financing and expertise while sharing project risks and returns.

- Climate Funds and Green Bonds: Climate funds, such as the Green Climate Fund (GCF), provide financial resources for clean energy projects, including geothermal. Green bonds, which are investment vehicles focused on environmentally friendly projects, can also attract investors interested in sustainable energy development.

- Renewable Energy Investment Funds: Specialized renewable energy investment funds, such as private equity funds or infrastructure funds, focus on financing renewable energy projects. These funds seek investment opportunities in geothermal projects and provide long-term capital.

- JETP financing under provision of the G20 Summit in Bali last November 2022, of about USD 20 billion could go to public utility companies such as PT. PLN and subsidiaries, PT. Pertamina geothermal energy and PT. Geodipa. Or, JETP financing goes to government initiative to de-risking geothermal exploration wells. The successful on determination of geothermal resource capacity will subject to announce on international open bid to attract the potential investors under geothermal contract.

Requirement for potential project developers need to demonstrate their technical and economic viability of geothermal projects, conduct thorough risk assessments, and ensure compliance with regulatory requirements. Collaboration with financial institutions, government agencies, and international partners can help unlock the financing potential and accelerate geothermal development in Indonesia.

5. CONCLUSIONS

One of the ETM is to prepare phasing out coal power plants, through accelerated early retirement or natural retirement or repurposing the existing coal power plants for reducing greenhouse gas emissions and combating climate change for making way for cleaner energy alternatives like geothermal, biomass, solar PV, and wind turbine.

This transition may pose on grid operation challenge because the renewable energy source economic challenges do not meet with base loader operation demand. Increase economic electricity tariff may give negative impact on the disruptions on economic growth in the short term, but the long-term benefits in terms of environmental sustainability outweigh the costs.

About more than 20 GW untapped potential for geothermal energy, will require a concerted effort from the government, private sector, and international partners to address de-risking on geothermal development, in order to invite developer and institutional financing on geothermal project.

REFERENCES

Habibi Alhusni, Tito Satria Putra Perdana, Eko Hari Purwanto, Herlambang Setyawan: Geothermal Business Outlook in Indonesia, *Proceedings*, 48th Workshop on Geothermal Reservoir Engineering Stanford University, Stanford, California, February 6-8, 2023

Asian Development Bank and The World Bank.: Unlocking Indonesia's geothermal potential, *Mandaluyong City, Philippines*. 2015

Surya Darma, Yaumil L. Imani, M. Naufal A. Shidqi, Tavip Dwiko Riyanto, M. Yunus Daud: Country Update: The Fast Growth of Geothermal Energy Development in Indonesia, *Proceedings*, Proceedings World Geothermal Congress 2020+1, Reykjavik, Iceland, April - October 2021

Ajeng Rachmatika Dewi Andayani, Andri Akbar Marthen, Henriette Imelda, Kevin Setiadi: Just Energy Transition Partnership (JETP) Indonesia, Indonesia Research Institute for Decarbonization (IRID) December 2022

Ajeng Rachmatika Dewi Andayani, Henriette Imelda, Kevin Setiadi: Just Energy Transition Partnership (JETP) Afrika Selatan, Indonesia Research Institute for Decarbonization (IRID) December 2022

The Ministry of Energy and Mineral: Resources Regulation No. 17 of 2014 on the Utilization of Geothermal Energy for Power Generation, *Jakarta, Indonesia*. 2014

The Ministry of Energy and Mineral: Ministry Regulation No. 169.K/HK.02/MEM/2021 Electricity Production Cost of the National Electricity Company of Indonesia 2020, *Jakarta, Indonesia*. 2021

The World Bank: Geothermal Clean Energy Investment Project, *June 14, 2019*

APPENDIX

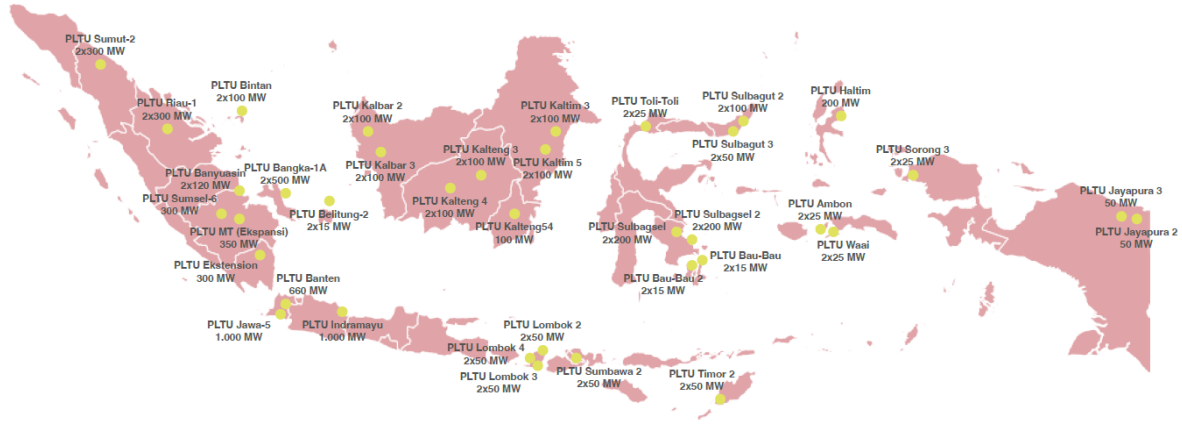


Figure 6: Locations of cancelled new CFSPP 8.770 MW, equivalent to 64,5 million tons CO2/year reduction.

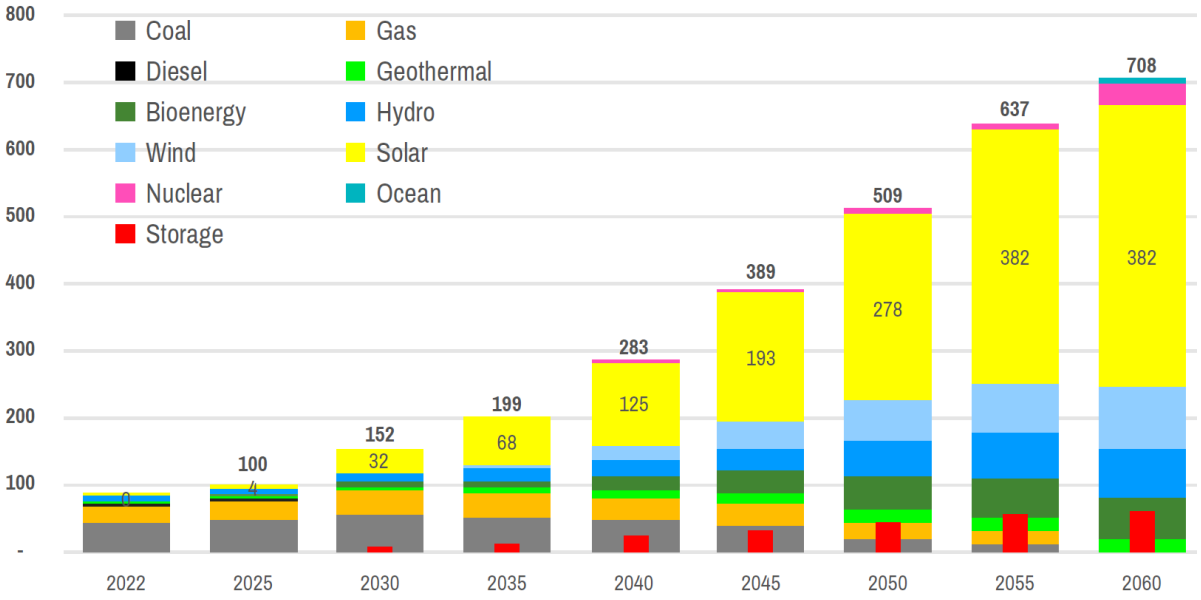


Figure 7: Capacity profiles of CFSPP up to 2060 to achieve NZE 2060.

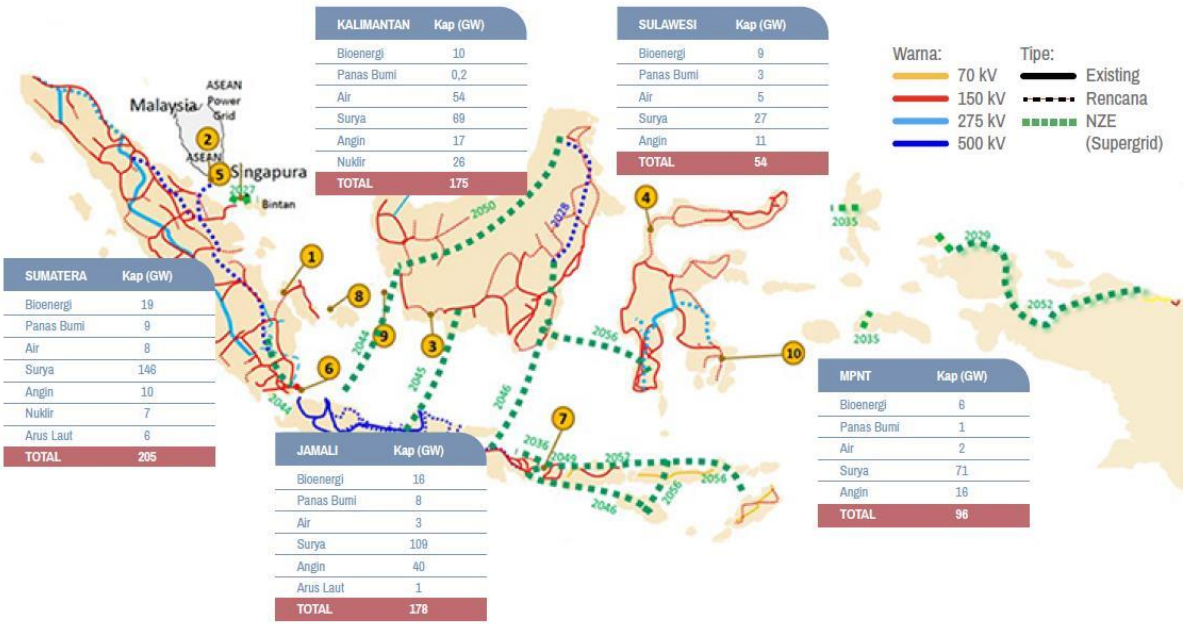


Figure 8: Planning Profiles of strengthening electricity grid to support the development of RE power plants.

Table 4: the current geothermal listed in the PLN' RUPTL needed for further resources confirmation.

No	Nama	Provinsi	Kap. (MW)
1	G. Geureudong	Aceh	50
2	Gn. Kembar	Aceh	330
3	Jaboi (FTP2) #3	Aceh	80
4	Lokop	Aceh	20
5	Seulawah Agam (FTP2) #1	Aceh	55
6	Seulawah Agam (FTP2) #2	Aceh	55
7	Sarulla II #2	Sumut	110
8	Sarulla II #3	Sumut	110
9	Sarulla II (FTP2) #1	Sumut	40
10	Sibual Buali	Sumut	590
11	Simbolon Samosir (FTP2)#1	Sumut	50
12	Simbolon Samosir (FTP2)#2	Sumut	60
13	Sipoholon Ria-Ria (FTP2)	Sumut	10
14	Bonjol (FTP2)	Sumbar	60
15	Cubadak	Sumbar	20
16	Gn. Tandikat & Singgalang	Sumbar	20

No	Nama	Provinsi	Kap. (MW)
61	Gunung Lawu #1	Jateng	55
62	Gunung Lawu #2	Jateng	55
63	Guci #1	Jateng	55
64	Guci #2	Jateng	55
65	Mangunan-Wanayasa	Jateng	40
66	Umbul Telumoyo (FTP2)	Jateng	55
67	Arjuno Welirang	Jatim	185
68	Bromo-Tengger	Jatim	20
69	Gunung Pandan	Jatim	60
70	Gunung Wilis #1	Jatim	10
71	Gunung Wilis #2	Jatim	10
72	Iyang Argopuro (FTP2)	Jatim	55
73	Krucil Tiris	Jatim	30
74	Songgoriti	Jatim	35
75	Banyu Wedang	Bali	10
76	Bedugul	Bali	110

No.	Power Plants	Province	Cap. MW
17	Panti	Sumbar	55
18	Simisioh	Sumbar	55
19	Sumani	Sumbar	20
20	Talamau	Sumbar	20
21	Graho Nyabu #1	Jambi	50
22	Graho Nyabu #2	Jambi	60
23	Sungai Penuh Semurup	Jambi	30
24	Sungai Penuh Small Scale	Jambi	5
25	Sungai Tenang	Jambi	10
26	Lumut Balai #3	Sumsel	55
27	Lumut Balai #4	Sumsel	55
28	Lumut Balai Small Scale	Sumsel	5
29	Margabayur #1	Sumsel	30
30	Margabayur #2	Sumsel	30
31	Tanjung Sakti	Sumsel	55
32	Bukit Daun #1	Bengkulu	55
33	Bukit Daun #2	Bengkulu	30
34	Hululais (FTP2) #3	Bengkulu	55
35	Hululais (FTP2) #4	Bengkulu	55
36	Hululais Small Scale #1	Bengkulu	10
37	Hululais Small Scale #2	Bengkulu	10
38	Lawang-Malintang	Bengkulu	20

No.	Power Plants	Province	Cap. MW
77	Gn. Batur	Bali	40
78	Tabanan	Bali	65
79	Pentadio	Gorontalo	10
80	Puhuwato	Gorontalo	10
81	Suwawa	Gorontalo	20
82	Klabat Wineru	Sulut	40
83	Klabat-Wineru	Sulut	10
84	Kotamobagu I (FTP 2)	Sulut	20
85	Kotamobagu II (FTP 2)	Sulut	20
86	Kotamobagu III (FTP 2)	Sulut	20
87	Kotamobagu IV (FTP 2)	Sulut	20
88	Lahendong #7	Sulut	20
89	Lahendong #8	Sulut	20
90	Lahendong Binary	Sulut	5
91	Lahendong Small Scale #2	Sulut	5
92	Lahendong Small Scale #3	Sulut	5
93	Bora Pulu (FTP 2)	Sulteng	40
94	Kadidia	Sulteng	55
95	Marana (FTP 2)	Sulteng	20
96	Lainea	Sultra	20
97	Bittuang	Sulsel	20
98	Massepe	Sulsel	55

Table 5: the current geothermal status and future developments as per December 2022.

Table A3.1: Project Status

	Project	Probable Capacity by Date	Possible COD Date	Cumulative	Additional Binary Capacity	Binary Date	Cumulative Binary	Total	Status
		MW		MW	MW		MW	MW	
1	Kamojang 1	30	1983	30			0	30	
2	Kamojang 2	55	1987	85			0	85	
3	Kamojang 3	55	1987	140			0	140	
4	Darajat 1	55	1994	195			0	195	
5	Salak 1 & 2	120	1994	315	18	2014	18	333	
6	Salak 3	120	1997	435	18	2014	36	471	
7	Salak 4	197	1997	632	30	2014	66	697	
8	Darajat 2	95	2000	727			66	792	
9	Wayang Windu 1	110	2000	837	5	2014	71	907	
10	Lahendong 1	20	2001	857	3	2014	74	930	
11	Mataloko	2.5	2004	859			74	933	
12	Darajat 3	110	2009	969			74	1,043	
13	Lahendong 2	20	2007	989	3	2014	77	1,066	
14	Kamojang 4	60	2008	1.049			77	1,126	
15	Sibayak	13.3	1998/ 2008	1,063			77	1,139	Significant resource issues probably preclude expansion
16	Wayang Windu 2	117	2009	1,180			77	1,256	
17	Lahendong 3	20	2009	1,200	3	2014	80	1,279	
18	Ulumbu	5	2012	1,205			80	1,284	Drilling complete
19	Lahendong 4	20	2012	1,225	3	2014	83	1,307	
20	Ulubelu	110	2012	1,335	16.5	2014	99	1,434	Running at ~80 MW because of resource constraints but those should be solvable

	Project	Probable Capacity by Date	Possible COD Date	Cumulative	Additional Binary Capacity	Binary Date	Cumulative Binary	Total	Status
		MW		MW	MW		MW	MW	
21	Mataloko	5	2013	1,340			99	1,439	Drilling complete (not confirmed)
22	Ulumbu	5	2013	1,345			99	1,444	Drilling complete (not confirmed)
23	Dieng	40	2014	1,385			99	1,484	Not currently operating; may be repaired to 80% capacity
24	Ulumbu	5	2014	1,390			99	1,489	Part drilled
25	Ulumbu 4	2.5	2015	1,392			99	1,491	Field drilled, but not necessarily this part
26	Lumut Balai 1 & 2	110	2016	1,502	16.5	2016	116	1,618	Part drilled but low success
27	Sarulla 2 (Silangkitang)	80	2016	1,582	6	2017	122	1,704	Part drilled, successful but small field
28	Kamojang 5	30	2014	1,612			122	1,734	Drilling complete
29	Ulumbu 5	2.5	2016	1,615			122	1,736	Field drilled, but not necessarily this part
30	Ulubelu 3 & 4	100	2016/2017	1,715	15	2018	137	1,851	Part drilled, moderate success, may be pushing limit of field capacity so down-rated
31	Muara Laboh	110	2017	1,825	16.5	2017	153	1,978	Exploration drilled, some success
32	Sarulla 1 (Namora-I-Langit)	220	2017	2,045	33	2017	186	2,231	Exploration drilled, some success, but difficult terrain, high gas, acidity
33	Sungai Penuh	110	2017	2,155	16.5	2017	203	2,357	Drilling just started; surface exploration advanced; part in national park
34	Karaha	30	2017	2,185	4.5	2018	207	2,392	Part drilled, moderate success, total capacity probably larger than shown
35	Wayang Windu 3	110	2017	2,295			207	2,502	Part drilled, moderate success
36	Lahendong 5 & 6	40	2017	2,335	6		213	2,548	Part drilled, low success, pertamina threatening to stop
37	Jailolo	10	2017	2,345			213	2,558	Not yet drilled, surface exploration advanced, potential market may be larger if mining goes ahead

	Project	Probable Capacity by Date	Possible COD Date	Cumulative	Additional Binary Capacity	Binary Date	Cumulative Binary	Total	Status
		MW		MW	MW		MW	MW	
38	Lumut Balai 3 & 4	110	2018	2,455	16.5	2018	230	2,684	This part not drilled yet, surface exploration advanced
39	Margabayur	55	2018	2,510	8.25	2018	238	2,747	Surface exploration advanced but not drilled within lumut balai wkp
40	Hululais	110	2018	2,620	16.5	2018	254	2,874	Exploration drilled, drilling problems
41	Rajabasa	110	2018	2,730	16.5	2018	271	3,000	Not yet drilled, land access issues
42	Cibuni	10	2018	2,740			271	3,010	One exploration well. Next to patuha - boundaries not clear
43	Wayang Windu 4	110	2018	2,850			271	3,120	Part drilled, moderate success
44	Patuha 1	110	2014	2,960			287	3,247	~50% drilled
45	Atadei	5	2018	2,965			287	3,252	Shallow drilled, resource may be larger than market
46	Hu'u Daha 1	20	2018	2,985			287	3,272	Not yet drilled, surface exploration advanced, market may be larger if mines can be supplied
47	Sokoria	15	2018	3,000			287	3,287	Shallow drilled, surface exploration advanced
48	Seulawah Agam	55	2019	3,055	8.25	2019	296	3,350	Shallow drilled, may be smaller demand than planned
49	Sorik Merapi	110	2019	3,165	16.5	2019	312	3,477	Not yet drilled, surface exploration advanced otp proceeding slowly, may be serious technical issues and some volcanic risk
50	Rantau Dedap	220	2019	3,385	33	2019	345	3,730	Part exploration drilled, should be a good field
51	Suoh Sekincau	220	2019	3,605	33	2019	378	3,983	Not yet drilled. Suoh and sekincau are 2 separate fields, may be technically difficult
52	Jaboi	7	2019	3,612			378	3,990	Not yet drilled

	Project	Probable Capacity by Date	Possible COD Date	Cumulative	Additional Binary Capacity	Binary Date	Cumulative Binary	Total	Status
		MW		MW	MW		MW	MW	
53	Rawa Dano	110	2019	3,722	16.5	2019	395	4,116	Shallow drilled, not successful but looks promising
54	Kamojang 6	60	2019	3,782			395	4,176	One well drilled, good success in field overall
55	Mataloko 2	5	2019	3,787			395	4,181	Shallow drilled
56	Way Ratai	55	2020	3,842	8.25	2020	403	4,244	Not yet drilled
57	Gunung Talang	20	2020	3,862			403	4,264	Not yet drilled, volcanic risk, preliminary exploration not promising; figure based on assuming this heading refers to bukit kili
58	Simbolon Samosir	20	2020	3,882			403	4,284	Not yet drilled, preliminary exploration not encouraging
59	Patuha 2 & 3	110	2020	3,992		2020	419	4,411	Part drilled, moderate success; this capacity only achievable if it includes the cibuni sector
60	Tampomas	0	2020	3,992			419	4,411	Not yet drilled, preliminary exploration not encouraging
61	Ungaran 1	55	2020	4,047	8.25	2020	428	4,474	Not yet drilled
62	Ngebel / Wilis	40	2020	4,087	6	2020	434	4,520	Shallow drilled, surface exploration advanced but not encouraging
63	Dieng	55	2020	4,142	8.25	2020	442	4,583	Not yet drilled, assuming this applies to the other fields within the Dieng WKP
64	Ciremai	40	2020	4,182	6	2020	448	4,629	Not yet drilled, only basic exploration done
65	Gunung Endut	40	2020	4,222	6		454	4,675	Not yet drilled
66	Guci	0	2020	4,222			454	4,675	Not yet drilled
67	Ungaran 2	20	2020	4,242			454	4,695	Not yet drilled
68	Umbul Telomoyo	20	2020	4,262			454	4,715	Not yet drilled, only basic exploration done

	Project	Probable Capacity by Date	Possible COD Date	Cumulative	Additional Binary Capacity	Binary Date	Cumulative Binary	Total	Status
		MW		MW	MW		MW	MW	
69	Iyang Argopuro 1	20	2020	4,282			454	4,735	Not yet drilled, only very basic exploration done
70	Tulehu	20	2020	4,302			454	4,755	Not yet drilled, may not be very large
71	Songa Wayaua	5	2020	4,307			454	4,760	Not yet drilled, surface exploration not promising; may only be ok for binary
72	Bora	5	2020	4,312			454	4,765	Not yet drilled
73	Mataloko 3	5	2020	4,317			454	4,770	Shallow drilled
74	Ulumbu 3	5	2020	4,322			454	4,775	Field drilled, but not necessarily this part
75	Kotamobagu 1	40	2020	4,362	6		460	4,821	Drilled, some success
76	Kotamobagu 2	40	2020	4,402	6		466	4,867	Drilled, some success
77	Jailolo 2	5	2020	4,407			466	4,872	Not yet drilled, surface exploration advanced
78	Bonjol	40	2021	4,447	6	2021	472	4,918	Not yet drilled, only basic exploration
79	Danau Ranau	40	2021	4,487	6	2021	478	4,964	Not yet drilled, only basic exploration
80	Kepahiyang	40	2021	4,527	6	2021	484	5,010	Not yet drilled, only basic exploration
81	Bedugul	50	2021	4,577	5	2021	489	5,065	Part drilled, moderate success, but stalled by environmental issues, unlikely to be resolved soon
82	Gunung Lawu	20	2021	4,597			489	5,085	Not yet drilled, may be technical issues
83	Mataloko 4	5	2021	4,602			489	5,090	Shallow drilled
84	Oka Larantuka	3	2021	4,605			489	5,093	Not yet drilled, only very basic exploration
85	Lainea	20	2021	4,625			489	5,113	Not yet drilled, only very basic exploration
86	Sokoria 4	5	2021	4,630			489	5,118	Not yet drilled
87	Tangkuban Perahu 2	0	2022	4,630			489	5,118	Not yet drilled, may not be technically feasible

	Project	Probable Capacity by Date	Possible COD Date	Cumulative	Additional Binary Capacity	Binary Date	Cumulative Binary	Total	Status
		MW		MW	MW		MW	MW	
88	Sipoholon Ria-Ria	0		4,630			489	5,118	Not yet drilled, preliminary exploration not encouraging
89	Cisolok Cisukarame	0		4,630			489	5,118	Drilled, unsuccessful
90	Tangkuban perahu 1	0		4,630			489	5,118	Not yet drilled, preliminary exploration not encouraging
91	Cisolok Cisukarame 2 & 3	0		4,630			489	5,118	Not yet drilled
92	Batu Raden	0		4,630			489	5,118	Not yet drilled, surface exploration advanced but not very encouraging
93	Ijen	0		4,630			489	5,118	Shallow drilled, may be serious issues with acidity
94	Arjuno Welirang	0		4,630			489	5,118	Not yet drilled, may be serious technical issues
95	Iyang Argopuro 2			4,630			489	5,118	Not yet drilled
96	Marana/Masaingi	0		4,630			489	5,118	Shallow drilled, surface exploration not promising
97	Hu'u Daha 2	0		4,630	0		489	5,118	Not yet drilled, surface exploration advanced, but no evidence of large resource
98	Sembalun	0		4,630	0		456	5,118	Not yet drilled

COD = commercial operation date, MW = megawatt, WKP = *wilayah kerja pertambangan* (geothermal work area).

Sources: Estimates of capacity are based on Castlerock Consulting. 2010. *Phase 1 Report: Review and Analysis of Prevailing Geothermal Policies, Regulations and Costs.* Jakarta: Ministry of Energy and Mineral Resources, as modified by more recent information, and as assessed by the technical experts on the study team. The estimates of COD are based on *PT Perusahaan Listrik Negara* (State Electricity Company of Indonesia). 2013. *Rencana Usaha Penuyediaan Tenaga Listrik* (RUPTL) (Electricity Power Supply Business Plan 2012-2021). Jakarta; Castlerock. 2010. Phase 1 Report.

LAMPIRAN
KEPUTUSAN MENTERI ENERGI DAN SUMBER DAYA MINERAL
REPUBLIK INDONESIA
NOMOR : 169.K/HK.02/MEM.M/2021
TANGGAL : 8 September 2021
TENTANG
BESARAN BIAYA POKOK PENYEDIAAN PEMBANGKITAN
PT PERUSAHAAN LISTRIK NEGARA (PERSERO) TAHUN 2020

BESARAN BIAYA POKOK PENYEDIAAN PEMBANGKITAN
PT PERUSAHAAN LISTRIK NEGARA (PERSERO)
TAHUN 2020

NO	WILAYAH / DISTRIBUSI / SISTEM / SUB SISTEM		BPP Pembangkitan	
			(Rp/kWh)	(cent US$/kWh)*
A	**SUMATERA**			
1	**SUMATERA BAGIAN UTARA**			
	a	**ACEH**	**1.349,72**	**9,26**
	a.1	Pulau Weh	1.995,80	13,70
	a.2	Pulau Simeulcu	2.148,71	14,75
	b	**SUMATERA UTARA**	**1.247,24**	**8,56**
	b.1	Nias	2.805,50	19,25
2	**SUMATERA BAGIAN TENGAH DAN SELATAN**			
	a	**SUMATERA BARAT**	**995,58**	**6,83**
	a.1	Kepulauan Mentawai	2.319,63	15,92
	b	**RIAU DAN KEPULAUAN RIAU**		
	b.1	**Riau**	**1.374,43**	**9,43**
	b.2	**Kepulauan Riau**		
	b.2.1	Bintan	1.833,55	12,58
	b.2.2	Tanjung Balai Karimun	1.544,96	10,60
	b.2.3	Natuna	1.972,24	13,53
	b.2.4	Anambas	1.994,58	13,69
	c	**SUMATERA SELATAN, JAMBI, BENGKULU (S2JB)**	**1.038,29**	**7,13**
	c.1	Pulau Enggano	2.805,50	19,25
	d	**LAMPUNG**	**995,98**	**6,83**
3	**BANGKA**		**2.006,52**	**13,77**
4	**BELITUNG**		**1.962,01**	**13,46**
5	**SUB SISTEM KECIL LAINNYA**		**2.805,50**	**19,25**
B	**JAWA BALI**			
1	**DKI JAKARTA**		**908,15**	**6,23**
	a	Kepulauan Seribu (terkoneksi kabel laut)	848,71	5,82
2	**BANTEN**		**907,75**	**6,23**
	a	Pulau Panjang	2.805,50	19,25
3	**JAWA BARAT**		**907,93**	**6,23**

NO	WILAYAH / DISTRIBUSI / SISTEM / SUB SISTEM		BPP Pembangkitan	
			(Rp/kWh)	(cent US$/kWh)*
4	JAWA TENGAH		907,77	6,23
	a	Karimun Jawa	2.805,50	19,25
5	JAWA TIMUR		911,59	6,26
	a	Madura Isolated	2.052,80	14,09
	b	Bawean	2.805,50	19,25
	c	Gili Ketapang	2.136,16	14,66
6	BALI		908,03	6,23
	a	Tiga Nusa (Nusa Penida, Nusa Lembongan, Nusa Ceningan)	1.935,97	13,29
7	SUB SISTEM KECIL LAINNYA		2.805,50	19,25
C	KALIMANTAN			
1	KALIMANTAN BARAT		1.539,19	10,56
2	KALIMANTAN SELATAN DAN TENGAH		1.244,07	8,54
3	KALIMANTAN TIMUR DAN UTARA		1.321,11	9,07
4	SUB SISTEM KECIL LAINNYA		2.805,50	19,25
D	SULAWESI			
1	SULAWESI UTARA, TENGAH, DAN GORONTALO			
	a	Sulawesi Bagian Utara (Manado, Gorontalo, Kotamobagu)	1.540,41	10,57
	b	Toli – Toli	1.914,90	13,14
	c	Tahuna	2.192,08	15,04
	d	Palu, Poso (Grid Sulbagsel)	1.090,58	7,48
	e	Luwuk	1.664,79	11,42
2	SULAWESI SELATAN, TENGGARA, DAN BARAT			
	a	Sulawesi Bagian Selatan (Sulawesi Selatan dan Sulawesi Barat)	959,02	6,58
	b	Kendari	1.059,86	7,27
	c	Bau – Bau	1.570,47	10,78
	d	Selayar	2.411,58	16,55
3	SUB SISTEM KECIL LAINNYA		2.805,50	19,25
E	NUSA TENGGARA			
1	NUSA TENGGARA BARAT			
	a	Tambora (Bima dan Sumbawa)	1.841,12	12,63
	b	Lombok	1.715,65	11,77
2	NUSA TENGGARA TIMUR			
	a	Sumba	2.147,66	14,74
	b	Timor	2.067,93	14,19
	c	Flores Bagian Barat	1.634,50	11,22
	d	Flores Bagian Timur	1.856,59	12,74
3	SUB SISTEM KECIL LAINNYA		2.805,50	19,25
F	MALUKU DAN PAPUA			
1	MALUKU DAN MALUKU UTARA			
	a	Ambon	2.413,34	16,56
	b	Seram	2.168,81	14,88
	c	Saparua	2.503,68	17,18
	d	Buru	2.351,91	16,14

Figure 9: geothermal ceiling tariff in accordance with ministry regulation 2014.

Using High-Pulsed Power for Successful Scale Removal in Geothermal

Chris Graham, Charles Fensky, and Mike Perri

Blue Spark Energy Inc.
Unit 134, 4303 – 26 Street NE, Calgary AB Canada T1Y 7K2

c.graham@bluesparkenergy.com

Keywords: Scale, High-Pulsed Power

ABSTRACT

BLUESPARK® technology offers a solution for fixing flow impediments that are caused by downhole scaling in geothermal wells using a proven solution from the petroleum industry. Our paper will overview the applicability of BLUESPARK® technology in geothermal wellbores and our innovations to further adapt to geothermal conditions.

The impact of scale accumulation can be significant for geothermal wells. The scale accumulation on both the near wellbore region and the casing often results in reduced flow and well performance. A technique using downhole pulsed power shockwaves has been used to remove scale in these locations successfully for nearly a thousand wells in the petroleum industry. This technology has recently been applied to geothermal wells, resulting in significant increases in flow. Details of these operations, including the outcomes, will be discussed. In addition to increased well productivity, this solution has many environmental benefits by not requiring any chemicals, in addition to having a very low carbon footprint.

BLUESPARK® technology is based on an electro-hydraulic tool that produces a shock wave using existing fluid in the well, powerful enough to break down scales in the well. Each hydraulic impulse travels at more than 1,500 meters per second, followed by a +10,000-psi high-pressure pulse. The shockwave opens existing fractures for the pressure pulse to dislocate any blockage at any depth.

Using a small amount of electrical energy, this engineered solution is reliable and efficient in tackling well scaling, reducing risk, and saving money on operations compared to conventional methods like reaming, scraping, hydro blasting, and acidizing.

1. INTRODUCTION

Geothermal energy will become a more important energy source globally in the coming decades. This industry will continue to grow and will become a more significant contributor to the movement towards renewable energy. It uses the natural heat from below the earth's surface to heat water which is circulated downhole and then back to the earth's surface. That thermal energy can be used directly for heating, but also for electricity generation. One specific technical challenge of this process is that there is usually also the production of scale. The changes in temperature and pressure cause the naturally occurring ions in the water to form scales within the wellbore. The typical scale types that would be encountered in a geothermal wellbore are calcium carbonate scales, silica-based scales, and metal sulfide & sulphate scales. The industry has pursued a variety of solutions to this challenge. Conventional approaches of mechanical scale removal devices and chemical treatments do work but have challenges (Thorhallsson, 2003). An alternative commercial scale removal solution from the petroleum industry that has been applied on many wells globally uses high-pulsed power to create scale-breaking pressure and shockwave pulses (Habibi et al., 2020a). This high-pulsed power technique has now been applied to geothermal wells with successful results.

2. CONVENTIONAL SCALE REMOVAL TECHNIQUES

Scale accumulation is a common problem in geothermal wells and these wells can have a variety of scales (Matoorian et al., 2022). The removal of scale has traditionally used two fundamental approaches of either mechanical techniques of scale removal such as milling, broaching, or dredging, or has used the technique of applying chemicals that dissolve or impede scale formation. Mechanical techniques can be effective but often involve the higher cost of using a drilling or service rig to perform the

operation. This technique has limitations that for the scale to be removed, the mechanical device needs to be in physical contact with the scale. The milling bit will only remove the scale that it touches which results in scale not being cleaned from areas beyond the bit OD such as completion profiles, perforations, and wellbore fractures. Chemical solutions have also had challenges, as they need to be the right chemical for the right scale. In simple homogenous situations this is not a problem, however when you have many different scale types in the same wellbore, its effectiveness can be reduced (Elfajrie et al., 2020). Chemical solutions for scale removal can be applied by injecting the chemical from surface where it flows down the well, dissolving the scale. This approach, although simple, has challenges as many of the acids used to dissolve scale will also dissolve and corrode the metal well completion. Application of the acid from surface also has no control on the precise location the acid will be applied. The chemical treatment can however be precisely applied using coiled tubing or drilling equipment, and this approach has had good results but adds significant extra cost (Flores-Armenta and Alcala, 2012). A hybrid solution has been used where high-pressure pumps spray water to hydro-blast the scale which has been effective in soft scales, but the pressure needs to be of sufficient magnitude to exceed the material strength of the scale.

3. HIGH-PULSED POWER APPROACH FOR SCALE REMOVAL

High-pulsed power is not a new technology. It is the process by which electrical energy is stored over a brief period of time in capacitors, followed by all of the stored energy being released in an extremely short time to substantially amplify the power produced. The downhole scale removal with high-pulsed power is done using an electric wireline unit that lowers a tool into the wellbore. This tool is positioned at the precise locations where the scale is to be removed. When electricity is applied to the wireline tool it creates high pressure pulses that can be used to remove scale or stimulate the well (Harthy et al, 2019).

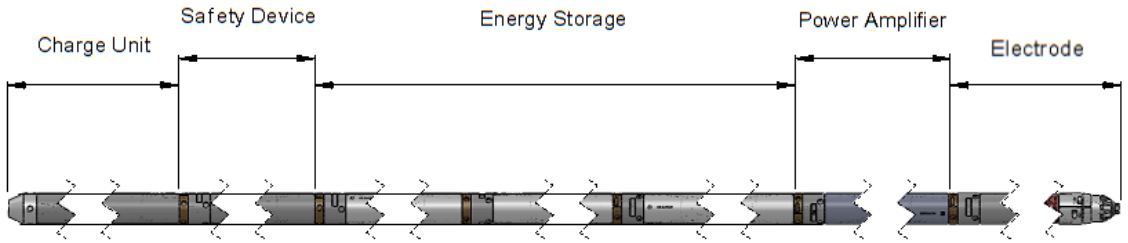


Figure 1: A typical BLUESPARK® toolstring, showing the major components of the downhole tool.

The high-pulsed power tool uses a combination of simple and advanced technology to transform the electrical energy into a high-pressure shockwave using the following technique. Low voltage is sent from the wireline unit through an electric wireline cable that connects to the downhole high-pulsed power tool. The tool transforms the voltage from a low value to a very high value. The electrical energy is stored in customized, proprietary high-pulsed power capacitors. The very high voltage allows for significant energy storage capacity per unit volume. Once the capacitors have reached their storage limit, a special switch is used to drain those capacitors very quickly, causing the power amplification (energy is stored for approximately 5 seconds and then released in about 5 micro-seconds, resulting in a power amplification of up to 1 million times). That amplified power is applied to a device that transforms the electrical power into a pressure wave. This conversion occurs by the following method: the electricity flows through an electrolyte solution between two electrodes whichh causes the electrolyte to become superheated, conducting the electrical energy in the form of a plasma arc. The plasma arc generates a very high temperature and the water that is in contact with it experiences rapid thermal expansion. This thermal expansion is the source of the high-pressure wave, and the instant the plasma arc is formed a shock wave is also created. The plasma arc lasts a very short time and the high-pressure wave it creates is also of very short duration, in the range of a few milliseconds. This high-pressure wave radiates away from the downhole tool and passes through the wellbore fluid to the scale.

If the amplitude of the high-pressure wave is sufficient to exceed the mechanical properties of the scale materials, it will cause those brittle scale materials to break.

Given that the high-pressure wave generated by the downhole high-pulsed power tool is of a very short time duration, it has no effect on plastic or ductile materials. In fact, for ductile materials such as metal casings, most of the energy is reflected on impact, creating tensile forces on the brittle scale which results in removal of the scale from the metal surface. Several pulses are used for scale removal depending on the scale type and cleaning objective (Habibi et al, 2020b). The process of downhole scale removal involves positioning the high-pulsed power tool at targeted intervals of 12" (0.3 m), performing 30-60 pulses, then moving to the next target interval. This allows for precise application over any location in the wellbore. This "stop and pulse" process is used over any target areas that have scale accumulation, with the treatment interval only being limited by the life of the electrodes used to make the plasma arc. Each set of electrodes lasts for many thousands of pulses.

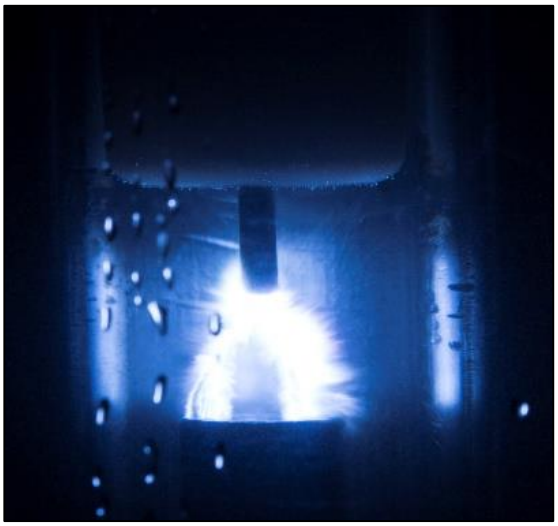


Figure 2: The plasma arc created between the electrodes of the BLUESPARK® tool.

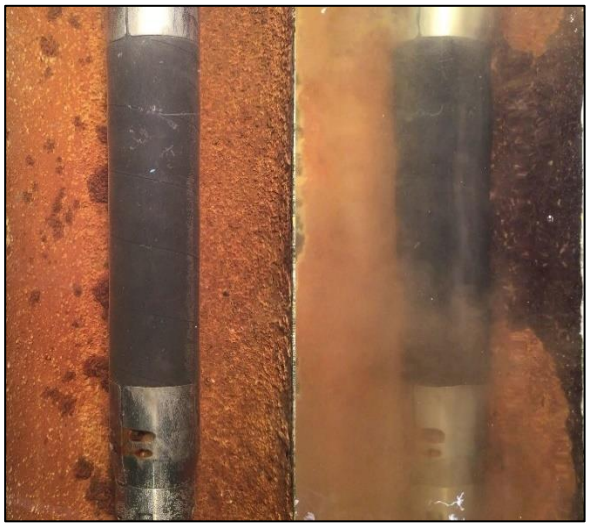


Figure 3: A section of scaled-up casing is shown on the left, with the electrode section of the BLUESPARK® tool above it. On the right is that same section of casing after 2 pulses from the BLUESPARK® tool.

An impediment to the high-pulsed power technique for scale removal is that to use it you need to be able to position the wireline tool adjacent to the scale. This high-pulsed power wireline tool is 2.75 inches in diameter and there needs to be sufficient clearance to pass through the scale. Some proactive well operators use the high-pulsed power tool to prevent this excessive scale build up as regular preventative maintenance. This works well as using the high-pulsed power technique does not cause any chemical corrosion nor any mechanical damage to the wellbore surface and can therefore be used as often as is required.

4. EXPERIENCE IN OIL AND GAS WELLS

The high-pulsed power downhole tool has been used in oilfield applications for over a decade. It has been used for both scale removal and to stimulate reservoirs by remediating near-wellbore damage in both production and injection wells. The results have been validated with caliper pre and post treatment and by well production details.

Table 2: Overview of oil & gas field case studies conducted for wells plugged by different types of components (Habibi et al, 2020a).

ID	Formation or Equipment	Country	Lithology	Depth, m	Temperature, C	Completion	Well type	Challenge
1	Montney shale	Canada	Silty shale	1900	65	Perforated	Vertical, production	$CaCO_3$-scale
2	SSSV	Norway	NA	550		NA	Deviated, production	$CaCO_3$-scale
3	Gething Formation	Western Canada	Sandstone	1500	35	Perforated,	Vertical, production	Carbonate scale
4	Casing	South west Texas, USA	Sandstone	550	NA	Perforated	Vertical, artificial lift	$CaCO_3$-scale
5	Slave Point	Western Canada	Limestone	1800	45	Perforated	Vertical	$CaCO_3$-scale
6	Clearwater	Canada	Shale	2000	<130	Cyclic steam	Horizontal, changing from production to injection	$CaCO_3$
7	Tubing	Denmark	NA	1770	NA	NA	Deviated, production	$CaCO_3$
8	SSSV	Denmark	NA	564	42	NA		$CaCO_3$
9	Permian Basin	USA	Sandstone	1600	NA	Perforated	Vertical, artificial lift	$BaSO_4$
10	---	USA	Sandstone	1460-1585	NA	Perforated	Vertical, production	$BaSO_4$
11	NA	Norway	Sandstone	3400	120	Premium screen, perforated liner	Horizontal, production	$BaSO_4$
12	SPM/GLV	Denmark	NA	2400	80	NA	Horizontal, production	$BaSO_4$
13	SSSV	Norway	NA	4700	NA	NA	Deviated, production	$BaSO_4$
14	San Andres	USA	Carbonate	1200	NA	Perforated	Vertical, production	$CaSO_4$-scale
15	Montney	Canada	Silty shale	1800	60	Perforated	Vertical, injection	Scale and suspended solids
16	SPM/GLV	Equatorial Guinea	NA	1830	60	NA	Horizontal, production	Scale

5. GEOTHERMAL WELL RESULTS

The high-pulsed power tool has successfully remediated flow issues on a few geothermal injection wells in the Asia Pacific region that had reduced injection rates related to scale accumulation. The high-pulsed power treatment was applied to the areas where the scale accumulation was preventing the injection water from entering the formation. The process used for the geothermal treatment was to first prepare the well so that the wireline tool could be run. The wells were then cooled as the reservoir temperature exceeded the current tool rating of 130 °C. The high-pulsed power treatment was then applied, followed by the wells being put back on injection. It was observed that there was a significant reduction in injection pressure, indicating that the flow blockage was removed and that the wells were restored to injection levels consistent with what was expected for the well. Several additional geothermal well treatments are scheduled for later this year.

6. CONCLUSIONS

This paper has reviewed the high-pulsed power technology that has been successfully used in the oil and gas industry to remove scale from casing and other completion components inside the wellbore. That same technology has now been deployed in several geothermal wells with similar success. Those wells exhibited a decrease in injection pressure and an increase in water injection rate.

The main conclusions of this paper, as to how the BLUESPARK® technology applies to the geothermal industry are:

- The technology is safe to use within the completion of a geothermal well as it will not cause any damage
- The technology is very safe for the environment as it uses no chemicals and it also has a very low carbon footprint
- The technology successfully removes all types of scale
- The technology is easy to deploy and is efficient to use, as the exact intervals with scale build-up can be targeted directly

REFERENCES

Elfajrie, I. et al: Well Intervention and Enhancement in Dieng Geothermal Field, Indonesia, ISSN 2703-4275 (2020)

Flores-Armenta, M. & Morales Alcalá, L: How Much Stimulation Can We Afford?, UNU-GTP-SC-14-32 (2012)

Habibi, A. et al: Unplugging Standalone Sand Control Screens with High-power Shock Waves: An Experimental Study, SPE-199294-MS (2020a), 14-17

Habibi, A. et al: Unplugging Standalone Sand-Control Screens Using High-Power Shock Waves, SPE Drilling & Completion Journal (2020b), SPE-19924-PA

Harthy, A. et al: The First Middle East Unconventional Well Stimulation Treatment by Applying WASP® Technology: Field Cases, SPE-195057-MS

Matoorian, R. & Malaieri, M., University of Calgary: Flow Assurance Management in Geothermal Production Wells, SPE-212144-MS (2022)

Thorhallsson, S.: Geothermal well operation and maintenance, UNU-GTP-2003-01-13 (2003)

Brine Drum Design Comparison

Wijaya Jatmiko Putro and Budi Permana Hadi

Star Energy

wjot@starenergy.co.id, bhgx@starenergy.co.id

Keywords: brine drum, scaling, vesse

ABSTRACT

Star Energy Geothermal Salak, Ltd, is one of the biggest Geothermal Power Plant that operate in Bogor and Sukabumi, West Java with gross capacity of 67 MW with 3 operational unit. Salak field is receiving wet steam where there is requirement to handle liquid (brine) that produced from the wells.

In Salak field there are brine drums in liquid handling system. Brine drum is utilized to accumulate brine from separator to make the brine level stable prior to be injected or pumped to injection well. There are two types of Brine Drum in Salak field. One is using bottom inlet and other is using side inlet. Among those two brine drums, there are different scaling development tendency.

Scaling that developed in brine drum will significantly reduced flow. At certain point, when scale is accumulated, shut down is required to be conducted to clean up the drum with consequence Loss of Production Opportunity.

Computational Fluid Dynamic (CFD) analysis has been conducted to clarify the difference of scaling development between those 2 drums.

As per CFD analysis, it was found that brine drum with bottom inlet has more stable pressure distribution so that scaling tendency in this brine is lower than brine drum with side inlet.

Based on that study, it is recommended to implement the bottom inlet Brine Drum design to minimize scaling tendency and reduce the requirement for shut down in geothermal power plant.

1. INTRODUCTION

Scaling phenomenon was occurred in V-18 and V-24 brine drum. V-18 is located at AWI-10 Well Pad System and V-24 is located at AWI-9 Well Pad System. However, more scale development was occurred at V-24 brine drum. It is suspected that the different design and configuration of those two vessels has affected the different scale development. Computational fluid dynamics (CFD) simulation needs to be performed to study Pressure and Temperature distribution in those 2 vessels (including its adjacent equipment). Interpretation to the simulation result of the Brine Drum Design Comparison will be used for further study of scale development.

2. CFD ANALYSIS

The CFD analysis follows CFD workflow as shown in Figure 1. The simulation process is started with model preparation (CAD model and meshing), then simulation scheme (determine and inserting boundary condition), performing the simulation, and extracting the results (volume fraction, pressure, and temperature distribution).

2.1 Methodology

CFD analysis is done by performing complex flow calculation involving various gases and liquids by computing heat transfer, mass transfer, energy balance, and related physical phenomena. Workflow of CFD analysis is as described in Figure 1.

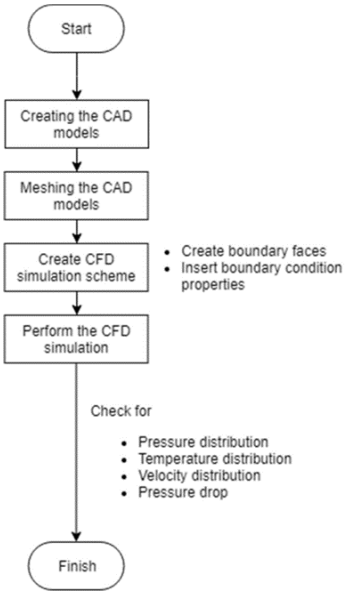


Figure 3: CFD Workflow.

The ANSYS CFD solver is based on the finite volume method. During the model and mesh preparation stage, the analysis model is discretized into a finite set of control volumes. Then, CFX perform numerical calculation based on the following equations:

- Conservation of mass.
- Conservation of momentum.
- Conservation of energy.

2.2 Simulation Process

The simplified flow diagram is shown in Figure 2.

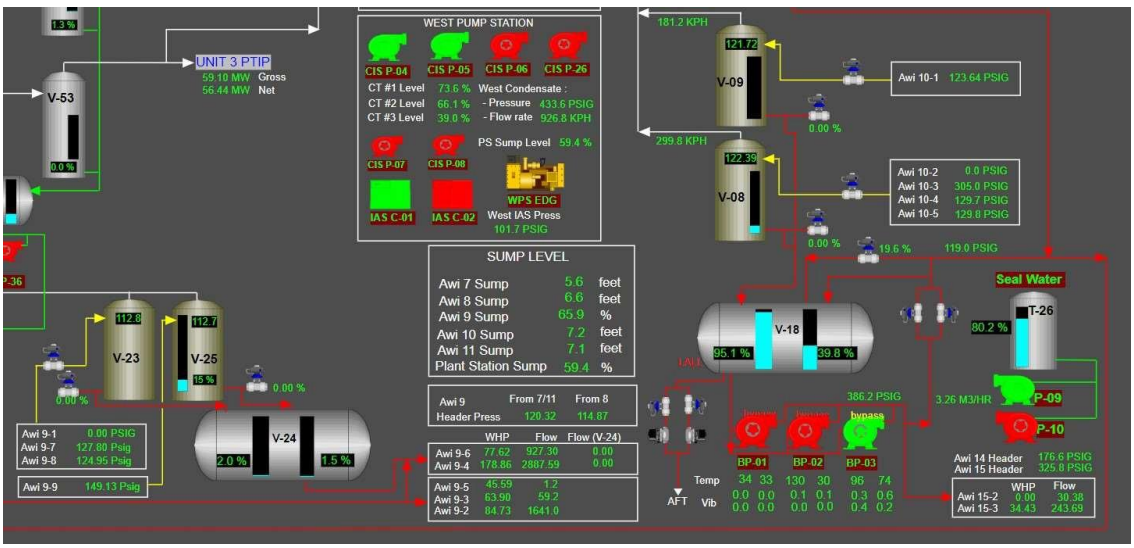


Figure 2: Simplified Flow Diagram of V-18 and V-24 Brine Drum.

Geometry used in the project is geometry of brine drum is shown in Figure 3 for V-18 brine drum and Figure 4 for V-24 brine drum.

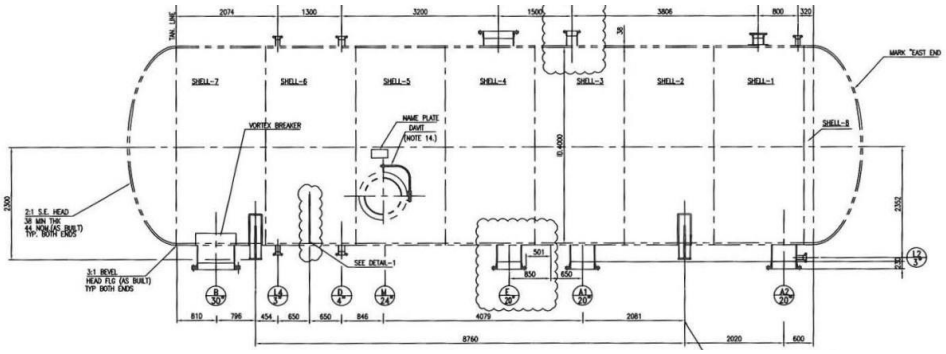


Figure 3: V-18 Brine Drum.

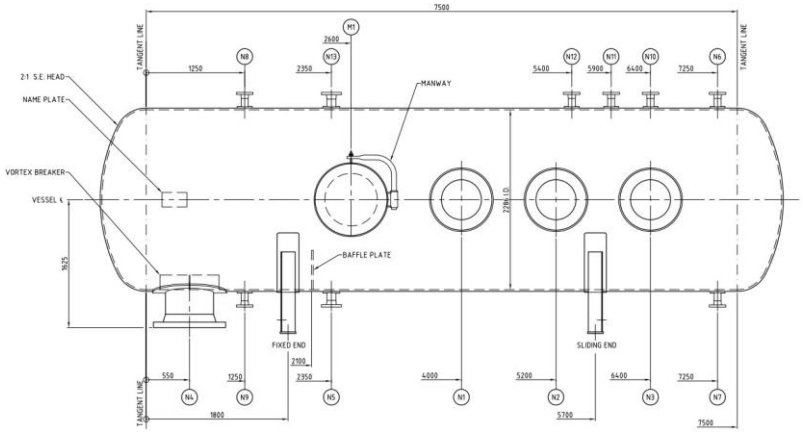


Figure 4: V-24 Brine Drum.

2.3 Computational Approach

3D geometry modelling is done based on the given detailed geometry. 3D Drawing model were created using AutoCAD. 3D drawing model were created to meet the Computational Fluid Dynamics simulation requirements. The 3D model of V-18 brine drum arrangement is shown in Figure 5. The brine is supplied from V-8 and V-9 separator.

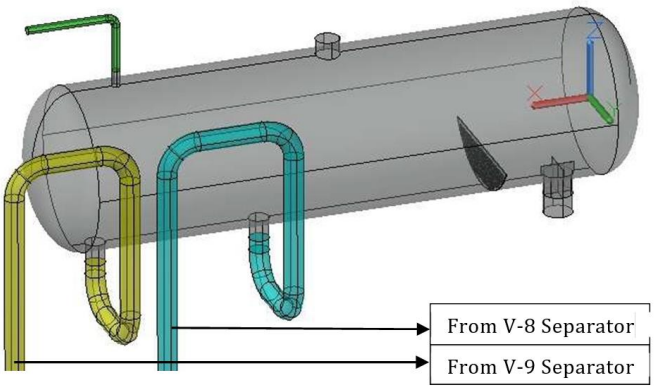


Figure 5: 3D Model of V-18 Brine Drum.

The 3D model of V-24 brine drum arrangement is shown in Figure 6. The brine is supplied from V-23 and V-25 separator.

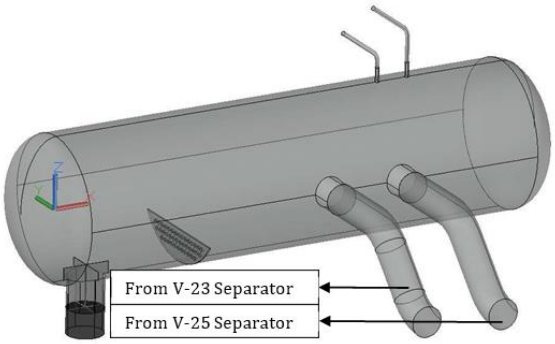


Figure 6: 3D Model of V-24 Brine Drum.

3. RESULT

The analysis will be conducted to determine the condition inside each brine drum which the velocity, pressure, and temperature will be the main point to be reviewed. At the end of the analysis, the comparison table of both brine drum will be shown.

3.1 V-18 Brine Drum

The collected brine inside V-18 brine drum is supplied from V-8 and V-9 separator. The simulation of each inflow brine is conducted to analyze the brine condition at normal and low brine level configuration before reaching the brine drum as well as the brine condition inside brine drum. The results are shown in the following figure.

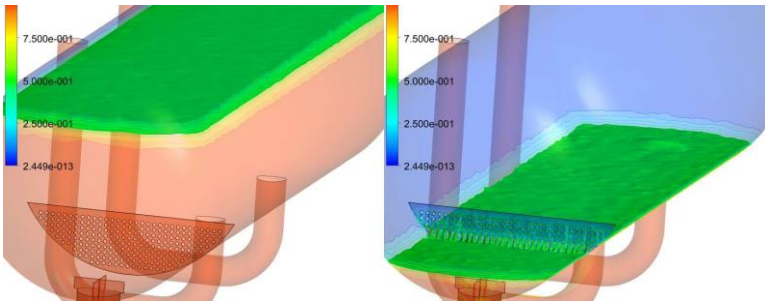


Figure 7: V-18 Brine Drum Fluid Fraction.

The inflow brine from V-8 and V-9 separator outlet is always submerged when reaching the brine drum on both brine level configuration. The only slight difference between both level configurations is when liquid level fell below baffle plate, where liquid is forced to flow through holes.

V-18 Brine Drum at Normal Level – Velocity

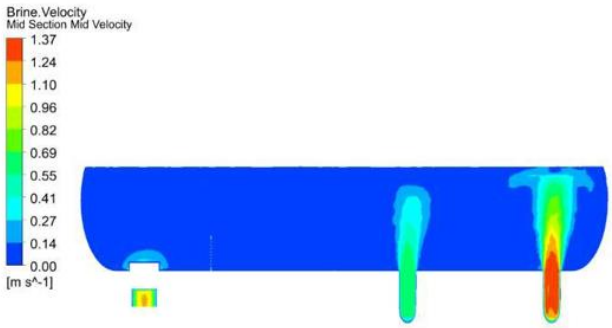


Figure 8: The Brine Velocity Inside V-18 Brine Drum at Normal Level.

V-18 Brine Drum at Low level – Velocity

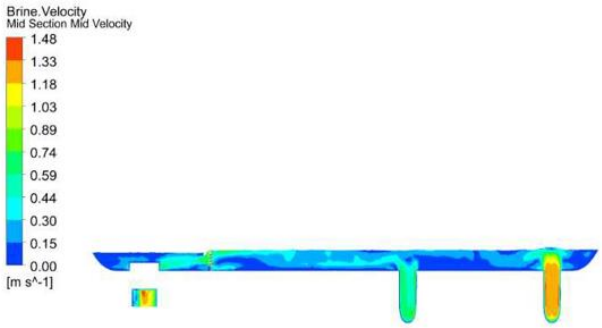


Figure 9: The Brine Velocity Inside V-18 Brine Drum at Low Level.

At normal level, the changes in velocity that occur when brine movement is unnoticeable on surface. Slight velocity increase on surface is detected at low liquid level due to the baffle. Overall, the characteristic of brine velocity in V-18 brine drum is the same in both brine level configurations.

V-18 Brine Drum at Normal Level – Pressure

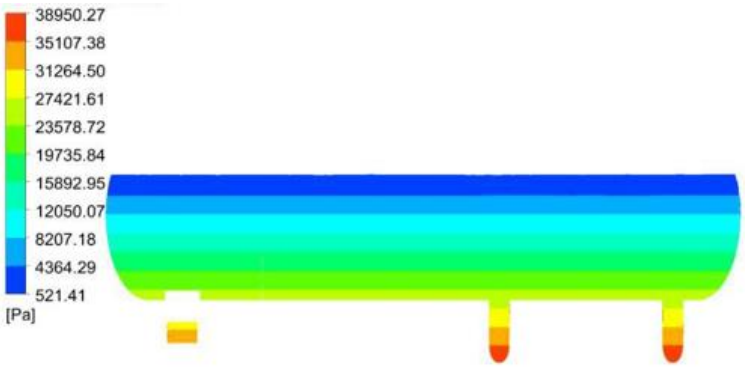


Figure 10: The Brine Pressure Inside V-18 Brine Drum at Normal Level.

V-18 Brine Drum at Low level – Pressure

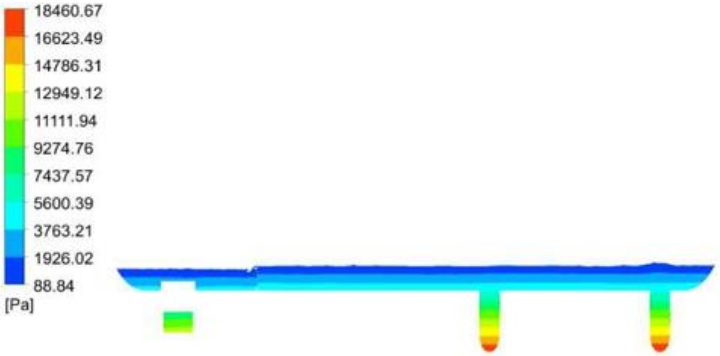


Figure 11: The Brine Pressure Inside V-18 Brine Drum at Low Level.

Because of the existing hydrostatic pressure on the submerged brine inflow, the chance of brine to boil (flash) is low. Both brine level configuration has the same pressure characteristic.

3.2 V-24 Brine Drum

The collected brine inside V-24 brine drum is supplied from V-23 and V-25 separator. The simulation is conducted to analyze the inflow brine from V-23 separator at high, normal, and low brine level configuration before reaching the brine drum as well as the brine condition inside brine drum. The inflow brine from V-25 separator is not included in simulation because there is no brine flow in the setup. The results are shown in the following figure.

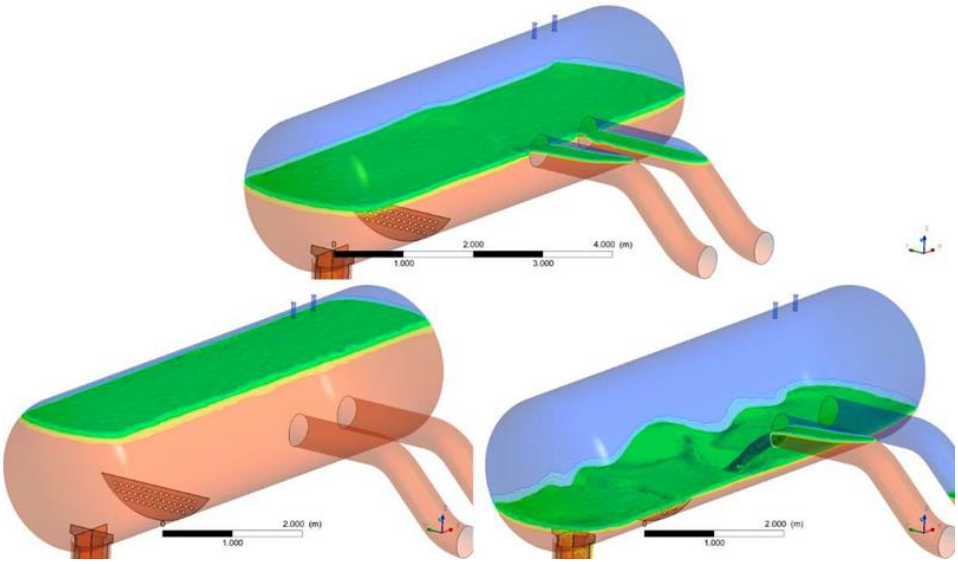


Figure 12: V-24 Brine Drum Fluid Fraction.

The inflow brine from V-24 separator is half submerged in normal liquid level and totally exposed to vapor in low level configuration. At high level, the inflow pattern is slightly the same as V-18 brine drum in high liquid level.

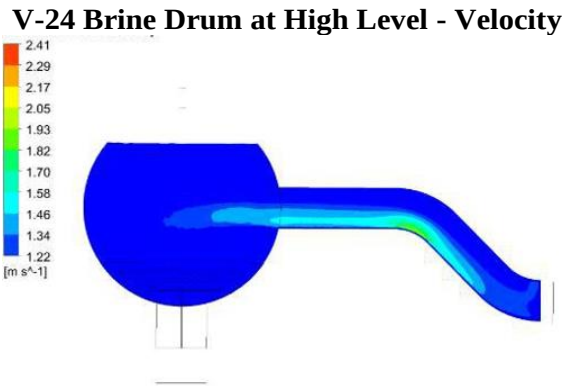


Figure 13: The Brine Velocity Inside V-24 Brine Drum at High Level.

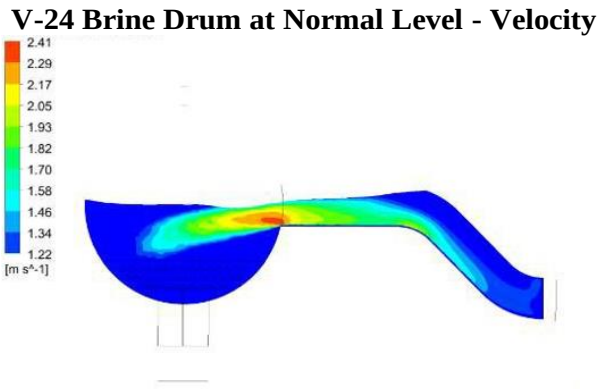


Figure 14: The Brine Velocity Inside V-24 Brine Drum at Normal Level.

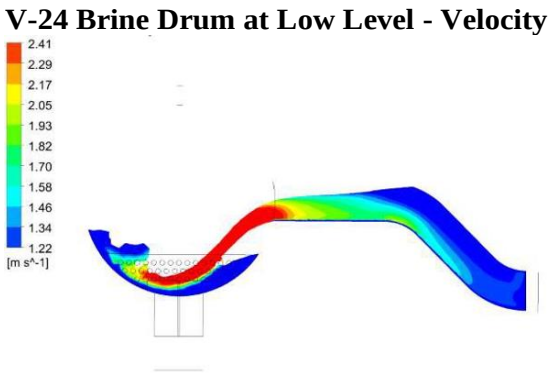


Figure 15: The Brine Velocity Inside V-24 Brine Drum at Low Level.

The significant velocity changes happened at normal and high liquid level because the brine is directly exposed to existing vapor in the drum. This condition might cause static pressure drop and exert a substantial effect to the liquid.

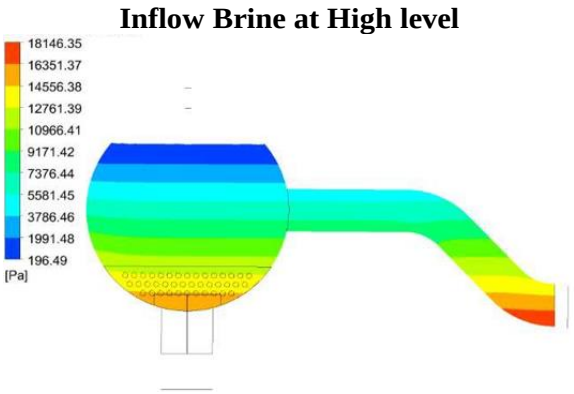


Figure 16: The Pressure of V-24 Separator Inflow Brine at High Level.

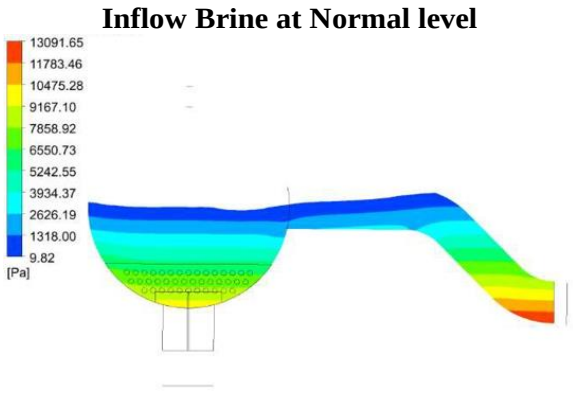


Figure 17: The Pressure of V-24 Separator Inflow Brine at Normal Level.

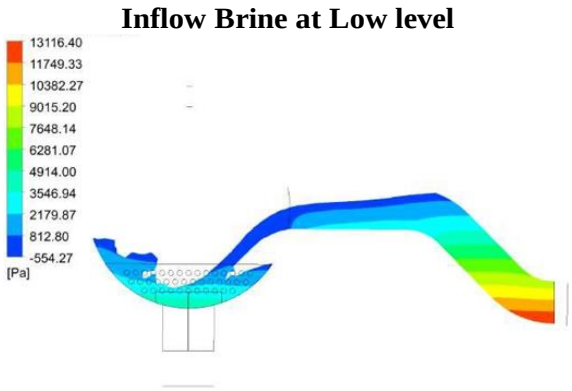


Figure 18: The Pressure of V-24 Separator Inflow Brine at Low Level.

At high liquid level, the inflow brine has the same characteristic as the V-18 brine drum where hydrostatic pressure exists. The half-submerged condition with partial brine exposed to vapor has relative pressure almost zero / same with surrounding vapor pressure.

3.3 Design Comparison

The brine drum design comparison is shown in Table 1.

Table 1: V-18 and V-24 Brine Drum Design Comparison.

Parameter	V-18	V-24
Flow Entrance	Submerged	Normally exposed to vapor
Velocity	No significant increase (tend to decrease after leaving nozzle)	Up to 3 times average velocity increase in low level configuration
Inflow Static Pressure	Back pressured (hydrostatic pressure)	No backpressure when liquid level is below high level (exposed to vapor pressure)
Flow Direction	Upward	Sideward

4. SUMMARY AND RECOMMENDATION

4.1 Summary

The conclusions of the simulation are:

- The only significant difference between V-18 and V-24 is velocity profile, due to its inlet nozzle configuration
- Bottom fill configuration might provide better stability to overcome pressure change (due to hydrostatic pressure)
- Side fill configuration might cause “flashing” due to pressure drop when liquid level is below high level
- Side fill might provide less resistance of incoming flow, compared to bottom fill

4.2 Recommendation

- Consider modifying inlet section of V-24 to bottom fill configuration (V-18)
- Maintaining liquid level, no lower-than-normal condition, is better than submerging the inlet section by extending inlet pipe section.

REFERENCES

GCS-021-ME-DS-001 Mechanical Data Sheet for AWI 10 Brine Surge Vessel (BIS-V-18)
143-2092-G General Arrangement for AWI 9 Brine Surge Vessel (BIS-V-24)
450902-000-A0-001 AWI Bengkok West Field Process Flow Diagram
AI013400-DRG-PE-006 Piping and Instrumentation Diagram – Brine Surge Vessel (BIS-V-24)
450902-000-00-042 Piping and Instrumentation Diagram – AWI-10 Well Head System sheet 2 of 4

Steam Trap Maintenance Using Ultrasound for Energy Efficiency and Reduce Emission

Raka Anugrah Pratama, Andisyah Purdanto, and Yana Handriana

PT Geo Dipa Energi (Persero) Unit Patuha, Kab Bandung, Indonesia

raka@geodipa.co.id, andisyah@geodipa.co.id, yana@geodipa.co.id

Keywords: Ultrasound, Steam Trap, Maintenance

ABSTRACT

PT Geo Dipa Energi has a commitment to environmental improvement, especially related to energy efficiency and emission reduction. There are several cases that can reduce energy efficiency and increase CO_2 emission. The steam trap is responsible for venting unwanted air or gases, removing condensate from the system, holding back steam in the system, and preventing excess steam from entering the air, so it can reduce energy losses due to steam loss. A damaged steam trap is one of the conventional emission sources that must be avoided. A damage steam trap can lead to energy and cost losses for the company. The steam trap can be maintained and inspected periodically to ensure its good condition and proper operation. Visual inspection of steam trap is used to see the working of the steam trap, whether it is in good condition or not. However, it has poor reliability because not at all symptoms of steam trap damage can be identified. Furthermore, with visual inspections that have been carried out routinely every month, steam loss is still found on the steam trap. Therefore, steam trap maintenance methods should be improved. Condition monitoring using ultrasound technology is one of the recently developed maintenance technologies to inspect steam trap performance. Utilizing ultrasound for this method is simple and effective. The ultrasound has a function to detect non-audible sound at high frequency. With ultrasound equipment and condition monitoring methods, we can know the damage that can't be seen visually, like worn valve seats and worn disc valves. A good steam trap has a cycle of 2-10 discharges per minute. This is the advantage of condition monitoring using an ultrasound device, which can be heard at high frequency and processed in spectrum and time wave form, which can help the user more accurately analysis the damage steam trap. Ultrasound condition monitoring is expected to reduce steam leakage so that the energy in steam can be used optimally.

1. INTRODUCTION

PT Geo Dipa Energi geothermal working area is located in Patuha, West Java province. Geothermal energy uses steam above ground system to deliver steam from a well to the powerplant area. The steam above ground system consists of the well pad, pipeline, steam trap, demister and rock muffler. Steam Traps are important parts of any steam system. Their basic function is to prevent the passage of steam while allowing condensate to flow, C.B. Oland (1996). In 2021 several steam trap conditions on the steam above ground system will be not optimally operational, including a steam trap failed to open condition, chattering condition, and leaky steam trap. The damage to this steam trap is not immediately remedied, because visual inspection method can't see the condition of the steam trap leak due to damage the component of the steam trap. Visual inspection can only see leaky or passing steam trap. As a result, steam trap maintenance method needs to be improved to reduce steam loss and increase the energy efficiency due to steam trap damage. In this study maintenance steam trap use predictive maintenance especially condition-based maintenance using ultrasound. These higher frequencies are useful for select applications, such as detecting leaks that generally create high-frequency noise caused by the expansion or compression of air, gases, or liquids as they flow through the orifice, or a leak in either pressure or vacuum vessels, Keith (2002). Ultrasound equipment also detect worn valve seat and worn disc valve which cannot be detected by visual inspection. A good steam trap has a cycle of 2-10 discharges per minute. This is the advantage of condition monitoring using an ultrasound device, which can be heard at high frequency and processed in spectrum and time wave form, which can help the user more accurately analysis the damage. Steam systems are great assets at transferring heat energy. Ultrasound condition monitoring is expected to reduce steam leakage so that the energy in steam can be used optimally.

1.1 Condition Based Maintenance (CBM)

Maintenance is concerned with keeping an asset in a good working condition so that the asset may be used to its full productive capacity, Ramesh and O'Hanlon (2013). Another definition maintenance concerned keeping in designed or an acceptable condition, keep from losing partial or full functional capabilities, preserve and protect. The condition of equipment could be measured using condition monitoring, statistical process control, or equipment performance, or through using human sense. The terms predictive maintenance (PdM) and condition-based maintenance (CBM) are used interchangeably. Condition based maintenance attempts to evaluate the condition of an asset by performing periodic or continuous asset monitoring. The ultimate goal of CBM is to identify proactive maintenance actions to be performed at scheduled point in time when the maintenance activity is most cost effective and before the asset fails in service. Condition based maintenance inspection typically are performed while the asset is operating, thereby minimizing disruption of normal system operation. More common technologies are vibration analysis, sound level measurement or ultrasonic, infrared thermography, oil analysis, partial discharge & corona detection.

1.2 Ultrasound

One of the condition based maintenance technologies is ultrasound. Ultrasound refer to sound pressure waves with a frequency of 20kHz or more. These sound waves are beyond human hearing and can only be detected with ultrasound technology. this predictive maintenance technique uses principles similar to vibration analysis, both monitor the noise generated by plant machinery. Unlike vibration monitoring, ultrasound monitors the higher frequency, frequency range of ultrasound from 20000 Hz until 100kHz. Ultrasound have many applications, it used for three primary application, first airborne noise analysis, second used for leak detection and the last used for material testing. One of application that can used using ultrasound is leak detection, the turbulent flow of liquids and gases through a restricted orifice will produce a high frequency signature that can easily be identified using ultrasonic technique, therefore, this technique is ideal for detecting leaks in valve, steam traps, piping and other process systems, Ramesh and O'Hanlon (2013). Steam trap is also inspected easily with ultrasound. During the steam trap operation and while observing the meter, trap conditions can be interpreted. The speed and simplicity of this type of test can allow every trap in a plant to be routinely inspected.

Figure 1: Ultrasound UP 10000 Kit.

Use of a sound analysis application is required to increase the effectiveness of ultrasound. Based on sound and spectral patterns, a technician or inspector can quickly and accurately analyze a steam trap. Certain types of steam trap damage, such as those with worn seat discs and worn discs on the discs, cannot be diagnosed just by sound.

1.3 Thermodynamic (Disc) Steam Trap

Steam traps are a type of automatic valve that filters out condensate and non- condensable gases. The type of steam trap which used at steam above ground system Patuha is thermodynamic steam trap. Thermodynamic steam trap works in the difference in kinetic energy or velocity between steam and condensate flowing through the trap, McCauley, J.F (1995). Another principle work is Thermodynamic

steam trap work on the difference in dynamic response to velocity change in flow of compressible and incompressible fluids. As steam enters, static pressure above the disc forces the disc against the valve seat, UE System (2004). As the steam starts to condense, the pressure against the disc lessens. the trap cycle steam with a good condition should have a cycle (hold – discharge-hold) 2-10 times per minute, Yarway (2017). It operates by means of the dynamic effect of flash steam as it passes through the rap. The only moving part is the disc above the flat face inside the control chamber or cap. The most widely used types are thermodynamic disc models. In these traps the valve consists of a simple disc which closes to high velocity steam but opens to lower velocity condensate. Some other, miscellaneous types include “impulse” or piston trap, labyrinth traps and even the rudimentary orifice plate.

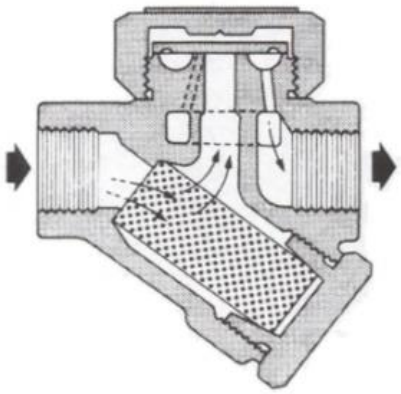


Figure 2: Thermodynamic Disc Steam Trap.

Advantages of the thermodynamic disc type, it can operate within their whole working range without any adjustment or change of valve size. They are compact, simple, lightweight and have a large condensate handling capacity for their size. This type of trap can be used on high pressure and superheated steam. It is not damaged by water hammer or vibration. The all stainless steel construction offers a high degree of resistance to corrosive condensate.

2. METHOD

2.1 Research Methods

This study uses a comparative study method between maintenance steam traps that use visual inspection and maintenance steam traps that use ultrasound condition base. Research methods start with identifying the problems that occur in the steam trap related to steam leakage. After that, conduct a literary study to find the best method of maintenance steam trap. The result of the literary study is applied to the maintenance process at the Patuha powerplant. Methods of maintenance for steam trap include visual inspection and condition based maintenance using ultrasound or sound analysis. This inspection is carried out once every month on all equipment in the steam above ground system at Patuha powerplant. The result of this inspection and condition based maintenance is processed in the inspection result data. After the data is obtained, the next step is to analyze steam loss data and analyze data related to greenhouse gas emissions. The flow diagram shown on the figure 3.

2.2 Ultrasound Data Collecting Method

2.2.1 Ultrasound UP 10000

Ultrasound UP 10000 is a condition based maintenance tool that works by detecting non audible sounds with sound detection specifications ranging from 20kHz to 100kHz, Ultrasound UP 10000 is equipped with several probes. Tri scanning module, this module is utilized to receive air-bone ultrasound such as the ultrasound emitted by pressure/vacuum leaks and electrical discharges. Stethoscope (contact) module, this module has a metal rod, this rod is utilized as a waveguide in that it is sensitive to ultrasound that is generated internally, such as within a pipe, bearing housing or steam trap.

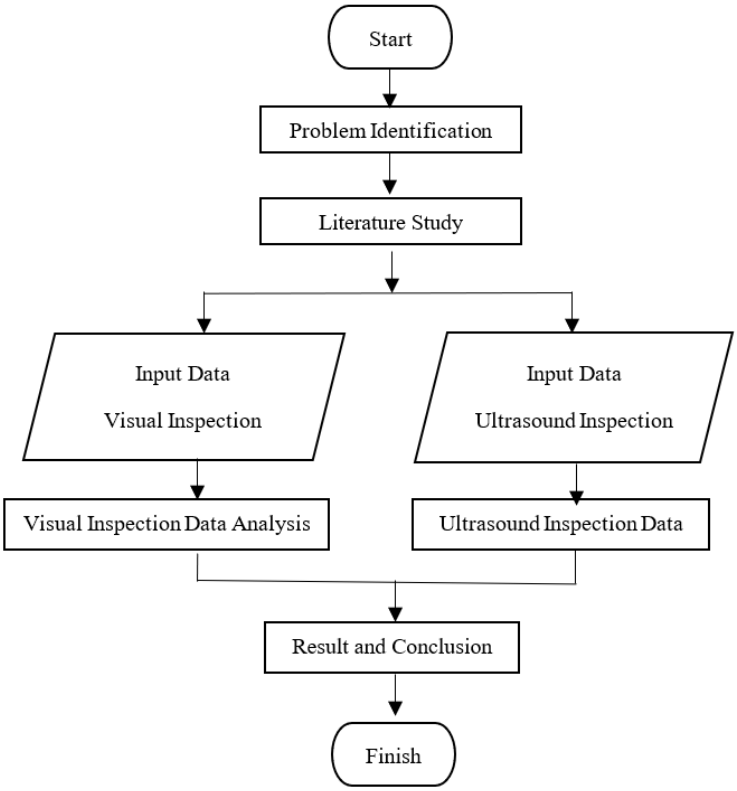


Figure 3: Research Method Flow Diagram.

2.2.2 Data Collecting find faulty steam trap using Ultrasound UP 10000

Ultrasound data collection started with the preparation of an ultraprobe 10000, a stethoscope contact module sensor, SD card, and headphones. Furthermore, align the pins located at the rear of module with the four jacks in the front end of the metered pistol housing and plug in. turn on the ultraprobe 10000, select setting, select menu, steam setting must be enabled. For detecting faults steam trap, set frequency at 25kHz. After the equipment preparation process is complete, the next step is to inspect the steam trap by making contact with the steam trap near the discharge orifice location using the stethoscope contact module, adjust the sensitivity and tune frequency to obtain a good quality signal. Listen for any operational deviation for a minimum of one complete cycle. Ensure inspectors have adequate operational knowledge of each type of steam trap prior to inspection. Always remember when recording WAV Files, Ensure accurate recording parameters, (2-4 Bars) within the intensity meter and setting. After data collection was completed, perform data accusation, it uses sound analysis application we call ultratrend data management system and UE Spectralyzer, retrieve data from ultraprobe to personal computer, and lastly, it performs sound analysis. If the result of sound analysis is not good, perform functional check the steam trap by throttling the downstream valve and upstream valve of the steam trap see the outlet steam trap. Flash steam should be visible at the steam trap outlet, if this method doesn't work disassembly steam trap and inspect the component of steam trap, major damage of steam trap needs to be replaced with the new one. The flow diagram inspection method using ultrasound shown on the figure 4

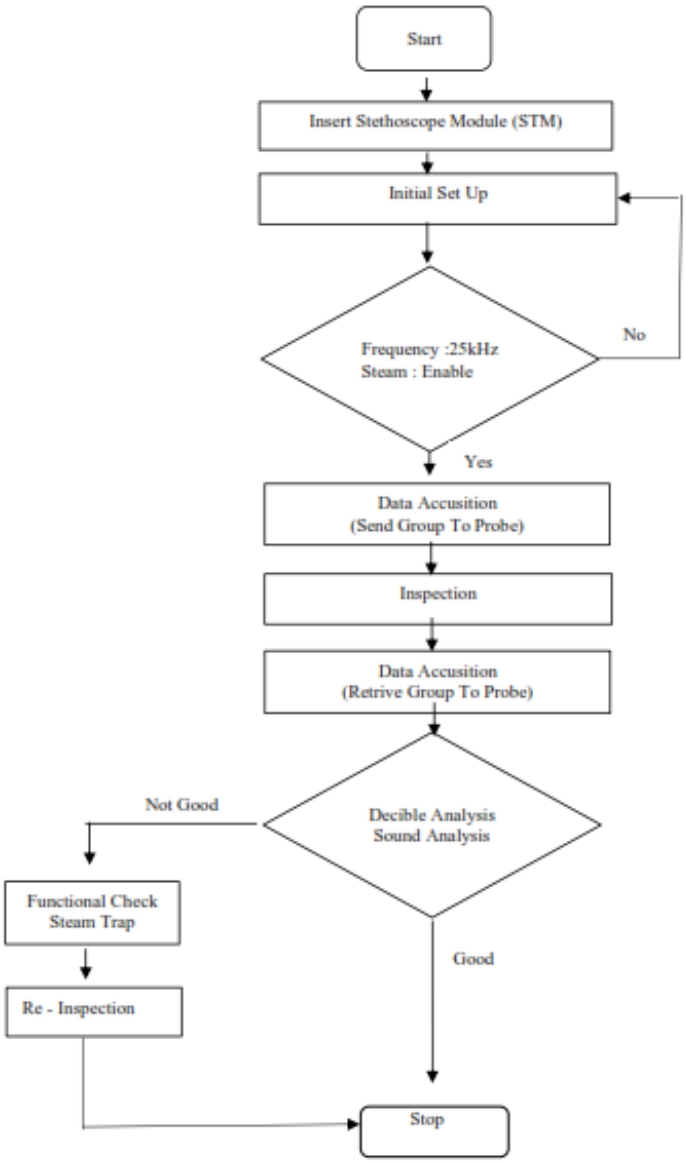


Figure 4: Inspection Method Using Ultrasound.

2.2.3 Sound Analysis

Sound analysis to find faulty steam trap uses the ultratrend data management system and spectral analysis software (UE Spectralyzer). Ultratrend data management system is a comprehensive record storage, data management and data analysis program, the program allows for multiple views or reviewing data, has a history table and trend chart to review any changes to any of the relevant test fields, such as decibel, frequency, test results, temperature or rpm. Spectral Analysis Software which converts PC into a fully functioning FFT analyzer or spectrum. It provides both spectra and time series views of your recorded sounds. With this software, sound images are easily produced for reporting. You can even attach each sound sample to a file or include an image of the spectra in report. Visually count the number of discharges per minute (dpm) through a spectral view, (Example: count discharges within a 10 second recording and multiply by six the reference to manufacturer specification)

2.3 Waste Steam Analysis

Faulty steam trap can negatively affect product quality in various processes such as paper, chemicals, even add to environmental pollution, and waste energy. Waste energy occurs due to steam coming out through the steam trap orifice, each thermodynamic steam trap has a different orifice size. The size of

the orifice determines the amount of wasted steam flowrate, this waste steam analysis uses the steam loss table shown on figure 5 as the basis for determining the wasted steam flowrate.

Orifice Diameter	100 psi	125 psi	150 psi	200 psi	250 psi	300 psi
Steam Loss, lb./hr.						
1/32"	3.30	4.02	4.74	6.17	7.67	4.05
1/16"	13.2	16.1	18.9	24.7	30.4	36.2
3/32"	29.7	36.2	42.6	55.6	68.5	81.5
1/8"	52.8	65.3	75.8	99.0	122	145
5/32"	8205	100	118	154	190	226
3/16"	119	145	170	222	274	326
7/32"	162	197	232	303	373	443
¼"	211	257	303	395	487	579
9/32	267	325	384	500	617	733
5/16"	330	402	474	617	761	905
11/32"	399	486	573	747	921	1095
3/8"	475	578	682	889	1096	1303
13/32"	557	679	800	1043	1286	1529
7/16"	674	787	928	1210	1492	1774
15/32"	742	904	1065	1389	1713	2037
½"	844	1028	1212	1580	1949	2317

Figure 5: Steam Flow Trough Steam Trap Orifice Table.

2.4 Greenhouse Gasses Analysis

Proper steam trap maintenance is essential to a steam system, faulty steam traps not only waste energy, they can contribute to pipe erosion due to poor water quality and even add to environmental pollution especially greenhouse gas (CO_2). This Emission analysis approach required steam loss data, the percentage of non-condensable gas obtained from laboratory examination results and the percentage of CO_2 gas obtained from laboratory examination result as well, the equation approach is as follows

$$CO_2 = Steam\ Losses\ x\ Percentage\ CO_2\ x\ Percentage\ NCG\ Content$$

3. RESULT AND DISCUSSION

3.1 Steam Loss Analysis and Energy Loss Analysis

Process analysis of steam loss on the thermodynamic disc steam trap with an orifice size of 3/8" and an operating pressure 125 psi obtained a steam loss 578lb/hour or 292 kg/hour. in 2021 when steam trap maintenance method still uses visual inspection, the total damage steam trap is 18 units from January to December, total steam loss that occurs in 2021 is 528 ton/ year. In 2022 when the steam trap maintenance method uses the condition based maintenance ultrasound, the total steam loss that occurs in 2022 is 113 ton/year. The decrease in steam loss after improving maintenance method is 415 ton per year. The comparison stem loss chart shown on figure 6.

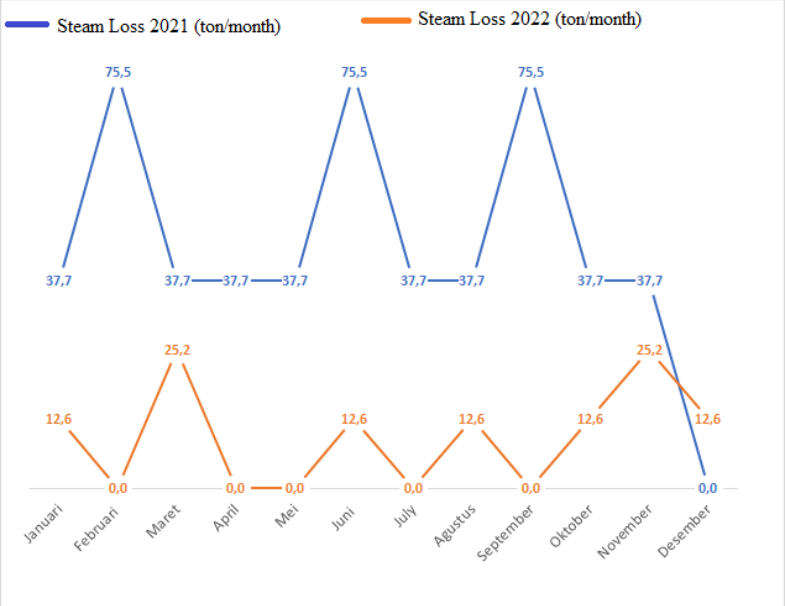


Figure 6: Steam Loss Comparison Chart 2021-2022.

In line with the decrease in steam losses, energy losses will also decrease. Geothermal powerplant Patuha need 6,5 ton/hour of steam to produce 1 MW. Energy loss in 2021 is 81MW and energy loss in 2022 is 17 MW. Energy loss comparison chart shown on figure 7.

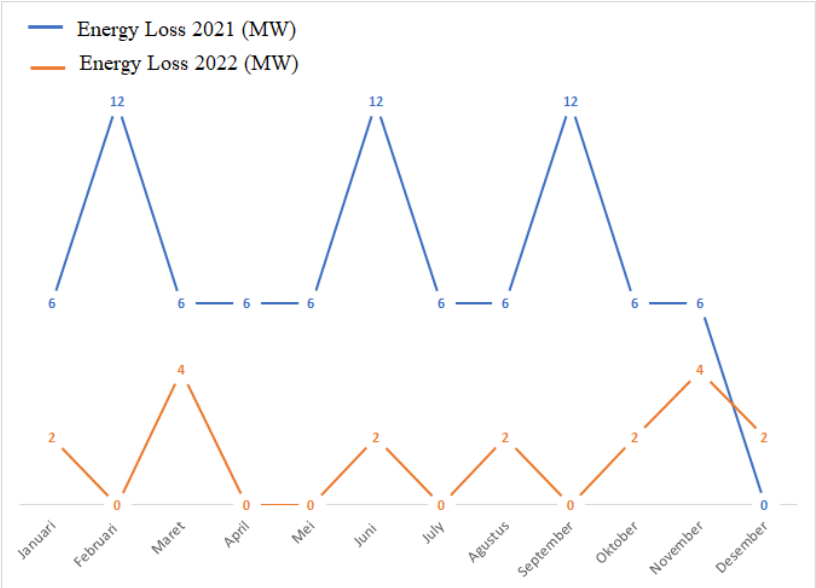


Figure 7: Energy Loss Comparison 2021-2022.

3.2 Process and greenhouse gasses analysis

Steam trapping poor condition not only reduce energy efficiency but also can affect CO_2 emissions. This sub chapter discusses the analysis of emissions that arise using the equation previously described. In 2021 the percentage of non-condensable gas is 0.68%, the percentage of CO_2 is 93.40% and the steam loss is 528 ton/year, with this equation, the CO_2 emission result is 3.36 ton CO_2. In 2022 the percentage of non-condensable gas is 0.68%, the percentage of CO_2 is 93.15% and the steam loss is 113 tons, with this equation the CO_2 emission result is 0.72 tons CO_2. The comparison decreases emission chart shown on figure 8.

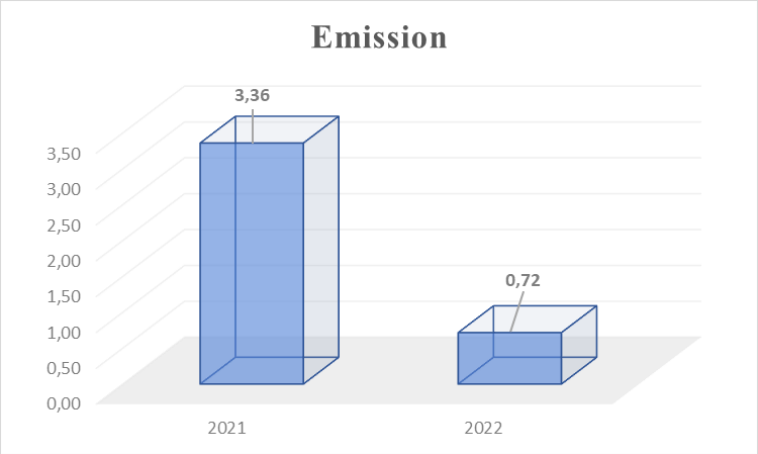


Figure 8: CO_2 Emission Comparation Chart 2021-2022.

3.3 Sound Analysis

The good steam trap works on the difference in dynamic response to velocity change in flow of compressible and incompressible fluids, as steam enters, static pressure above the disc force the disc against the valve seat. The static pressure over a large area overcomes the high inlet pressure of the steam. As the steam starts to condense, the pressure against the disc lessens and the trap cycle, normally a good steam trap should have cycle (hold-discharge- hold) 2-10 times per minute, Yarway (2017). The Spectrum operational steam trap when hold position is illustrated in figure 9.

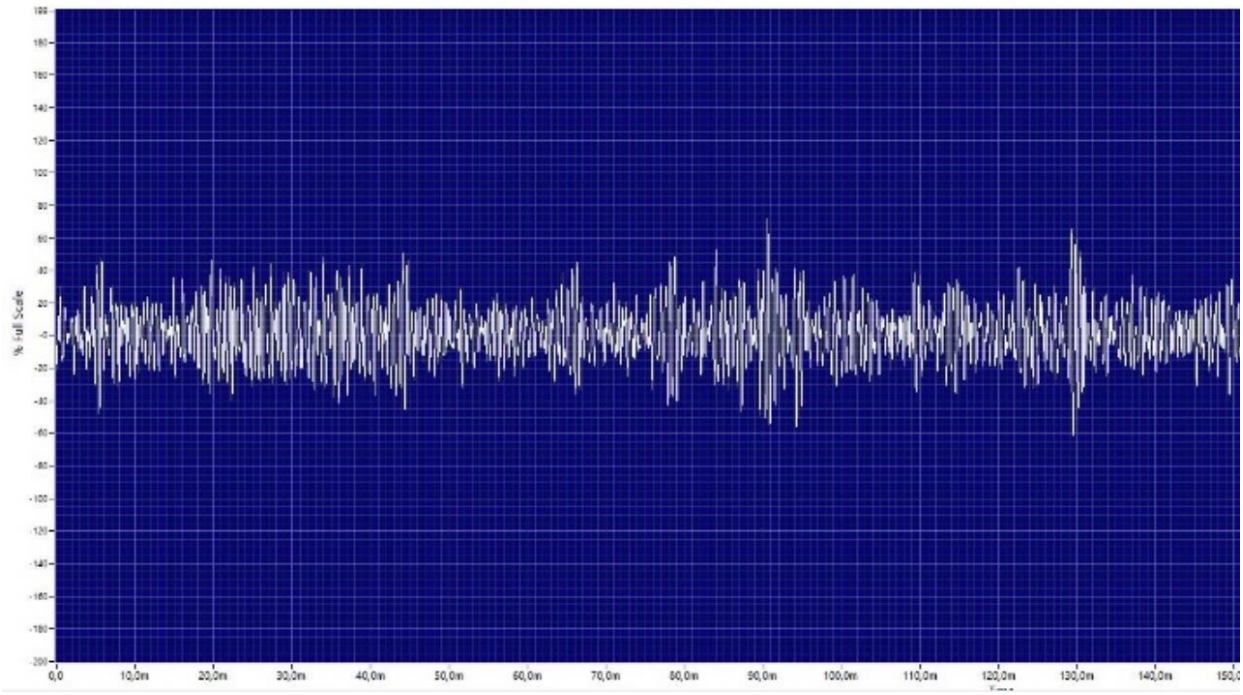


Figure 9: Hold Position.

Y Axis is % Full Scale of Spectrum Sound, X axis is time. Normally, when holding position, the value amplitude of steam trap smaller than when discharge position. In figure 9 the spectrum has amplitude 40, with peak to peak 80 (-40 to 40) on the full scale of spectrum.

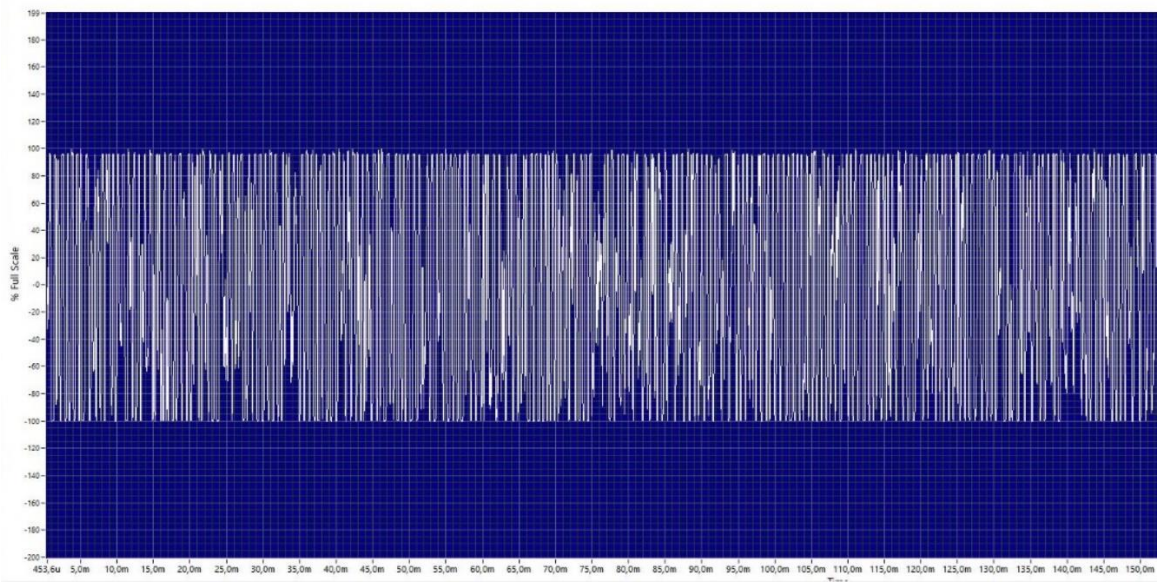


Figure 10: Discharge Position.

Figure 10, illustrates that when the steam trap in discharge position, the value amplitude of the steam trap is normally higher than in the hold position. The amplitude at 100, with a peak to peak 200 (100 to 100) full scale spectrum. With the spectrum result as above, condensate, air and other incondensable gases from a steam system while not permitting the escape of live steam. The spectrum example above is the result of an inspection with condition based maintenance ultrasound on steam trap no 2 (DP PPL 02) at Patuha steam above ground system.

leaky steam trap will never shut and will produce a slight hissing sound, Yarway (2017). A leaking steam trap due to the disc become worn, a condition referred to as “chattering’ ’or machine gunning can occur. This produces a very rapid rattling sound that closely resembles the above descriptive terms. The condition allows steam to leak through and is a predictor of more severe problems to come. Figure 11, illustrates the spectrum of steam trap with disc damage (worn) steam trap no 7 (DP 7) Patuha steam above ground system.

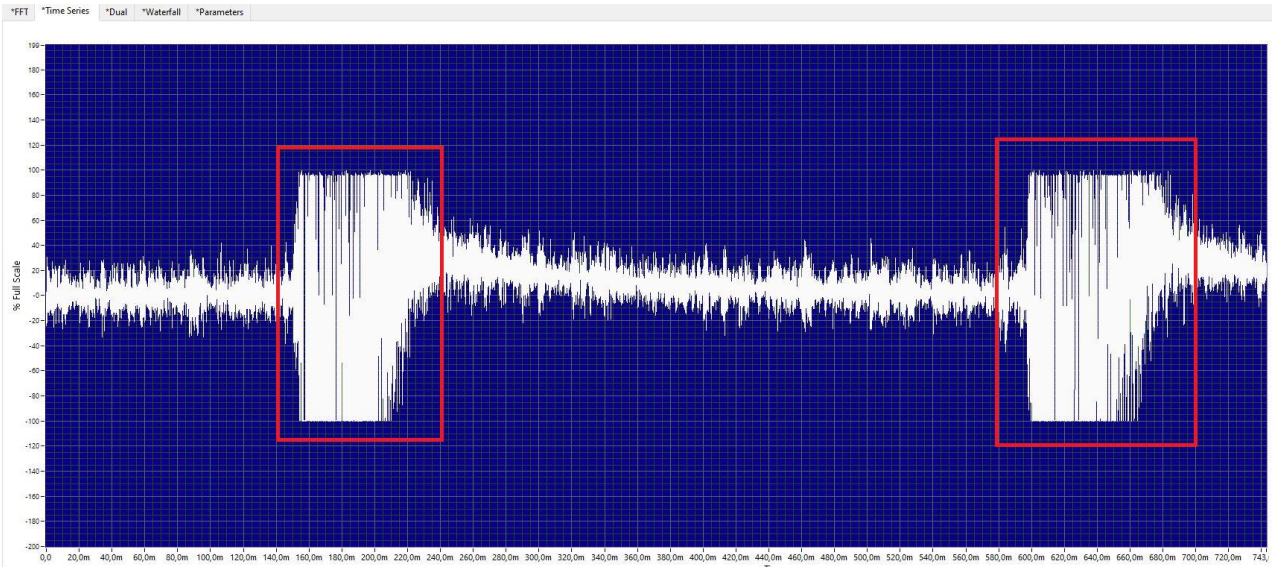


Figure 11: Spectrum of the steam trap with worn Disc Condition.

It can be seen on the red square figure 11, that the chattering has an irregular and non standard sound discharge pattern, this pattern can produce 20-40 discharge per minute, therefore the condition of this steam trap is in a bad condition and must be repaired and replaced immediately. This condition makes it difficult for technicians to analyze steam trap damage, many technicians or inspector estimate this condition is the condition of a steam trap that works well because it has a hold – discharge – hold pattern, but the difference with a good steam trap is related to the period between the discharge and hold patterns. Steam traps with worn disc have a fast period, while for steam trap in normal condition, the pattern is in regular periods between 2-10 discharge per minutes. This is what causes the loss of steam which result in wasted energy and contributes to increase CO_2 emissions. Figure 12 illustrated disc worn steam trap.

Figure 12: Worn Disc.

When the valve disc and the valve seat or the valve disc alone are worn out or otherwise compromised, the pressure within the chamber drops more rapidly, causing the valve to open and close more frequently, McCauley (2000). A steam trap that fails in the open position or a leaky steam trap usually allows for a continues blow-through of steam, this condition is easy to check, visual inspection can describe this problem, for more details sound analysis can also display spectrum condition with the condition trap fails to open.

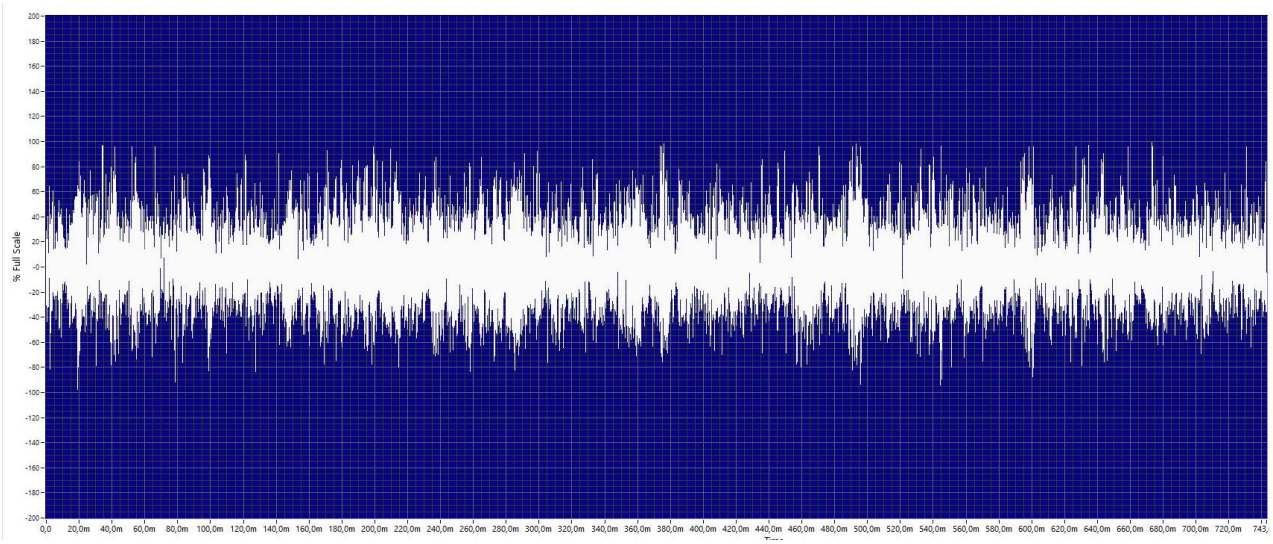


Figure 13: Leaking Steam Trap Spectrum.

Leaky steam trap and steam trap in the failed to open condition produce a spectrum with an amplitude that does not change throughout the inspection time. While a trap operating in good condition will have a distinctive shut off between discharges, a leaking trap will never shut and will produce a slight hissing sound. This is what causes the loss of steam which result in wasted energy and contributes to increase CO_2 emissions like steam team trap with worn disc condition.

4. CONCLUSION

Patuha geothermal powerplant has a steam above ground system, and one of the component steams above ground system is steam trap. The type of steam trap which used in Patuha geothermal powerplant is a thermodynamic disc steam trap. The steam trap should be maintained, repaired or replaced to keep it in a good condition and according to the manufacturer's standard. Damage thermodynamic disc steam trap can negatively affect product quality in various processes, they can increase the steam loss, decrease the energy efficiency, and causes to environmental pollution. In this paper, we continue to improve the steam trap maintenance method from visual inspection to condition based maintenance using ultrasound technology. This maintenance method works by detecting non-audible sounds with sound detection specifications ranging from 20kHz to 100kHz and ultrasound has a sound analysis program. this is advantage for a technician or inspector. It can be easily used for troubleshooting, problem solving and decision making for the steam trap condition. The result of the process improvement maintenance method using ultrasound show that there is a decrease of losses from 2021 to 2022. In 2021 steam loss was 528 tons/year, and in 2022 steam losses was 113 tons/year. In line with the decrease in steam losses, energy losses will also decrease, energy loss in 2021 will be 81 MW energy loss in 2022 will be 17 MW. Steam loss also affect to emissions, decreasing steam losses also reducing CO_2 Emissions. CO_2 emissions in 2021 are 3,36 tons/year, CO_2 emissions in 2022 are 0,72 tons/year. In this research, analysis focuses on thermodynamic disc steam trap maintenances using Condition base maintenance ultrasound, further research is needed related to ultrasound condition monitoring if it's applied to other types of steam trap such as mechanical float traps with continue flow traps, thermostatic steam trap, and inverted buckets steam trap.

REFERENCES

Industrial Steam Trapping Handbook, 3rd E., Yarway Stram Trap Corporation, Blue Bell, Pennsylvania (2017)

Keith, M : Maintenance Engineering Handbook Seventh Edition, Mc Graw Hill, New York (2008)

Keith, M. : An Introduction To Predictive Maintenance, Elsevier Science, Amsterdam (2002)

Mohie,S., and Kotwal, G. : A Review on Industrial Steam Trap. Vishwakarma Institute of Technology, Pune (2017)

McCauley, J.F. : The Steam Trap Handbook, The Fairmont Press, Inc., Liburn, Georgia (1995)

McCauley, J.F.: Steam Distribution System Deskbook, The Fairmont Pres, Inc., Liburn, Georgia (2000)

Ramesh,G., and O'hanlon, T. : Maintenance and Reliability Best Practices, Industrial Press, Inc., 989 Avenue Of the America, NY(2013)

Sreedevi, K,P,. : Analysis of Steam Traps at Process Plants. International Journal of Engineering Science and Research Technology (2015)

Steam Trap Inspection Methods And Steam Cost Analysis, UE System The Ultrasound Company, Haye Street, Elmsford NY (2004)

Yarway, A : Industrial Steam Trapping Handbook, Emerson (2017)

NOMENCLATURE

Measurement Units

kW	kilowatts
MW	megawatts
psi	pound per square inch
kHz	kilo hertz
bar	bar
lb	pon

Abbreviations

PdM	Predictive Maintenance
CBM	Condition Based Maintenance
DPM	Dicharge Per Minute
SAGS	Steam Above Ground System

Success Story of Implementation and Stabilization during Performance Test of Lumut Balai Geothermal Power Plant's Governor Free in Compliance with Indonesia's Grid Code Regulation 2020

Surya H. Silitonga, Erwandi Yanto, Azhari S. Adiputro,
Dzuriat Khasani, Priatna Budiman, and Hadi Suranto

Pertamina Geothermal Energy

surya.silitonga@pertamina.com, erwandi.yanto@pertamina.com, azhari.surya@pertamina.com
dkhasani@pertamina.com, priatnab@pertamina.com, hadi.suranto@pertamina.com

Keywords: Free Governor, Deadband, Grid Code, Performance Test, Frequencies

ABSTRACT

According to the Indonesian Minister of Energy and Mineral Resources Regulation No. 2020, clause CC.4.4.2.7, power-generating units at the Lumut Balai Geothermal Power Plant must be equipped with a free governor to maintain stability and reliability on the grid. The free governor operates by controlling the steam flow, maintaining a constant turbine speed of 3000 rpm and grid frequency of 50 Hz. However, measurements indicated that the plant had not implemented the free governor as required. A Further check implies that the free governor deadband also was not comply with the latest grid code.

Consequently, the plant conducted a successful modification in the free governor deadband, successful implementation and stability performance test of the governor-free system, using a speed droop configuration of 5% and a modified deadband value of 0.1% (0.05 Hz). Two testing stages were conducted involving the Governor Free + Automatic Load Regulator and the Governor Free + Manual Load Regulator. The tests demonstrated the plant's ability to respond effectively to varying grid frequencies, reducing or increasing the active load as needed. For instance, Manual Mode Governor Free Test for over-frequency conditions with of 50.1 Hz and 50.2 Hz, the governor-free system successfully reduced the active load by -0.57 MWe and -1.8 MWe respectively. Manual Mode Governor Free Test for under-frequency condition of 49.82 Hz and 49.79 Hz, the governor-free system successfully increase the active load by +3.7 MWe and +4.78 MWe respectively. In Automatic Load Regulator Governor Free test for under frequency conditions of 49.9 Hz and 49.8 Hz, resulting no change in the load generation.

1. INTRODUCTION

The study focuses on the deadband setting and governor-free implementation, including performance tests during free governor mode operation, specifically for Geothermal Power Plant Lumut Balai U1. The study aims to comply with Indonesian Minister of Energy and Mineral Resources Regulation No. 2020, clause CC.4.4.2.7, which pertains to governor-free implementation. PGE, the entity responsible for operating and maintaining Geothermal Power Plant Lumut Balai-1 (hereafter referred to as LMB-1), plans to conduct the Free Governor Test to ensure adherence to grid regulation standards. During this test, the grid frequency will be simulated to observe how the LMB-1 governor responds. If necessary, the default governor deadband setting will be modified to align with the simulated value.

In Sumatera Island, speed governors are intentionally restricted from responding by utilities, with a range configured from 47.5 Hz to 52.5 Hz. Emergency unloading of a unit is only permitted when the frequency reaches 52.5 Hz. To enhance control and address these issues, ongoing efforts are directed towards enabling frequency governors to respond across the entire frequency range. This operational mode is known as the free governor mode of operation.

2. GOVERNOR FREE MODE

The Governor Free Mode is a critical operational state in power plants, where the governor is designed to respond freely to varying grid frequencies and power demands. The governor system plays a crucial role in controlling the turbine speed, power output, and contributing to grid frequency regulation, ensuring smooth and stable power generation.

Key Functions of the Governor:

- Initiating Turbine Startup: During the turbine's startup process from a stationary state, the governor is responsible for initiating and controlling the acceleration of the turbine. This ensures a gradual and controlled increase in turbine speed to reach the desired operating conditions.
- Load Adjustment during Synchronization: Once the turbine is synchronized with the grid, the governor adjusts the load on the turbo-generator to match the grid's frequency and power demand. This helps maintain grid stability and balance the power supply with demand.
- Safeguarding the Turbine: The governor acts as a safeguard for the turbine during potentially unsafe operating conditions. It continuously monitors the turbine's speed, load, and other parameters, and if any unsafe conditions are detected, it takes corrective actions to prevent turbine damage or system failure.

The Governor Free Mode provides several advantages in power plant operation:

- Frequency Regulation: By allowing the governor to respond freely to grid frequency fluctuations, the power plant can actively participate in grid frequency regulation. It helps maintain grid stability and ensures a consistent and reliable power supply.
- Dynamic Response: The Governor Free Mode enables the governor system to quickly respond to changes in load demand and grid conditions. This dynamic response capability enhances the power plant's ability to adapt to varying power demands and maintain optimal performance.
- Improved Efficiency: The flexibility of the Governor Free Mode allows the power plant to operate more efficiently by adjusting power output in real-time to match the grid's needs. This efficiency optimization reduces wastage of resources and contributes to overall energy conservation.

The steady-state and dynamic response behavior of the turbine is primarily influenced by the characteristics of the governing system.

2.1 Governing System LMB-1

The load on the turbine generator is not always constant but will vary according to the load on the grid, and the free governor is a system used in power plants to maintain the stability of the grid frequency.

The governing system of LMB-1, as shown in Figure 2, ensures this regulation and adjustment when the turbo-generator is connected to the grid by controlling the steam inflow to the turbine. Various control logics and operation of control valves in the turbine enable this regulation. Moreover, the governing system incorporates stop valves to protect the turbine by blocking steam flow during unsafe conditions, as shown in Figure 1.

The Free Governor at LMB-1 works with 5% speed droop (Toshiba, 2019a) with a range configured from 47.5 Hz to 52.5 Hz (Toshiba, 2019b). By constantly controlling the turbine speed at 3000 rpm, the free governor helps to maintain grid stability and frequency, ensuring that the electrical power system operates reliably and efficiently. It plays a vital role in balancing power generation and demand, thus preventing disruptions and blackouts in the electrical grid.

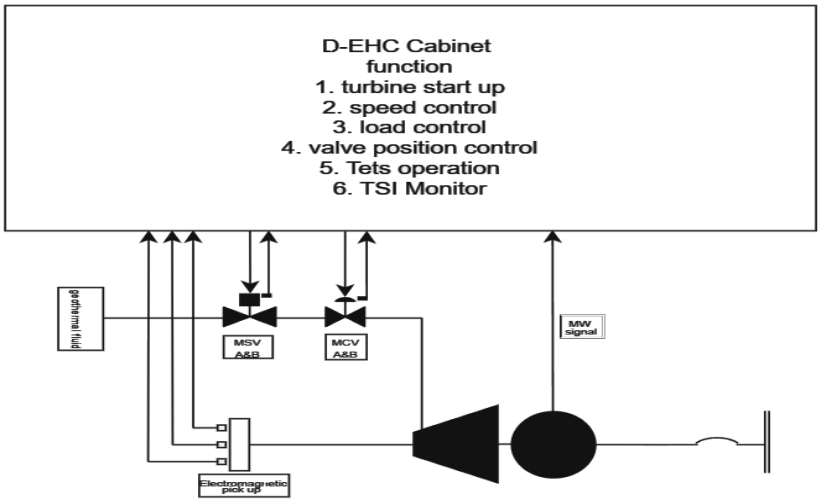


Figure 1: Governing System Block Diagram (Toshiba, 2019a).

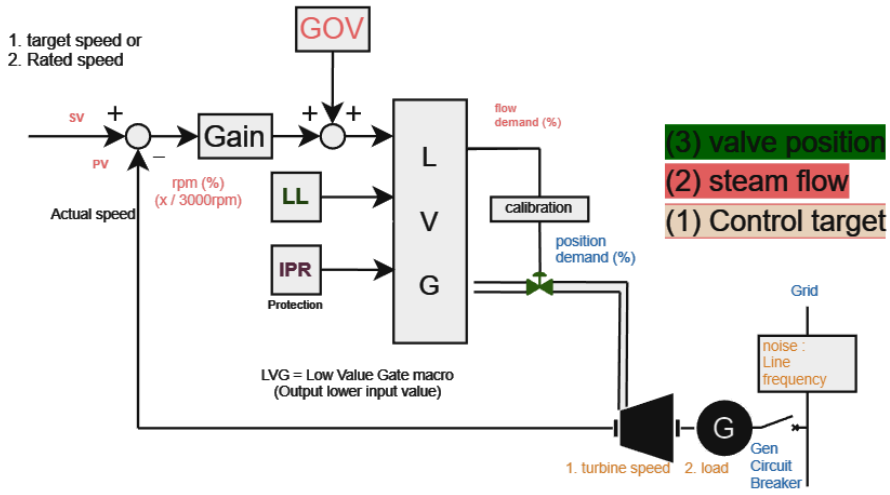


Figure 2: Governing System (Toshiba, 2019c).

2.2 Speed Droop LMB-1

Droop refers to the percentage change in speed corresponding to a change in load. Whenever there is a power mismatch, the speed of the system will be adjusted accordingly. The governing system detects this speed variation and adjusts the valve opening. Droop gain setting in LMB-1 based on the as built document is 5% as shown on Figure 4 and located in the DEHC. Droop gain affects how fast the CV move to compensate for the deviation.

The speed droop refers to the decrease in speed that occurs in an engine or generator as the load increases. It is an important parameter in the control and stability of power system. Speed droop is typically expresses as a percentage change in speed for a given percentage change in load.

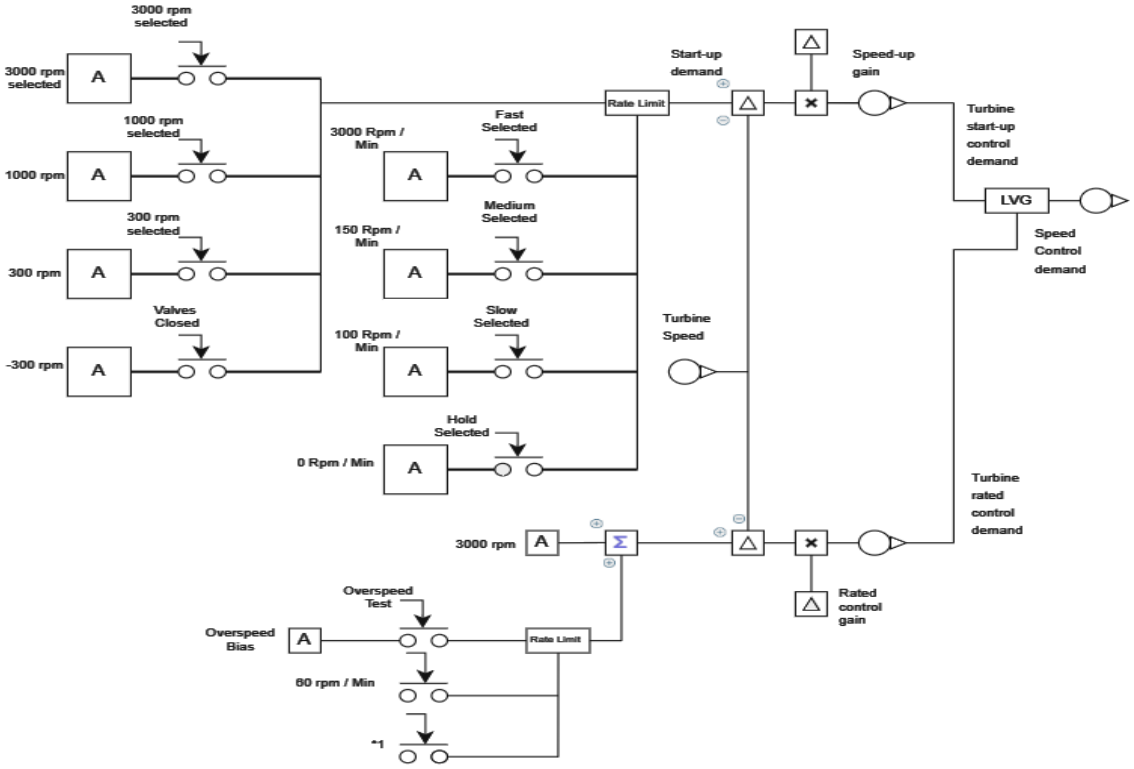


Figure 3: Speed Control LMB-1 (Toshiba, 2019a).

The Geothermal Power Plant Lumut Balai is currently operating under base load conditions, meaning there is no additional load added if the grid frequency decreases, as the load is already at 100% capacity (59 MWe gross). However, in the event of an over frequency condition in the grid, the Geothermal Power Plant Lumut Balai will reduce its load by 1.18 MWe for every 0.05 Hz decrease in grid frequency, thereby restoring grid stability from an initially over frequency state as shown on figure 4.

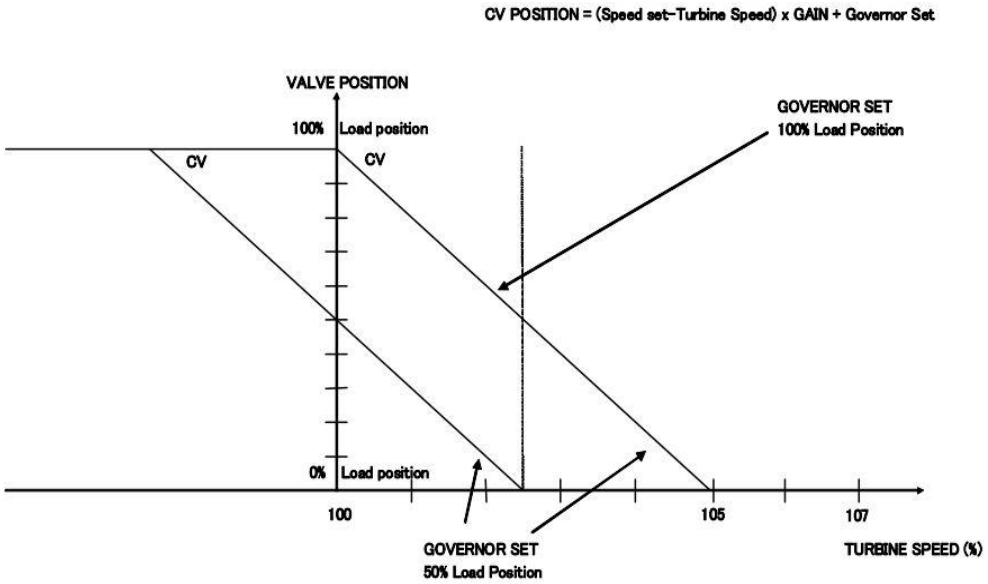


Figure 4: Speed droop 5% (Toshiba, 2019a).

2.3 Free Governor Deadband LMB-1

Free Governor Deadband (hereafter referred to as deadband) setting affect the sensitivity of the governor related to the changes in grid frequency. If the deviation between target frequency and measured frequency is lower than the deadband setting, the governor will ignore it. However, if the deviation is higher than the deadband setting, the governor will make a response for it. The deadband for LMB-1 originally 0% as shown on Figure 5.

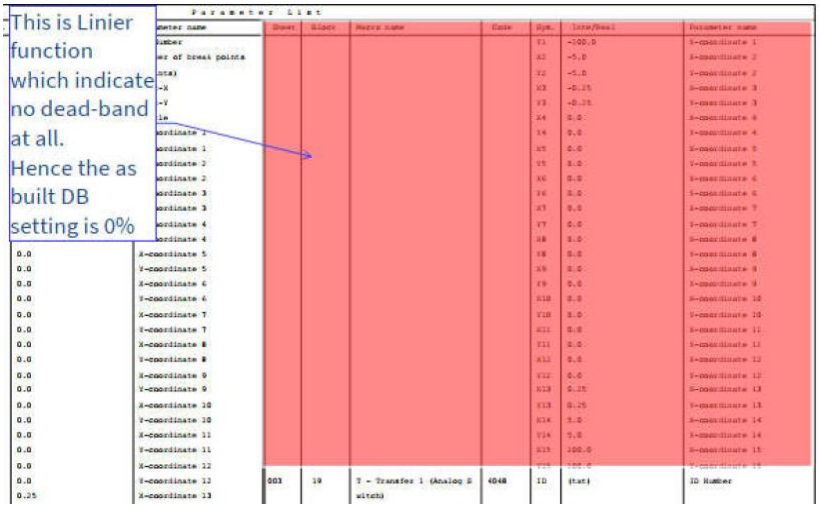


Figure 5: As Build deadband LMB-1 (Toshiba, 2022a).

2.4 Flow Chart For Free Governor Deadband Parameter Tuning

The procedure is specific for LMB-1 to perform the deadband parameter tuning, summarized by the following Figure 6. The tuning is necessary to comply with the grid code deadband requirement for governor free testing purpose.

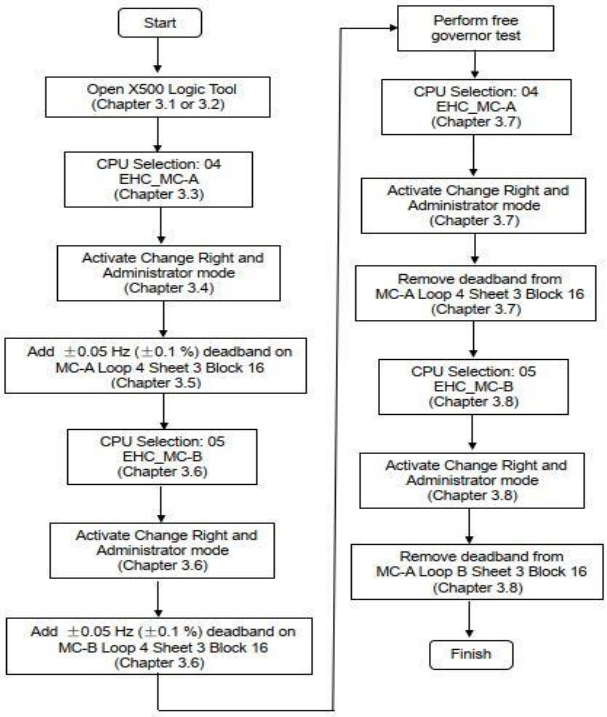


Figure 6: Deadband parameter tuning flowchart (Toshiba, 2022b).

3. TESTING

As found, the dead band at LMB-1 has a value of 0% which is does not comply with the existing grid code 2020. Therefore, PGE plans to adjust the dead band value before conducting the free governor test from 0% [± 0 Hz] to 0.1% [± 0.05 Hz]. The test will involve simulating the grid frequency to a specific value while observing the response of the free governor.

3.1 Deadband setting

Based on the as-build document, the deadband setting is 0% which means that in GOV Mode the governor is always trying to match the grid frequency no matter how small the change is. The results are Main Steam Control Valve (CV) will always move to follow grid frequency fluctuation.

Then PGE changed the deadband value at LMB-1, which was initially set at 0% [± 0 Hz] , to 0.1% [± 0.05 Hz] as requested by PLN UIP3B to comply with the Grid Code 2020 prior to perform Free Governor test. The behavior of the governor after the deadband change is as the following Table-1. Figure 7 and Figure 8 shows the detail change in the DEHC to apply 0.1% deadband.

Table 1: Deadband setting value (Toshiba, 2022a).

Unit	As built setting	Test setting
· RPM	0%	± 0.1 %
· Hz	0 Hz	± 0.05 Hz

Parameter	Before	After	Note
X1	-100	-100.1	Add -0.1%
Y1	-100	-100	No Change
X2	-5	-5.1	Add -0.1%
Y2	-5	-5	No Change
X3	-0.25	-0.35	Add -0.1%
Y3	-0.25	-0.25	No Change
X4	0	-0.1	Add -0.1%
Y4	0	0	No Change
X5	0	0	No Change
Y5	0	0	No Change
X6	0	0	No Change
Y6	0	0	No Change
X7	0	0	No Change
Y7	0	0	No Change
X8	0	0	No Change
Y8	0	0	No Change
X9	0	0	No Change
Y9	0	0	No Change
X10	0	0	No Change
Y10	0	0	No Change
X11	0	0	No Change
Y11	0	0	No Change
X12	0	0.1	Add 0.1%
Y12	0	0	No Change
X13	0.25	0.35	Add 0.1%
Y13	0.25	0.25	No Change
X14	5	5.1	Add 0.1%
Y14	5	5	No Change
X15	100	100.1	Add 0.1%
Y15	100	100	No Change

Figure 7: Detail changes at DEHC controller (Toshiba, 2022b).

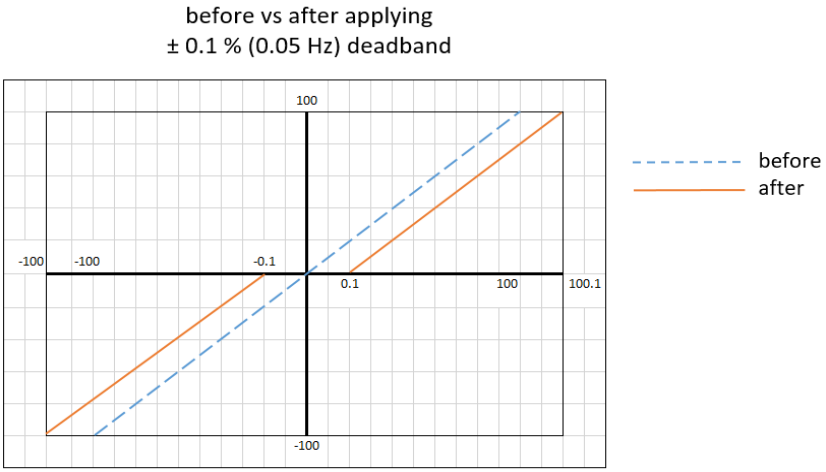


Figure 8: Before and After the modification of deadband (Toshiba, 2022b).

3.2. Performance Test of Governor Free

LMB-1 has two control mode, ALR (Auto Load Regulator) and MANUAL Mode. Testing was conducted for both of the mode and the result than compared. The test conducted in two schemes, frequency down simulation and frequency up simulation. The result describes in the following graph.

3.2.1 Performance test of Governor Free with MANUAL Mode

During governor free with Manual mode test, the load is set to around 53 MWe. As shown on Figure 9a, while the ALR Mode is in-active (MANUAL Mode), then the grid frequency is simulated down to 49.82 Hz from Grid Dispatcher (PLN). The load is then responding, going up to 56.7 MWe (delta P = 3.7 MWe). Further frequency down to 49.79 Hz, causing an increase of load generation respectively to 57.78 MWe (delta P= 4.78 MWe).

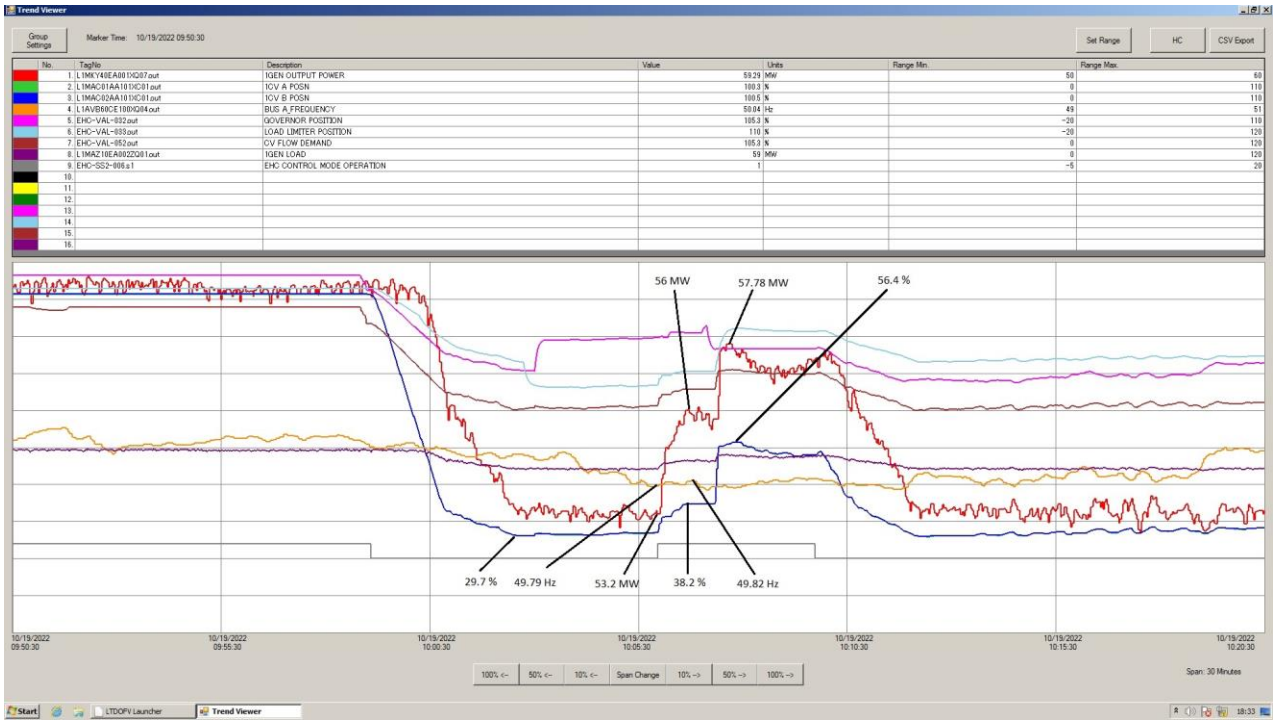


Figure 9a: Trending while testing using MANUAL Mode, frequency down (Tosmap, 2022).

During governor free with Manual mode test, the load is set to around 53.4 MWe. As shown on Figure 9b, while the ALR Mode is in-active (MANUAL Mode), then the grid frequency is simulated up to 50.1 Hz from Grid Dispatcher (PLN). The load is then responding, going down to 52.83 MWe (delta P = -0.57 MWe) Further frequency up to 50.2 Hz, causing a decrease of load generation respectively to 51.6 MWe (delta P= -1.8 MWe) the lowest value during Governor free with Manual Mode.

Figure 9b: Trending while testing using MANUAL Mode, frequency up (Tosmap, 2022).

3.2.2 Performance test of Governor Free with ALR Mode

In the beginning of the test, the load is set to around 53 MWe. As shown on Figure 10 and Figure 11, the ALR Mode is active, then the grid frequency is simulated down to below 50 Hz from Grid Dispatcher (PLN). The load is not responding, still at around 53 MWe. Further frequency down from the grid to 49.79 Hz, resulting also no change in the load generation. The load is always stays in its set point of 53 MWe.

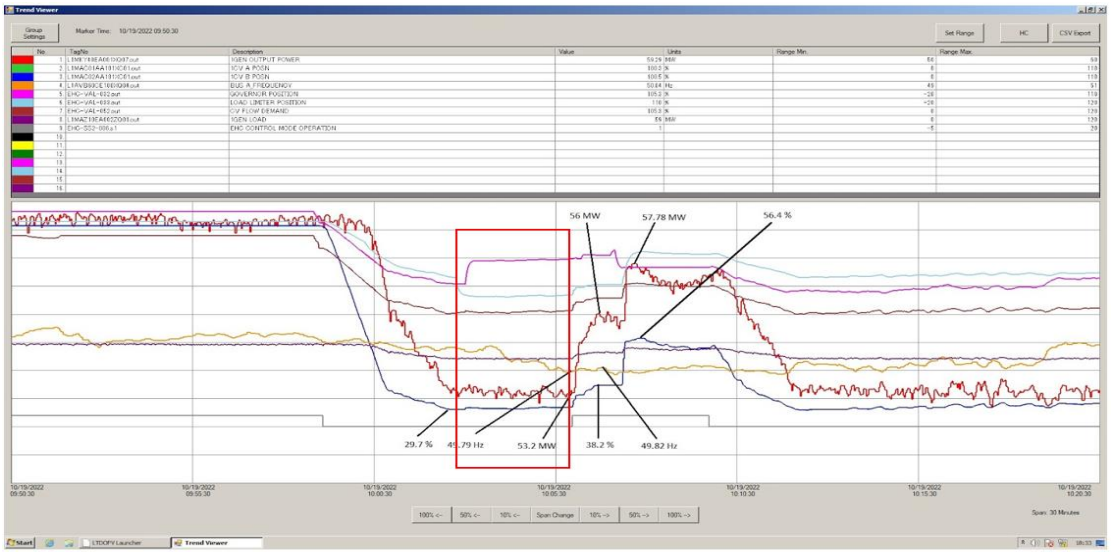


Figure 10: Trend while testing using ALR Mode (1), in red highlight (Tosmap,2022).

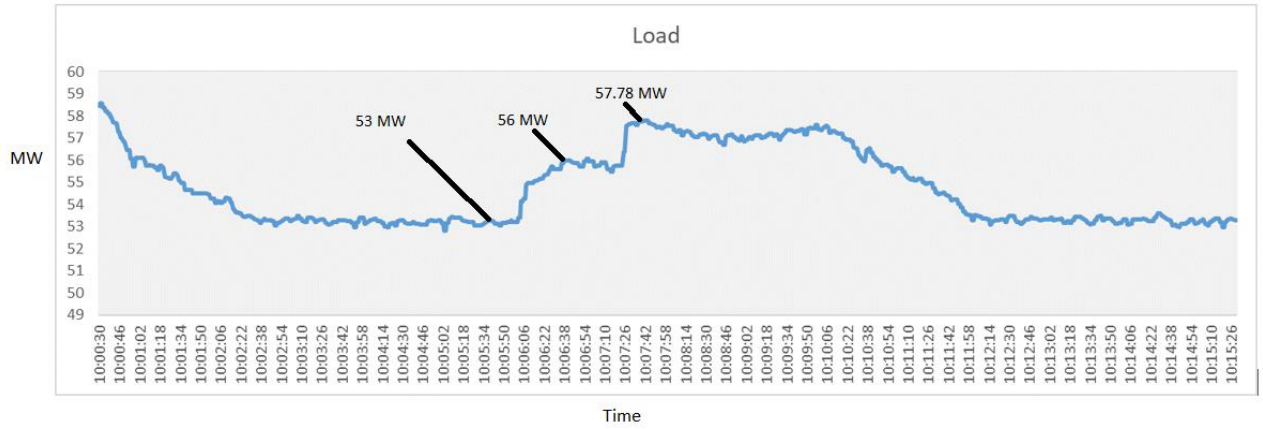


Figure 11a: Trend Load while testing using ALR mode (2).

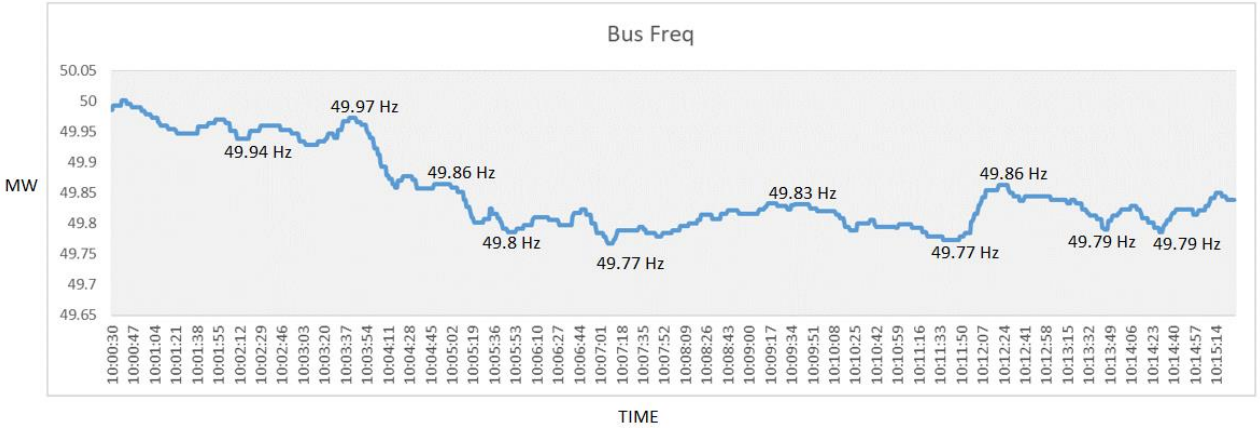


Figure 11b: Trend frequency while testing usung ALR mode (2).

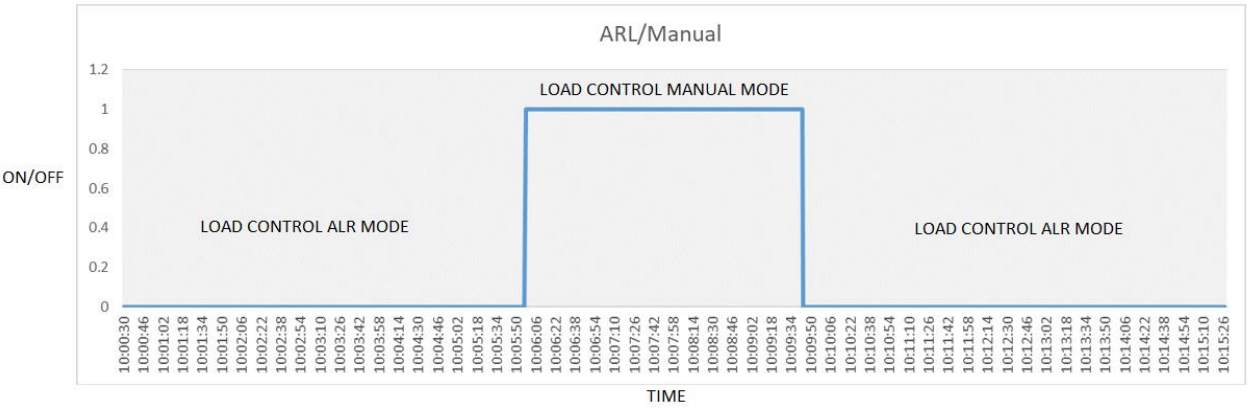


Figure 11c: Trend while testing using ALR Mode (2).

4. RESULT AND DISCUSSION

In Manual mode, the testing result is clearly shows the load is increasing from around 53 MWe to 57.78 MWe respective to the changing of the frequency from 50 Hz to 49.79 Hz (delta f = -0.21 Hz) and the load is decreasing from around 53 MWe to 51.6 MWe respective to the changing of frequency from 50 Hz to 50.21 Hz (delta f = +0.21 Hz).

While in ALR mode, the change in frequency in not followed by changing of the load. This phenomenon happened because the ALR is basically set point of the load of the generator, in which the inside have the speed control. The turbine control system (DEHC) is always trying to match with the set point, so that the change of frequency resulting change in load in a very short time and cannot clearly observed. However, after those changes, the load is going back to the set point.

In Manual mode, the set point is not the load anymore but only the speed (Toshiba, 2019c) as shown at Figure 12, so that the changing in frequency directly resulting in changing of the load to try to match the speed set of 3000 rpm. This condition resulting the load changing is more clearly visualized while there is a frequency change.

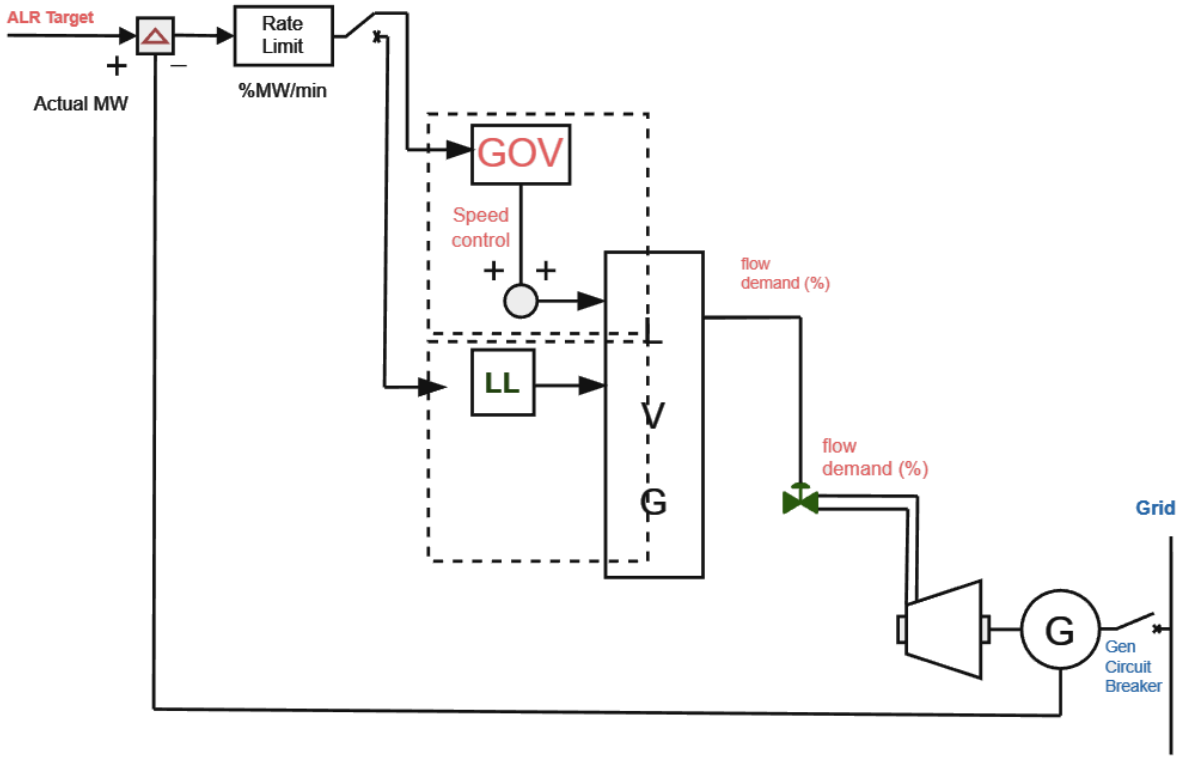


Figure 12: Block diagram if using Manual Mode (Toshiba, 2019c).

In response to frequency changing below 50 Hz, LMB-1 increase the load respectively. This situation can be achieved because the initial load for the test is 53 MWe and there is enough steam at the venting system (rock muffler) for supplying the turbine until full load condition of 58.9 MWe. For LMB-1 there is a load limiter if GOV value already 110% (slightly above 58.9 MWe depends on vacuum condition) so that the load cannot be increased further. In this case, if there are any changes of frequency down to below 50 Hz, the load will be maximum at 58.9 MWe and cannot be increased anymore.

5. CONCLUSION

1. In Manual mode the free governor is **working properly** with load response changing from 53 MWe to 57.78 MWe in frequency difference of -0.21 Hz and load response changing from 53 MWe to 51.6 MWe in frequency difference of +0.21 Hz.
2. Manual Mode Governor Free Test for over-frequency conditions with of 50.1 Hz and 50.2 Hz, the governor-free system successfully reduced the active load by -0.57 MWe and -1.8 MWe respectively.
3. Manual Mode Governor Free Test for under-frequency condition of 49.82 Hz and 49.79 Hz, the governor-free system successfully increase the active load by +3.7 MWe and +4.78 MWe respectively.

4. In ALR mode, the load is not changing while there is any change in frequency.
5. In ALR mode, the free governor response is harder to observe.

ACKNOWLEDGEMENT

Thank you for Pertamina Geothermal Energy Lumut Balai for permission to share the data.

REFERENCES

Toshiba. (2019a). Operation & Maintenance Manual for D-EHC System. Toshiba.

Toshiba. (2019b). Unit Interlock Diagram (Electrical). Toshiba

Toshiba. (2019c). Classroom Lecture for Toshiba Steam Turbine Control System. Toshiba

Toshiba. (2022a). Offshore Engineering of Deadband Setting Adjustment. Toshiba

Toshiba. (2022b). How to Perform Parameter Tuning for Free Governor Deadband. Toshiba

The GreenLoop Closed-Loop Geothermal (CLG) System: Optimizing Power Generation and Evaluating Its Impact on the Reservoir

Joseph Scherer[1], Glenn Golla[1], Harish Chandrasekar[1], Alvaro Amaya[1], Hollis Chin[1], Steven Brown[1], Eric Sonnenthal[2], Jonny Rutqvist[2], and Curt Oldenburg[2]

[1]1990 N. California Blvd., 8th Floor, Walnut Creek, CA USA 94596-3701
[2]Lawrence Berkeley National Laboratory (https://www.lbl.gov/)

glenn.golla@greenfireenergy.com

Keywords: GreenLoop, working fluid, The Geysers, mineral dissolution and precipitation, micro-seismicity

ABSTRACT

Since its founding in 2014, GreenFire Energy Inc. (GreenFire) has been developing its versatile GreenLoop Closed-Loop Geothermal (CLG) technology. GreenFire's GreenLoop™ consists of a downbore tube-in-tube (co-axial) heat exchanger that circulates large volumes of a working fluid. The working fluid returns at elevated temperatures to the surface through a vacuum-insulated tubing (VIT) and can be flashed to produce power either in an existing steam condensing power plant or an Organic Rankine Cycle (ORC) power-generating system. Aside from power generation, the hot working fluid can also directly be used for space heating/cooling and other industrial applications. GreenLoop only extracts heat and conserves mass and pressure in the reservoir, thus ensuring the long-term sustainability of the geothermal resource. This technology has the potential to dramatically expand power production from geothermal resources where conventional geothermal technology is challenged and to substantially de-risk new geothermal projects and drilling programs. As part of GreenFire's continuous improvement program, Baker Hughes, GreenFire's major investor and partner, has launched the Wells2Watts Consortium with the main objective of testing the GreenLoop technology at its Energy Innovation Center using a sophisticated physical laboratory setting. In addition, GreenFire recently completed its analysis of different working fluids to optimize power generation from GreenLoop. Lastly, the Lawrence Berkeley National Laboratory (LBNL) recently validated GreenFire's modeling of its Steam and Two-Phase GreenLoop (S2PGL) with particular focus on its favorable resource and aseismic impact relative to conventional geothermal technology. Summaries of these recent developments are presented in this paper.

1. INTRODUCTION

GreenFire Energy Inc. (GreenFire) is a San Francisco-based company that was established in 2014. Since its incorporation, GreenFire has been developing solutions with its GreenLoop Closed-Loop Geothermal (CLG) technology (Amaya et al., 2021; Higgins et al., 2021). GreenLoop is a downbore heat exchanger (DBHX) consisting of a tube-in-tube assembly installed into an existing well. The DBHX consists of a liner with a plugged end at the bottom to keep the working fluid from escaping into the wellbore, and, inside the plugged liner, is a vacuum-insulated tube (VIT) that extends nearly to the bottom of the liner (Figure 1). Normally, a working fluid is injected in the annulus of the VIT and the plugged liner. The working fluid can either be water, supercritical carbon dioxide (sCO2), refrigerants or organic hydrocarbons (Chandrasekar et al., 2023). As this cold working fluid travels downbore, it gathers heat from the geothermal fluids that enter the wellbore. The hot working fluid returns to the surface through the VIT where the thermal energy is converted to electrical energy through existing steam condensing turbines, via a surface heat exchanger coupled with an Organic Rankine Cycle (ORC) power generation unit or used for direct use (space heating and cooling) and some industrial applications.

GreenFire successfully field-tested its GreenLoop CLG technology at the Coso geothermal field (southern California, USA) in 2019 using a grant from the California Energy Commission (CEC). Results of this field test indicate that the DBHX installed in the idle well could produce ~1.2 MW of net electric power using water as working fluid and that both water and super critical carbon dioxide

(sCO_2) can be effectively used as working fluids for CLG systems. This project at Coso validated GreenFire Energy's GreenLoop™ technology and modeling approach and assisted in the quantification of field-scale CLG projects. A full report of the GreenLoop pilot test at Coso (CEC-300-2020-007) is available to the public at https://www.energy.ca.gov/.

As part of its continuous improvement initiative, GreenFire has continued to develop its GreenLoop solutions. Aside from projects in different parts of the world, GreenFire is working on evaluating further expansion of the GreenLoop technology for deployment in oil and gas wells. A recently completed study focused on the analysis of different working fluids for the best techno-economic results. Lastly, a third party national laboratory has recently validated GreenFire's predictions and evaluated the impact of continuous GreenLoop operation on the reservoir. These activities allow GreenFire to further move from the technical modeling stage to the implementation phase of deploying its GreenLoop CLG technology.

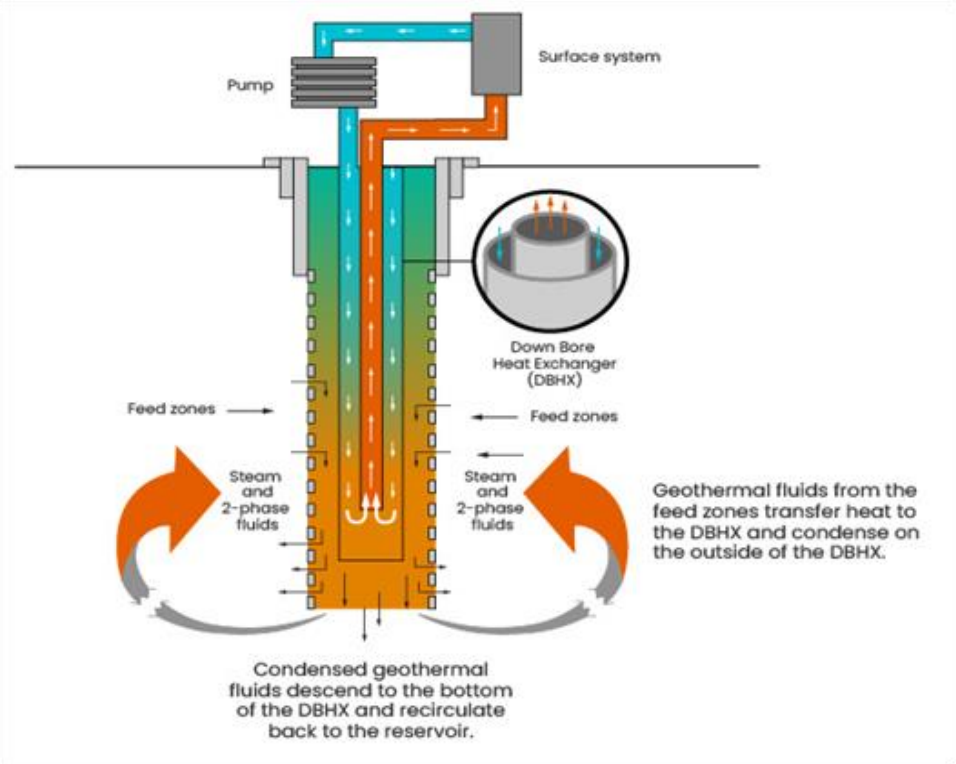


Figure 1: Schematic representation of a GreenLoop system showing the processes that occur within the DBHX and the near-wellbore region of the reservoir. Typically, a cold working fluid is pumped into the annulus between the insulated VIT and a plugged (at the bottom) outer liner. As the working fluid descends, it is heated by the geothermal fluids that enter the wellbore and hot fluid flows to the surface through the VIT. Condensation occurs outside the plugged liner and the condensate flows downward in the well (see black arrows). The condensate is then heated by the reservoir rocks and recycled back into the reservoir to gain heat and provides recharge to the DBHX and other nearby wells (Figure adapted from Higgins et al., 2022).

2. RECENT DEVELOPMENTS ABOUT GREENLOOP

2.1 Wells2Watts Consortium: CLG Test Facility

GreenFire's partnership with Baker Hughes and Vallourec, both key investors and partners of GreenFire, provides access to world class laboratories to advance its CLG technology. Currently, GreenFire is working with the Wells2Watts consortium to test GreenLoop at the first-ever CLG test facility in the world at the Hamm Institute for American Energy, Oklahoma State University (OSU), Oklahoma City, Oklahoma, USA (Figure 2). The Wells2Watts consortium is a private industrial partnership between Baker Hughes, Continental Resources, INPEX (Japan) and Chesapeake Energy Corporation. The consortium aims to explore technologies to retrofit and repurpose oil and gas wells for geothermal energy, revitalize dry non-productive geothermal wells, and develop greenfield opportunities for geothermal energy production.

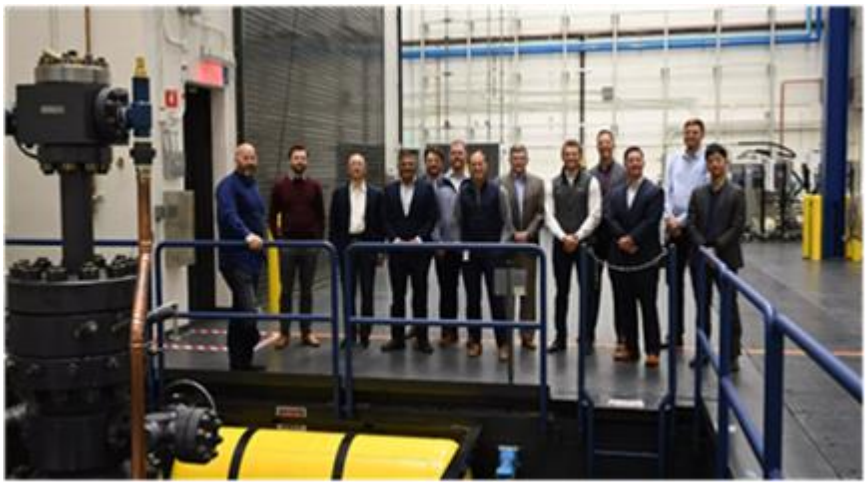


Figure 2: Wells2Watts consortium board members pose at the Baker Hughes laboratory test well that will be used to evaluate the GreenLoop CLG system at Oklahoma State University's Hamm Institute of American Energy, USA. (Photo from www.bakerhughes.com).

The test well at the test facility has already been drilled and cased to prevent any local aquifer communication. It is presently being updated to accommodate the GreenLoop system by installing a large diameter casing and the vacuum insulated tubing (VIT). The plan is to simulate relative oil and gas environments using the well at a bench scale system including casing sizes, flow rates, and bottom hole temperatures. The main goal of the testing is to understand thermal efficiency transfer in the downhole environment using the above-mentioned parameters. Additionally advanced modeling of the GreenLoop system can give further insights into the expansion of the technology for future deployment at several reservoir locations for oil and gas companies. The laboratory is available to take field learnings and advance the GreenLoop technology even further to improve both cost and thermal efficiency through design improvements, materials, or advanced working fluids and power conversion technology.

2.2 Optimizing Power Generation: Comparison of Different GreenLoop Working Fluids

Since its establishment in 2014, GreenFire had been fine-tuning its GreenLoop technology to extract residual thermal energy from geothermal wells that are performing below the minimum requirements for power generation, especially in mature geothermal fields. During the field test and validation at Coso, both water and supercritical carbon dioxide (sCO2) were used as working fluid for the Steam and 2-Phase GreenLoop (S2PGL) as these fluids are considered "benign" and any accidental leakage into the reservoir should not result to any environmental issues. As GreenFire customizes its GreenLoop solutions to each project, the S2PGL is intended for steam- and two-phase dominated geothermal systems. Meanwhile, SDGL stands for Steam-Dominated GreenLoop and, as the name suggests, for

steam-dominated geothermal systems. Lastly Hot, Dry Rock (HDR) GreenLoop for systems with no commercial permeability but hot.

An in-house study aimed at understanding the thermal-hydraulic behavior of different working fluids, namely, water, sCO_2, and n-pentane, within the GreenLoop system was recently performed by GreenFire. Another objective of this analysis was to explore possible system efficiency enhancements using different working fluids to achieve better techno-economics and further minimize the surface footprint of geothermal developments using GreenLoop. This analysis was done by calibrating the S2PGL model with collected data from the 2019 field test in Coso.

A stable thermal power extraction rate of ~5 MWth was used for each of the working fluids, namely, water, sCO_2, and n-pentane, to mimic low enthalpy geothermal sources. Also, the thermal power was set as a constant for the analysis between different working fluids. Thermal-hydraulic simulations were conducted considering uniform thermal heat extraction from the three working fluids. For the case with water as working fluid, GreenLoop was coupled with a surface ORC unit that uses n-butane as working fluid. For the scenarios where sCO_2 and n-pentane were the working fluids, GreenLoop was directly paired to a turbine/expander unit for power production. Figure 3 shows the results of simulating these three working fluids for a GreenLoop system.

Simulations indicated that water as working fluid for GreenLoop (and connected to an ORC unit using n-butane) had the highest estimated net power (Table 1). As expected, using water as a working fluid did not result in any phase change within GreenLoop unlike sCO_2 (which expands) and n-pentane (which boils at relatively lower temperature). This makes water a good and practical working fluid for GreenLoop from a control/stability standpoint (i.e., better control of velocity and pressure can be obtained); also, water (and sCO_2) is not flammable/combustible unlike n-pentane and other organic hydrocarbons.

Table 1: Net power estimates for water, sCO2 and n-pentane as working fluid for GreenLoop.

	Water	**sCO_2**	**n-pentane**
Heat Extraction, MWth	5	5	5
Gross Power at Turbine/Expander, MWe	0.55	0.70	0.43
Parasitic Load (from GreenLoop, cooling water and ORC pumps), MWe	0.10	0.40	0.03
Net Power, MWe	**0.45**	**0.30**	**0.40**

Using sCO_2 as working fluid resulted in the lowest net power as it has the highest parasitic power requirement (Table 1). Using sCO_2 is probably appropriate for low enthalpy geothermal systems (and, also, retrofitting depleted oil and gas wells) as the use of this working fluid can lead to thermosiphon scenarios (i.e., the working fluid can circulate on its own within the CLG system without continuously using a mechanical pump). Commercial development of sCO_2 expanders can lead to superior techno-economics, although this type of turbine is probably still many years from now. The U.S. DOE (Supercritical CO2 Tech Team | Department of Energy) believes that the sCO_2 Brayton Cycle for energy production has superior economic and environmental advantages, namely, applicability to a variety of heat sources, higher plant efficiency (>40% compared to ~33% for ORC units), low fuel consumption and emissions, minimal cooling water consumption, and compact design (small footprint that lowers capital cost).

Lastly, n-pentane as working fluid for GreenLoop had the second highest estimated net power (Table 1). As n-pentane has a boiling point of about 36 °C, it is well suited for a wide range of geothermal systems and heat sources. A negative in the use of organic hydrocarbons is that any subsurface leaks through the casing joints can potentially lead to environmental issues. However, leak-free casing and connection designs, as touted by tubular OEMs, can accelerate the use of organic hydrocarbon working fluids in GreenLoop leading to increased extraction of thermal energy and, consequently, power generation. The use of n-pentane as the GreenLoop working fluid appears to be the most techno-economical as the need for the surface heat exchanger is eliminated and its net power output is almost similar to water.

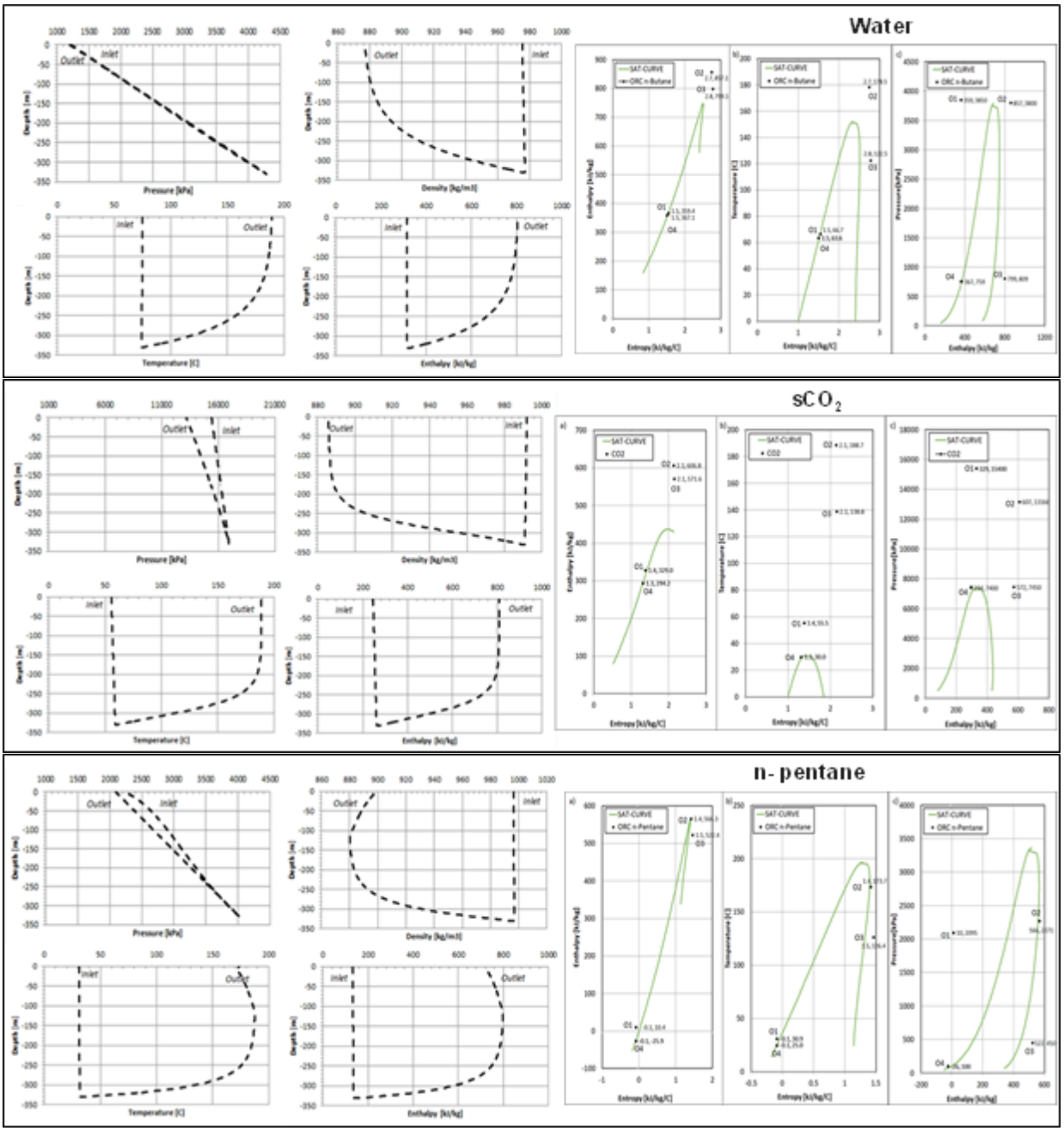


Figure 3: The top charts on the left show the inlet and outlet pressure, temperature, density and enthalpy of GreenLoop using water as working fluid. The produced hot water is fed into an ORC unit using n-butane as working fluid. The top charts on the right (L-R) show entropy vs. enthalpy, temperature and pressure at different measuring points in the GreenLoop-ORC system where O1 is at the GreenLoop pump inlet, O2 is at the GreenLoop inlet, O3 is at the GreenLoop outlet, and O4 is at the ORC turbine outlet. The middle and bottom panels show the same charts for sCO2 and n-pentane, respectively.

2.3 Optimizing Power Generation: Comparison of Different GreenLoop Working Fluids

A frequently asked question about the GreenLoop CLG system is its long-term impact on the reservoir, especially where condensate forms at the outer surface of GreenLoop and percolates back to and cools the reservoir. To address this question, the Lawrence Berkeley National Laboratory (LBNL) analyzed the resulting temperature, chemical and geomechanical changes that may potentially occur with the

continuous operation of GreenLoop at a test well in The Geysers geothermal field, California where GreenFire has an ongoing project with Calpine Corporation to test GreenLoop in one of their idle wells. This project is being implemented at The Geysers with a $2.7 MM funding from the California Energy Commission (CEC) under EPC-21-015 to prove GreenLoop's commercial feasibility.

After GreenFire estimated the potential generation from retrofitting the test well with its Steam-Dominated GreenLoop (SDGL), LBNL evaluated the thermal (T), hydrological (H), mechanical (M), and chemical (C) responses of The Geysers reservoir to the operation of the SDGL. In this validation exercise, LBNL investigated the technical feasibility of extracting geothermal heat from a steam-dominated geothermal reservoir using the SDGL. The first task that LBNL performed was to develop a coupled SDGL-wellbore-reservoir model using TOUGH-REACT, TReactMech (Sonnenthal et al., 2014; Xu et al., 2011; 2006), and TOUGH-FLAC (Rutqvist et al., 2002; Rutqvist, 2011 and 2017; Rinaldi et al., 2022). Chandrasekar, et al. (in progress, 2023) report in detail the validation by LBNL of GreenFire's predictions and results using reservoir simulations. The following sections present summaries of the LBNL work but focused on the reservoir impact of GreenLoop operations.

2.3.1 Thermal-Hydrological-Chemical (THC) Simulation: Evaluating Permeability Change and Scaling in the Reservoir

To study the chemical changes near-wellbore, LBNL built a THC model based on the TH model used to validate GreenFire's modeling results of net power, produced fluid flow rates, outlet temperature and pressure, etc. The basic assumption in building the THC model is that chemical changes are expected to occur in the reservoir because of the acidity of the condensate and presence of other acid gases at The Geysers reservoir. Information related to the shallow pore water above the caprock was obtained from the Allen thermal-meteoric water composition (Peters, 1993). The pore water conditions for the deeper rock layers (caprock, reservoir, and hornfels) were adapted initially from Wilbur Hot Spring (Goff et al., 1993) and then equilibrated with reservoir mineral assemblages (Moore et al., 2000). The gas chemistry was calculated through equilibration with the mineral-fluid system.

LBNL ran a six-month reactive-transport simulation including water-rock-gas reaction, aqueous and gaseous species advective/diffusive transport using the four-month TH simulation of the SDGL at the preferred flow rate of testing. Gas compositions were calculated based on the reaction of pore water with reservoir minerals [pyrite, magnetite, quartz, albite, plagioclase, microcline, chlorite, epidote, prehnite, wairakite and actinolite (only in hornfels)] while non-condensable/acid gases vary in composition owing to condensation, boiling, and water-rock reaction.

Simulation results show that most effects in rock composition are from the reaction of colder condensate draining at the wellbore bottom and the hotter reservoir rocks. There were some dissolutions of primary silicates as well as formation of secondary minerals below the wellbore (Figure 4). For example, condensate drainage dissolves quartz but, at the same time, precipitates secondary albite and epidote. Furthermore, condensate drainage plus its boiling dissolves plagioclase, microcline and wairakite but also precipitates minor dolomite and microcline. Overall, net changes in mineral alteration are fairly minor over six months and are not expected to impact the test (Sonnenthal et al., 2023). Future work will include evaluation of longer-term permeability/capillary pressure effects after calibrating the TH and THC simulators based on the test results.

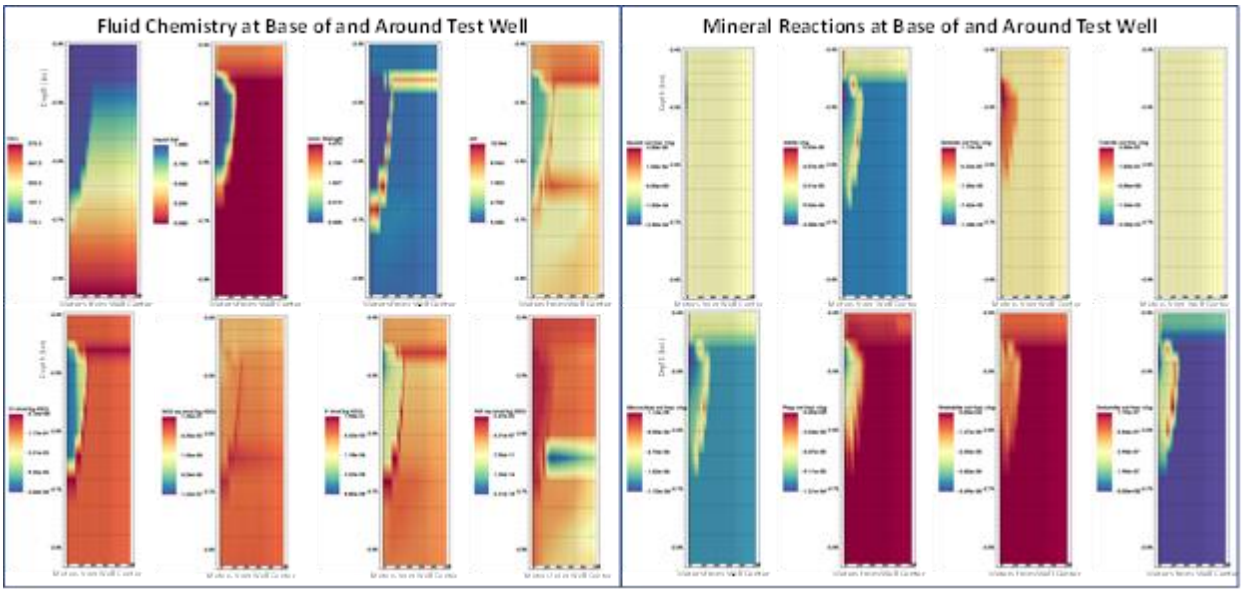


Figure 4: Fluid chemistry (left column) and mineral reactions (right column) at the base and around the test well after six (6) months of simulating the THC model. As condensate at the outer surface of the SDGL percolates by gravity at the base of the well and reacts with the hot reservoir, some primary minerals get dissolved (e.g., quartz, plagioclase, microcline, wairakite) while secondary minerals are formed (e.g., albite, epidote, minor dolomite). Overall, net changes in mineral alteration are fairly minor over six months and are not expected to impact the SDGL test.

2.3.2 Optimizing Power Generation: Comparison of Different GreenLoop Working Fluids

The last analysis that LBNL conducted was to model the geomechanical changes in the reservoir from continuous operation of the SDGL by building a THM model that was based on the TH model. In this simulation, LBNL calculated the mechanical stress changes and studied potential wellbore integrity and micro-seismicity issues.

As geomechanical changes will be driven by pressure and temperature changes and SDGL does not extract nor inject any fluid in the reservoir, pressure changes are expected to be not significant at the steam-dominated Geysers reservoir (Sonnenthal et al. 2023). Figure 5 shows the liquid saturation, temperature and pressure changes and micro-seismicity potential near-wellbore of the test well. Temperature changes are relatively small, just -8 °C in the casing, with the biggest cooling (-30 °C) occurring at the bottom of the well. Temperature changes along the open borehole wall (at r = 0.15 m) are not significant for borehole instability (Sonnenthal et al. 2023).

The 30 °C cooling below the bottom of the well could potentially induce micro-seismic events. However, the "micro-seismic volume" of 150 m height and 100 m horizontal extent is small and would not be expected to induce seismicity that could be felt on the ground (Sonnenthal et al. 2023). At four (4) months of continuous operation of the SDGL, the area of seismic potential has increased in size, but its magnitude is still small for micro-seismicity to be felt at the surface (Figure 6). These simulations indicate that GreenLoop operation in the test well will result in an aseismic (i.e., no felt earthquakes) response of the reservoir.

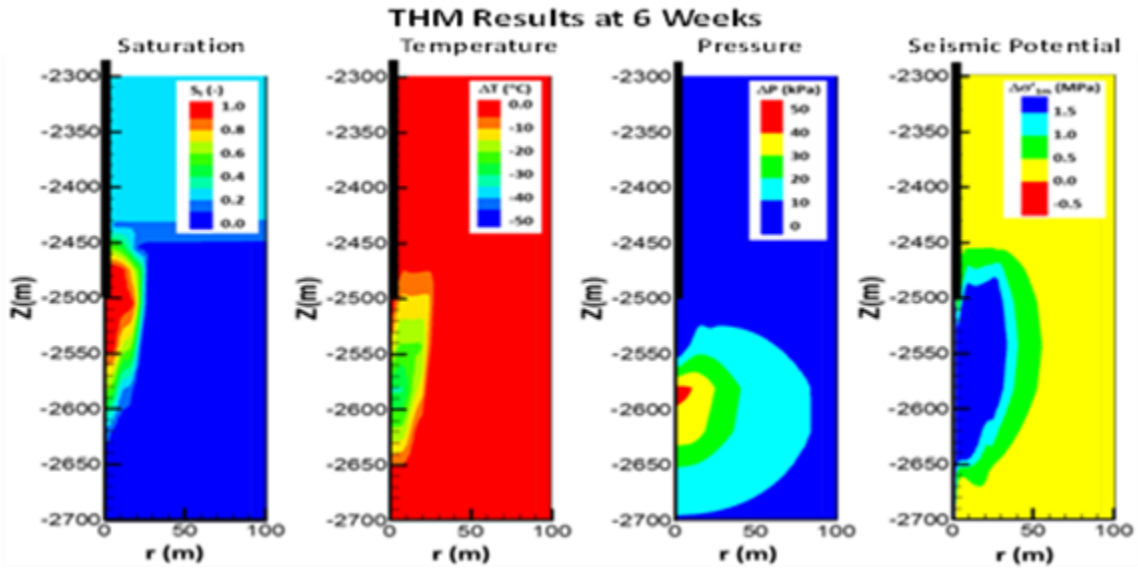


Figure 5: **(L-R) Liquid saturation, temperature and pressure changes around the wellbore of DS-1 (x-scale is radius from the wellbore) at six (6) weeks of continuous operation of the SDGL. The right-most chart shows the seismicity potential of SDGL operation; the dark blue contour indicates areas where micro-seismicity could potentially occur, which correlate with areas of cooling below the well. Pressure changes are negligible and have no significant impact on stress (SDGL bottom at -2500 m).**

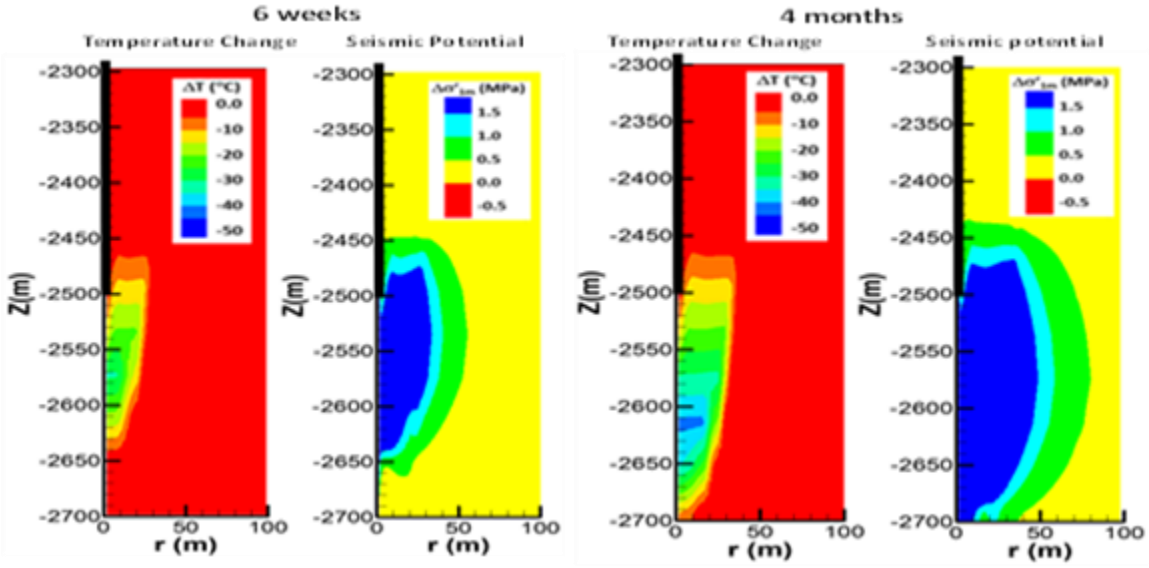


Figure 6: **Comparison of short- and longer-term temperature change and seismic potential of SDGL operation. The zone of temperature change and seismic potential has expanded from 6 weeks to 4 months but is still small (SDGL bottom at -2500 m).**

3. SUMMARY AND CONCLUSIONS

Although GreenLoop has already been successfully field-tested in 2019 at Coso, California, and is currently being implemented at The Geysers and in other geothermal projects worldwide, GreenFire is working with the geothermal energy consortium, Wells2Watts, to further fine-tune GreenLoop at the CLG test facility in Oklahoma City for oil and gas well repurposing.

Using data from the successful field validation test at Coso geothermal field, water, sCO_2 and n-pentane were evaluated in terms of their effectiveness as working fluids in GreenLoop. For sCO_2 and n-pentane, GreenLoop was directly coupled to a turbine/expander for power generation; for water, GreenLoop was coupled to a surface ORC system that uses n-butane as the working fluid. Results indicate that sCO_2 (as the GreenLoop working fluid) is suitable for low enthalpy systems. Although water as GreenLoop working fluid attained the highest net power, using n-pentane appears to be the most techno-economic.

Lastly, a third-party national laboratory has validated GreenFire's predictions of the performance of GreenLoop at The Geysers. The LBNL's simulations using TOUGH-REACT are in good agreement with GreenFire's predictions. Also, gravity drainage of condensate in the well fills the lower 60-80 m of the well and flows by gravity and imbibition into the surrounding unsaturated reservoir rock, thus, creating a near-wellbore closed-loop system in the reservoir. Chemical simulations show minor dissolution of primary silicates and precipitation of some secondary minerals at the base and around the wellbore with continuous operation of GreenLoop. However, net changes in porosity due to mineral precipitation are minor over six (6) months and are not expected to impact the proof-of-concept test at The Geysers. Furthermore, changes in mechanical stresses due to cooling will not affect borehole stability and the percolation of condensate from GreenLoop is not expected to induce seismicity that could be felt on the ground. These simulations will be updated for longer-term performance of GreenLoop and its impact on the reservoir based on the test results.

As geothermal resources continue to produce, the GreenLoop closed-loop geothermal technology has the potential to dramatically expand power production from mature geothermal fields and reservoirs where conventional geothermal technology is challenged. Also, geothermal exploration can be de-risked and the economics improved by considering GreenLoop installation in new geothermal projects.

ACKNOWLEDGEMENT

The authors wish to convey their thanks to both GreenFire Energy, Inc. and Baker Hughes managements for allowing publication of this paper. We hope that this paper will be a catalyst to accelerate the Energy Transition in Indonesia and elsewhere in the world.

REFERENCES

Amaya, A., Chandrasekar, H., Scherer, J., and Higgins, B. (2021). "Closed-Loop Geothermal in Steam and 2-Phase Dominated Reservoirs," National Geothermal Association of the Philippines' 2nd Philippine International Geothermal Conference, Manila, Philippines, October 27-29, 2021.

California Energy Commission (CEC-300-2020-007). "Closed-Loop Geothermal Demonstration Project: Confirming Models for Large-Scale Closed-Loop Geothermal Projects in California," June 2020.

Chandrasekar, H., Amaya, A., Molina, S., Alvarado, R., Scherer, J., and Golla, G. (2023). "Comparison of Water, sCO2, and Organic Hydrocarbons as Working Fluids for the GreenLoop System and ORC Unit," PROCEEDINGS, 48th Workshop on Geothermal Reservoir Engineering, Stanford University, Stanford, California, February 6-8, 2023, SGP-TR-224.

Chandrasekar, H., Amaya, A., Golla, G., Scherer, J., Sonnenthal, E., Rutqvist, J., Oldenburg, C., Manuel, F., Klenner, R., Ng, A., Ellis, S, and Gilbert, B. (in progress, 2023). "Coupled Thermal Hydraulic Mechanical and Chemical (THMC) Modeling of the GreenLoop system in the Southeast Geysers, California," Geothermal Rising Conference TRANSACTIONS, Vol. 47, Reno, Nevada, October 1-4, 2023.

Goff, F., Kennedy, B.M., Adams, A.I., Trujillo, P.E., and Counce, D. (1993). "Hydrogeochemical evaluation of conventional and hot dry rock geothermal resource potential in the Clear Lake region, California," TRANSACTIONS Geothermal Resources Council, Vol. 17, 335-342, Burlingame, California, October 11-13, 1993.

GreenFire Energy, Inc. (2022). https://www.greenfireenergy.com/cec-geysers.

Higgins, B., Muir, J., Scherer, J. and Amaya, A. (2019). "GreenFire Energy Closed-Loop Geothermal Demonstration at the Coso Geothermal Field," Geothermal Rising Conference TRANSACTIONS, Vol. 43, Palm Springs, California, August 25-28, 2019.

Higgins, B., Scherer, J., Amaya, A., Chandrasekar, H., and Van, A. (2021) "Closed-Loop Geothermal in Steam-Dominated Reservoirs," Geothermal Rising Conference TRANSACTIONS, Vol. 45, San Diego, California, October 3-6, 2021.

Higgins, B. S., Scherer, J. A., Hoyer, D. (2022). U.S. Patent No. 11,255,576. Washington, DC: U.S. Patent and Trademark Office.

Moore, J.N., Adams, M.C., and Anderson, A.J., (2000). "The fluid inclusion and mineralogic record of the transition from liquid- to vapor-dominated conditions in The Geysers Geothermal System, California," Economic Geology, 95, 2000, 1719-1737.

Peters E.K. (1993). "D-18O enriched waters of the Coast Range Mountains, northern California: Connate and ore-forming fluids," Geochimica et Cosmochimica Acta, 57(5), 1093-1104 (1993).

Rinaldi, A.P., Rutqvist, J., Luu, K., Blanco-Martín, L., Hu, M., Sentís, M.L., Eberle, L., and Kaestli, P. (2022). "TOUGH3-FLAC3D: a modeling approach for parallel computing of fluid flow and geomechanics," Computational Geosciences, 26, 1563–1580 (2022). https://doi.org/10.1007/s10596-022-10176-0.

Rutqvist, J. (2011). "Status of the TOUGH-FLAC simulator and recent applications related to coupled fluid flow and crustal deformations," Computers & Geosciences, 37, 739–750 (2011).

Rutqvist, J. (2017). "An overview of TOUGH-based geomechanics models," Computers & Geosciences, 108, 56–63 (2017). https://doi.org/10.1016/j.cageo.2016.09.007.

Rutqvist, J., Wu, Y-S., Tsang, C-F., and Bodvarsson, G.A. (2002). "Modeling approach for analysis of coupled multiphase fluid flow, heat transfer, and deformation in fractured porous rock," International Journal of Rock Mechanics and Mining Sciences, 39, 429-442 (2002). https://doi.org/10.1016/S1365-1609(02)00022-9.

Sonnenthal, E. and Spycher, N. (2014). "TOUGHREACT (TREACT) v3. 32 (No. TREACT V3. 32)," Lawrence Berkeley National Lab.(LBNL), Berkeley, CA (United States).

Sonnenthal, E., Rutqvist, J., and Oldenburg, C. (2023). "EPC-21-015 Final SDGL Model Report by LBNL: Simulation Studies to Investigate the Technical Feasibility of the SDGL," Unpublished technical report submitted to GreenFire Energy Inc., March 27, 2023.

United States Department of Energy. Supercritical CO2 Tech Team | Department of Energy (https://www.energy.gov/supercritical-co2-tech-team).

Xu, T., Sonnenthal, E., Spycher, N., and Pruess, K. (2006). "TOUGHREACT – a simulation program for non-isothermal multiphase reactive geochemical transport in variably saturated geologic media: applications to geothermal injectivity and CO2 geological sequestration," Computers & Geosciences, 32(2), 145-165 (2006).

Xu, T., Spycher, N., Sonnenthal, E., Zhang, G., Zheng, L., and Pruess, K. (2011). "TOUGHREACT Version 2.0: A simulator for subsurface reactive transport under non-isothermal multiphase flow conditions." Computers & Geosciences, 37(6), 763-774.

3rd Generation Silica Inhibitor Technology: Breakthrough Solution for Higher Energy Extraction

Nugraha Y. Arifpin, Muhamad Andhika, Mona N. Siahaan, and Tomy Suryatama

Ecolab International Indonesia, Pondok Indah Office Tower 5, 5th Floor,
Jalan Sultan Iskandar Muda Kav V-TA Jakarta, Indonesia

nyohanesarif@ecolab.com, muhamad.andhika@ecolab.com,
monanatalia.siahaan@ecolab.com, tsuryatama@ecolab.com

Keywords: Silica, Silicate, Inhibitor, High SSI, Binary Power Plant

ABSTRACT

Geothermal energy extraction is a complex energy generation that typically depends on the reservoir condition, with increasing complexity as the reservoir enthalpy decreases. Typically, geothermal energy extraction prefers to extract energy from high enthalpy well. But, with the limited high enthalpy reservoir, the exploitation of medium enthalpy reservoir becomes an option for renewable energy resources, with binary power plant as the instrument to extract energy from medium enthalpy reservoir.

In a binary power plant, the energy from the brine is transferred to evaporate secondary working fluid. The vapor will then be used to generate electricity through an expander or a turbine. With this energy transfer, the brine temperature will be reduced, and the saturation of prograde solubility mineral (such as silica and metal silicate) will increase. In conventional power plant, the saturation indexes of these minerals are controlled by limiting the outlet brine temperature, with typical silica saturation index (SSI) between 1.2 – 1.5.

In recent years, the binary power plant design has been pushed to the limit beyond the conventional design with SSI up to 2.5 through implementation of Nalco Water 2nd generation silica inhibitor that inhibit the prograde mineral scaling and deposition. Having said that, as the energy demand from geothermal increases, some new binary power plant is designed with even higher SSI. In this SSI level, both pH mod and Nalco Water 2nd generation silica inhibitor are not able to provide good control on silica and silicate scaling which cause losses in generation opportunities and high cleaning and maintenance cost. Therefore, an innovative chemical inhibition is needed to help the geothermal power plant extracting more energy in safe and reliable manner. This paper shares a breakthrough Nalco Water 3rd generation silica inhibitor technology that developed to meet the requirements of extracting energy at higher SSI.

1. INTRODUCTION

Energy transition from fossil energy to renewable energy received much traction in recent years, which include geothermal energy as one of the energy sources that considered as green, predictable, and consistent. The predictability and consistency of geothermal energy to generate electricity makes geothermal energy favorable to replace coal and gas power plant as the base load power plant to accommodate the unpredictability of other renewable sources (solar and wind). Nevertheless, the utilization of geothermal energy has huge drawbacks such as its cost of development and low heat to power efficiency (Zarrouk and Moon, 2014) which makes geothermal energy less affordable compared to other renewable sources.

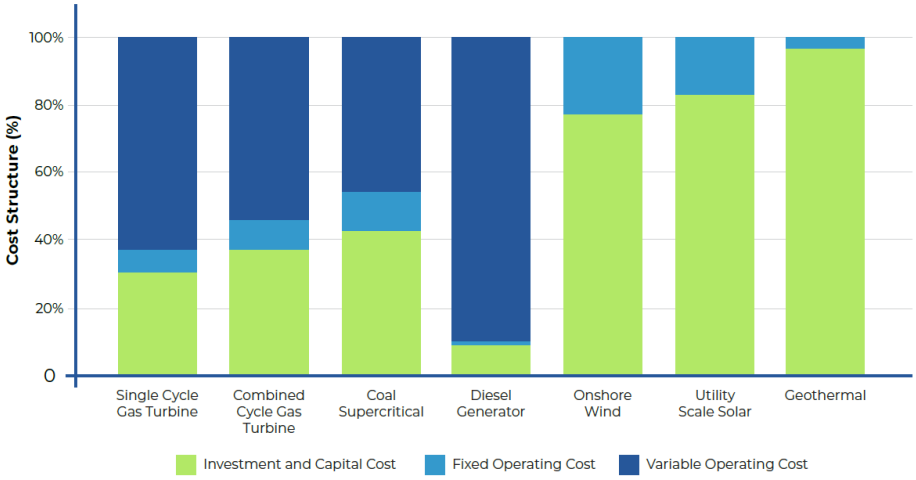


Figure 1: Cost Structure of Renewable Energy and Fossil Energy (Arinaldo and Pujantoro, 2019).

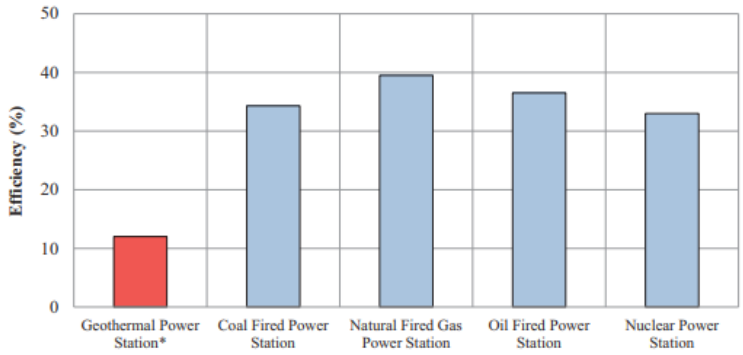


Figure 2: Geothermal Heat to Power Conversion Efficiency (Zarrouk and Moon, 2014).

Apart from the issue of its affordability, geothermal energy also faces challenges from the availability of high-quality resources. In terms of availability, high enthalpy resources are getting limited which forces the utilization of medium enthalpy resources. Medium enthalpy resources are technically difficult to exploit and less feasibility to generate electricity. The utilization of medium enthalpy resources commonly used Rankine cycle with secondary working fluids as the medium to absorb energy from the geothermal fluid (binary power plant). Once the energy absorbed, the secondary working fluid is vaporized and used to generate electricity in the turbine. The energy extraction from geothermal fluid is limited by scaling formation, which is typically comes from silica and other dissolved metals. With the increases in concentration and reduction in temperature, the silica becomes oversaturation and will cause deposition. The degree of silica saturation is known as silica saturation index (SSI), which measure the ratio of silica in solution to the solubility of amorphous silica at the fluid/brine temperature. SSI > 1.0 implies that the solution is supersaturated and SSI < 1.0 implies the solution is under-saturated (Brown, 2011). Therefore, binary power plant is typically designed with low SSI, up to 2.0 (Zarrouk et al., 2014). as the safety factor to mitigate scaling formation. Unfortunately, this effort will reduce the heat transfer efficiency as depicted in Figure 3.

This limitation makes energy extraction from medium enthalpy resources becomes more less affordable. Therefore, mitigation of prograde solubility minerals becomes more critical to help the continuity, reliability, and affordability of medium enthalpy utilization. There are numerous studies on pH mod and polymer-based inhibitor that aim to mitigate the scale and deposition. The previous work (Arifpin et al., 2022) has proved that the polymer-based inhibitor able to mitigate the scaling formation up to SSI 2.58. Unfortunately, the polymer-based inhibitor that used cannot be implemented to mitigate the scaling formation at higher SSI.

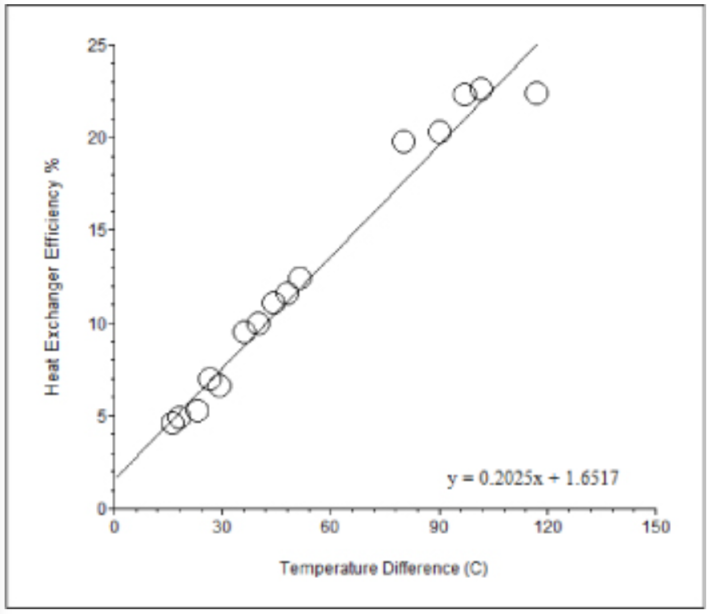


Figure 3: Heat Exchanger Efficiency Dependence on Temperature Difference (Domanski et al., 2015).

2. 3RD GENERATION SILICA INHIBITOR TECHNOLOGY

Based on the previous work (Arifpin et al., 2022), the 2nd generation of silica inhibitor (GEO981 and GEO962) able to withhold silica in monomeric form by 94.6% at SSI up to 3.05 with binary operation run length 103 days. Another run with SSI 2.92 gives similar performance with the data displayed in table 1.

Table 1: Example of 2nd Generation Silica Inhibitor Performance in Binary Power Plant.

Parameter	Value
Aluminum (ppm)	0.19
Silica (ppm)	760
Iron (ppm)	3.8
Binary average inlet temperature (^{0}C)	150
Binary average outlet temperature (^{0}C)	73.5
Average % Monomeric Silica Retention	94.3%
Average % Metal Retention	66%

With these performances, the average system scaling rate is registered around 0.3 mm/year and the system needs to be cleaned within 3-5 months' timeframe. Although the performance is acceptable if we compared it against other inhibition technologies, there is a demand for better scale and deposition control to increase the generation by reducing the temperature and keeping the cleaning frequency as low as possible.

With this goal in mind, the next generation of silica inhibitors program must encompass certain criteria which are:

Table 2: Success Criteria for 3rd Generation Silica Inhibitor Program.

Leading Indicator	Lagging Indicator
Better % monomeric silica retention (>95%)	Better scaling rate (< 0.3 mm/year)
Better % metal retention (>70%)	Better heat transfer (stable U value)
	Reduced cleaning frequency (< 3 times/year)
	Better differential pressure (stable DP)
	Stable MW generation

With the limitation onsite, the 3rd generation silica inhibitor performance will be reviewed through analysis of % monomeric silica retention, % metal retention, and scaling rate. And to justify the new generation inhibition performance, we will compare it against the performance of 2nd generation silica inhibitor.

2.1 Percent (%) Monomeric Silica Retention

Percent (%) monomeric silica retention is an indicator of the amount of silica that remains in the monomeric form (equation 1). High % monomeric silica retention indicates that monomeric silica doesn't react with other monomeric silica to form polymeric silica or doesn't react with metal to form metal silicate.

$$\% \text{ Monomeric Silica Retention} = 1 - \frac{\text{Monomeric Silica at Binary Outlet}}{\text{Monomeric Silica at Binary Inlet}} \quad (1)$$

To understand the performance, we compare the % monomeric silica retention between the 2nd and 3rd generations silica inhibition program. The result is displayed in figure 4 and table 3.

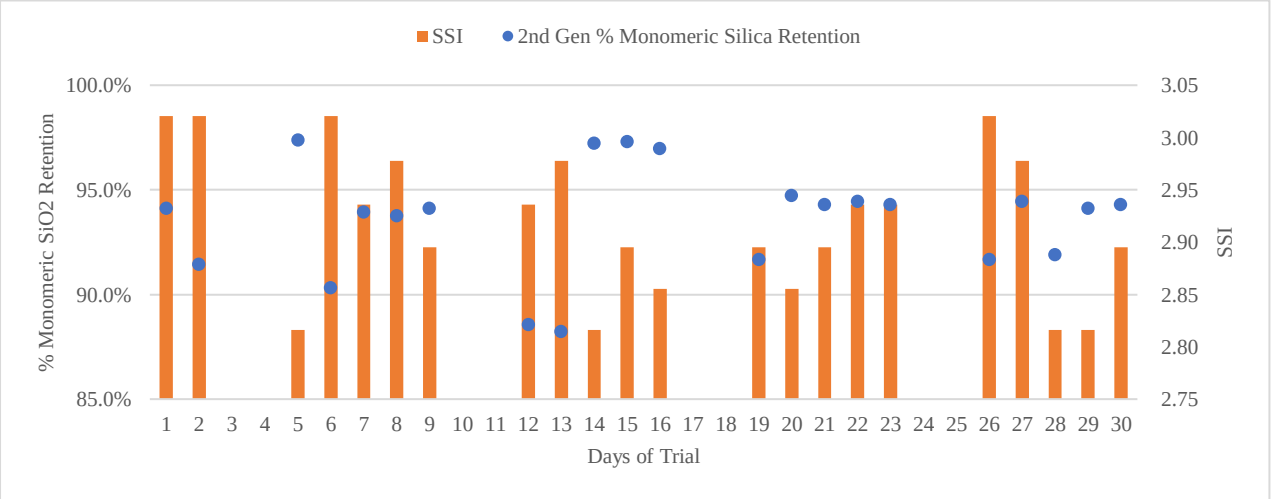


Figure 4: 2nd Generation % Monomeric Silica Retention Performance.

Table 3: 2nd Generation % Monomeric Silica Retention % Monomeric Silica Retention Performance Summary.

SSI LSL	SSI USL	% of Data	Avg % Monomeric SiO2 Retention
2.78	2.85	18.2%	95.2%
2.85	2.92	31.8%	94.8%
2.92	2.99	31.8%	92.5%
2.99	3.06	18.2%	91.9%

It can be inferred from the data above that % monomeric silica retention of 2nd generation silica inhibitor program is declining as the SSI increases. As the % monomeric silica declines, the risk of silica and/or metal silicate scaling deposition is increases. But, with this data alone, it is not enough to predict the scaling potential that might arises.

The graph below shows the performance of 3rd generation silica inhibitors program that used in the same operating conditions and binary design.

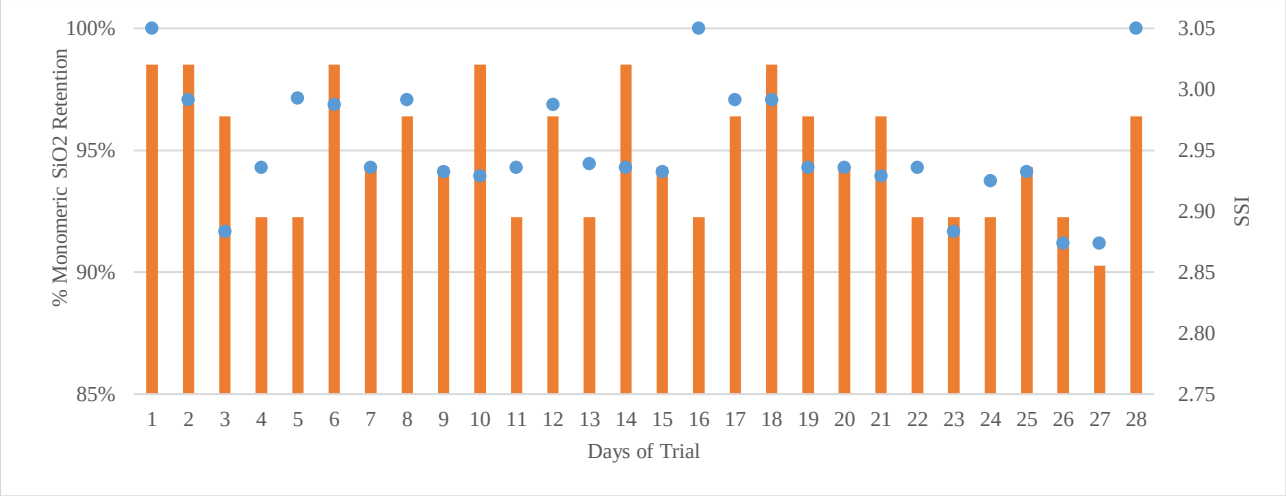


Figure 5: 3rd Generation % Monomeric Silica Retention Performance.

Table 4: 3rd Generation % Monomeric Silica Retention % Monomeric Silica Retention Performance Summary.

SSI LSL	SSI USL	% of Data	Avg % Monomeric SiO2 Retention
2.85	2.90	35.7%	94.2%
2.90	2.95	17.9%	94.2%
2.95	3.00	25.0%	95.8%
3.00	3.05	21.4%	96.5%

It can be inferred from the Figure 5 and Table 4 that 3rd generation program is more capable to retain the silica in monomeric form even at high SSI compared to 2nd generation program (Figure 4 and Table 3).

2.2 % Metal Retention

The presence of metal ions in the brine can cause the formation of metal silicate which has a much lower solubility (Zarrouk et al., 2014). Therefore, it is crucial to understand and manage the risk of silica and metal silicate formation in binary heat exchangers. % metal retention indicates the amount of metal (aluminum, iron, manganese, etc.) that remains in the bulk water after it passes through the binary heat exchanger. High % metal retention indicates that most of the metal remains stable and does not react with silica to form metal silicate. This indicator will help to differentiate the scaling risk between amorphous silica and metal silicate in the binary heat exchanger.

$$\% \text{ Metal Retention} = 1 - \frac{\text{Metal at Binary Outlet}}{\text{Metal at Binary Inlet}} \quad (2)$$

With the information of metal retention, the program can be adjusted to accommodate better metal silicate control if we found a situation where the propensity of metal silicate deposition risk is higher than silica deposition risk.

Table 5: % Metal Retention Comparison.

	2nd Generation Program	3rd Generation Program
Average % Metal Retention	66.4%	80.1%

Table 5 above displays the comparison between % metal retention (aluminum) between 2nd generation and 3rd generation silica inhibitors program at the same operating condition and equipment designs. Metal retention from the 3rd generation silica inhibitor is better than the 2nd generation by 20.6%, which indicates better control to prevent metal silicate formation.

2.3 Scaling Rate

Scale deposition is a complex mechanism that influenced by (Hirtz (2016), Pardelli et al. (2021))

1. Degree of supersaturation
2. Induction period
3. Flow velocity and turbulence
4. Ionic strength and salinity
5. pH
6. time
7. Availability of nucleation site

Typically, the binary power plant is designed to minimize the negative impact of the scaling formation by adjusting the parameter above. With this complexity, monitoring the leading chemistry indicators as above will not be sufficient to guarantee the system performance. Therefore, monitoring the scaling rate through coupon measurement is a good indicator to estimate the condition within binary heat exchanger. A good inhibition program will have to show good performance on both chemistry leading indicators (% monomeric silica retention and % metal retention) and deposition lagging indicators (scaling rate, MW declined, DP, etc.).

Table 6 displayed the scaling rate measurement from both generation of silica inhibitor at two different tests (pilot test and plant trial). As can be seen, both tests show consistent performance of 3rd Generation program both in terms of chemistry performance (% metal retention and % monomeric silica) and scaling rate. From these two sites, it can be seen that the performance is consistent even with different types of metal ions that available and different level of silica concentration in the brine.

Table 6: Chemistry & Scaling Rate Comparison between 2nd and 3rd Generation.

	Pilot Test	Site Application
Average Operating Condition		
Silica Concentration (ppm)	1010	760
Metal Concentration (ppm)	1.9 (Fe)	0.19 (Al)
Heat Exchanger Inlet Temperature (^{0}C)	160.0	150.0
Heat Exchanger Outlet Temperature (^{0}C)	121.0	73.5
Average % Metal Retention		
2nd Generation	77.0%	66.4%
3rd Generation	84.5%	80.1%
Average % Monomeric Silica Retention		
2nd Generation	94.7%	93.6%
3rd Generation	94.8%	95.1%
Scaling Rate (mm/year)		
2nd Generation	0.38	0.30
3rd Generation	0.15	0.12

We can see that the scaling rate from 3rd generation silica inhibitor is better compared to 2nd generation silica inhibitor by ~60% improvement. The reduction in scaling rate is mainly driven due to the ability of 3rd generation silica inhibitor to handle amorphous silica (high % monomeric retention) and metal silicate (high % metal retention) better compares to 2nd generation silica inhibitor, thus providing less polymerization and nucleation site for seeding reaction to occur.

3. CONCLUSION

Without solving the issue on the scaling formation in binary plant, utilization of medium to low enthalpy geothermal resources will be limited, and the energy extraction efficiency will be low. Thus, innovation and improvement of existing mitigation program is needed to ensure the plant operation.

From the test and trial that aforementioned, it can be concluded that 3rd generation silica inhibitor program can deliver better performance compared to 2nd generation program by showing:

1. Improvement on monomeric retention
2. Improvement on metal retention
3. Improvement on scaling rate

With the performance that shown, we expect 3rd generation silica inhibitor program can help geothermal industry to achieve better reliability and affordability which are needed criteria to become a base load electricity resource.

REFERENCES

Arifpin, N. Y., Hidayat, R., Andhika, M., and Suryatama, T.: Experience in managing High Saturation Index Silica Deposition in Brine ORC (Study Case Sorik Marapi Geothermal Field), *Proceedings*, the 8th Indonesia International Geothermal Convention & Exhibition (IIGCE) (2022).

Arinaldo, D., and Pujantoro, M.: Levelized Cost of Electricity in Indonesia Understanding the Levelized Cost of Electricity Generation, *Institute for Essential Services Reform*, (2019).

Brown, K.: Thermodynamics and Kinetics of Silica Scaling, *Proceedings*, International Workshop on Mineral Scaling (2011).

Domanski, I., Cappadona, M., Fuller, O., and Krix, Z.: Geothermal Power: Factors Affecting the Performance of Binary Plants, *PAM Review*, **2**, (2015). Subject 68412.

Hirtz, P. V.: Silica Scale Control in Geothermal Plants – Historical Perspective and Current Technology, *Geothermal Power Generation*, (2016), 443 – 476.

Pardelli, P. T., Tempesti, C., Mannelli, A., Kravos, A., Sabard, A., Fanicchia, F., Paul, S., Sengun, R., Sahiller, H. A., Halacoglu, U., Pekduz, I., Stefansson, A., and Galeczka, I. M., Design of a Scaling Reduction System for Geothermal Application, *E3S Web of Conferences*, **238**, (2021).

Zarrouk, S. J., and Moon, H.: Efficiency of Geothermal Power Plants: A Worldwide Review, *Geothermics*, **51**, (2014), 142-153.

Zarrouk, S. J., Woodhurst, B. C., and Morris, C.: Silica Scaling in Geothermal Heat Exchangers and Its Impact on Pressure Drop and Performance: Wairakei Binary Plant, New Zealand, *Geothermics*, **51**, (2014), 445 - 449.

An Approach to Using PDC Refurbished Bits Delivers Effective Bit Utilization in Geothermal Drilling Sorik Marapi

Triadi H. Aribowo[1], Juliana Phan[1], Ari Budiman[1], Kiki Yustendi[2], Ashadi[2], and Kurnia D. Huway[1]

[1]National Oilwell Varco, Kawasan Taman Tekno Blok C No.1, Tangerang Selatan
[2]KS ORKA, Recapital Building 5th Floor, Jakarta

Triadi.Aribowo@nov.com, Juliana.Phan@nov.com, Ari.Budiman@nov.com,
Kiki.Yustendi@ksorka.com, Ashadi@ksorka.com, Kurnia Darmawan@nov.com

Keywords: Drilling, PDC Drill Bits. Refurbishment, Sorik Marapi

ABSTRACT

Nowadays, the use of Polycrystalline Diamond Compact (PDC) bit has been expanded to geothermal drilling applications due to their improved performance compared to Roller Cones (RC) bit. Other benefits of PDC bit compared to RC bit also include no bearing life limitation in which no worry to drill a such long interval section and high potential of repairability by replacing PDC cutter and/or secondary components.

In geothermal drilling Sorik Marapi in North Sumatera, PDC bit has been considered to be used in 17.5" section by targeting to drill over 800 to 950 meters interval in single run. To optimize the used PDC bit and its utilization, the bit was refurbished using a repair quality system to produce a high standard of repair while assuring no degradation in design-intended bit performance.

The study examines the result of 17.5" single PDC bit performance used in three wells with refurbishment condition on the second and the third runs. The results showed very beneficial. In the third run, refurbished bit successfully drilled 950 meters interval at an average ROP 10 m/hr and achieved a single run to TD. In the cumulative interval, the 17.5" PDC bit has achieved total interval 2,135 meters with single serial number. Compared to purchasing a new bit and seeing the performance result, an approach to use refurbished 17.5" PDC bit have been cost-effective seeing the price different between a new bit and a refurbished bit at around 55-64%.

As a result of the usage of refurbished PDC bits and its repair quality system, geothermal drilling operations now have a new way to maximize bit utilization while retaining performance on par with that of a brand-new bit.

1. INTRODUCTION

Sorik Marapi Geothermal Field is one of the largest developing geothermal projects in Indonesia operated by PT Sorik Marapi Geothermal Power (SMGP). The project is located approximately 650 km south-southeast of Medan, the capital city of North Sumatera province and situated within the Mandailing Natal district area. Figure 1 shows the field location.

Since the beginning of drilling operation in Sorik Marapi until mid-year of 2020, the 17 wells have been drilled with total bit consumption was up to 161 bits, and it will continue to increase in line with ongoing drilling operations.

The 94% of bit consumption is dominated by utilization of bit type roller cone or Tungsten Carbide Insert (TCI) bit with condition most likely un-rerunnable again. Figure 2 shows the sample of total bit consumption until mid of 2020.

Figure 1: Map of Sorik Marapi Geothermal.

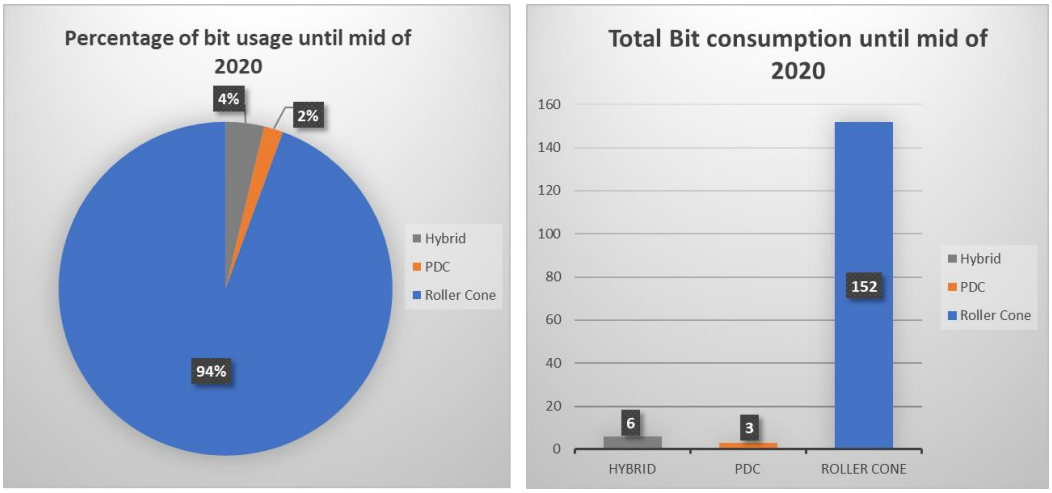


Figure 2: Sample of bit consumption until mid of 2020 in Sorik Marapi.

Roller Cone (TCI) bits or hybrid bits that are combined PDC and Roller Cone are designed for single-use or are made from material that are difficult to repair effectively. At the end, they are recommended to be junked. It is different with PDC bits that are made from replaceable materials, the refurbishment is highly possible with some criteria.

As part of an initiative to optimize bit utilization and improve drilling efficiency, and together as PDC bit has been advancing in cutter technology, we started implementing PDC bit and refurbish the bit after used.

In this paper, we discuss a case history of using 17.5” PDC refurbished bits in the drilling process as well as recognizing on how refurbishment procedure and process could ensure the refurbishment quality system produce a high standard without impacting to the bit performance.

2. BENEFIT OF PDC BIT REFURBISHMENT

Refurbishment drill bits can offer several benefits, both economically and environmentally. Here are some of the key advantages:

1) Sustainability

Repairing drill bits is a more environmentally friendly option than disposing of them and buying new ones. It reduces the demand for new raw materials and decreases the waste generated from old drill bits.

2) Time Savings

This is most likely related to bit manufacturer that has repair facility in country. Purchasing a new drill bit will require more time from ordering, manufacturing, and delivering process compared to just repairing in the country's facility. This also includes reducing turn-around time for refurbishment (in case ordering the new bit has an issue during import delivery).

3) Customization

Some drill bits are probably designed for specific tasks or materials, and it may not always find to suit with the application. With continues advance PDC cutter technology, repairing existing drill bits can allow to customize or upgrade with the latest cutter technology.

4) Backup options

Having a set of refurbished drill bits as backups can be beneficial, especially if we encounter unexpected tool failures. This can be more cost-effective and reducing the risk of downtime.

5) Reduces bit inventory

By repairing the drill bits, it is inline with reducing bit inventory. In the result, there will be no holding cost for storage and maintenance.

6) Cost Savings

Refurbishing drill bits is generally more cost-effective than purchasing new ones. New bits can be expensive, especially if they are specialized or made from high-quality materials. By repairing worn or damaged parts, it can just expense on the repair cost.

3. METHOD OF PDC REFURBISHMENT PROCESS

Before it goes through refurbishment process, there are some criteria of standard acceptance in advance for bit refurbishment. The criteria may not be the same on each bit manufacturer.

Below are the criteria:

1) Same bit manufacturer

The different bit manufacture can cause to the different quality and standard. In the end, it will impact to the bit performance or failure.

2) No visual cracks or excessive damage on the bit body.

3) No severe erosion.
4) The bit is still in gauge or max under gauge 2/16".
5) No damage PIN connection.
6) No severe PDC cutter pocket damage.

When the criteria above have been accepted, the bit is going to refurbishment process. At the bit manufacturer facility, all the repairable bits are segregated and then washed to remove any mud, formation cuttings, and grease. Then the bits are cleaned and further with sand blasting to make sure the surface is free of any foreign particles. The bit body is then visually inspected to make sure there are no erosion or cracks in it. Figure 3 and Figure 4 shows example of the bits for inspection and sand blasting process.

Figure 3: Example of bit for inspection.

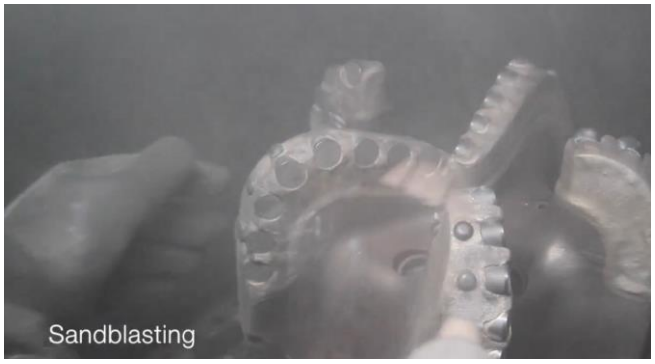


Figure 4: Sand Blasting process.

The good bits are subjected to a die penetrant test to see any micro cracks in cutters. In case any cracks or major erosion is seen on the body, or the cutter pockets are damaged, then the bit is recommended to be junked. If not, the damaged cutters, including those that are chipped, broken, or worn, are marked for replacement. The bit crown is then pre-heated in an induction oven to 500ºC for cutter removal.

Figure 5: Cutter Removal process.

Once cutters are removed, the bit is cooled, and then the bit was cleaned further with sand blasting again for cutter pocket cleaning as shown in fig-6. At the same time, the bit refurbishing process starts with preparing the new cutters for cutter assembly based on the location of the damaged cutter.

Figure 6: Cutter pocket cleaning with sand blasting.

Once new cutters are placed for assembly as shown fig-7, the bit was then pre-heated again in oven to the same temperature for brazing propose. Once the set temperature is attained, the technicians start brazing new cutters in place, and make sure that there is good seating of the cutters in the cutter pocket. Once the cutter replacement is finished, the hot bit is allowed to cool at a controlled rate to avoid inducing thermal stresses, which otherwise can damage the bit.

Figure 7: Cutter assembly, pre-heat in oven and brazing process.

Once the bit is cooled, it is cleaned for all the excess braze and flux coatings using sand blasting. If the gauge cutters are replaced, then the bit is loaded into a grinding machine and the gauge cutters are

ground to make the bit the required size. After this, the final inspection is done as per the QC norms and then the bit is sent for painting and boxing as shown in fig-8. The completed bits are transported back to the customer.

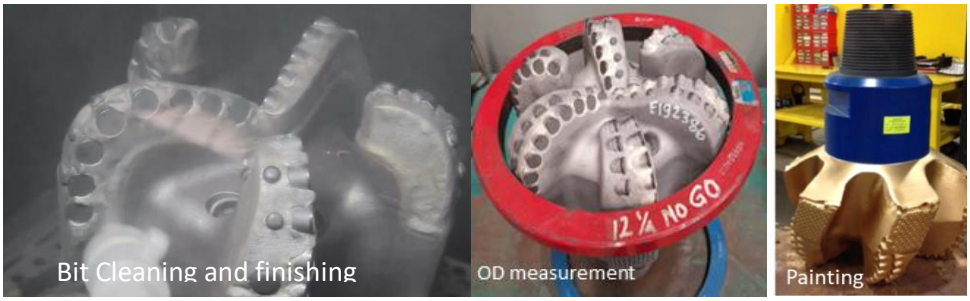


Figure 8: Bit cleaning, finishing, OD measurement and painting.

4. PERFORMANCE RESULT OF NEW AND REFURBISHED BIT

The performance result discusses about one single serial number of 17.5" PDC FTKC76 bit that was utilized from brand-new bit until two times of refurbishment. Although the 17.5" PDC bit was run on two distinct pads, its trajectory and formation were comparable. The bit was run on mud motor BHA and drilled directionally with long interval consist of interbedded andesite lava, dacite lava, rhyolite tuff and coarse sandstone.

The 17.5” PDC FTKC76 has basically been designed for geothermal drilling application with 7 blades and 16mm cutters. The bit was already equipped with prism shaped cutter and can be refurbish able. The V-shaped or called as prism shaped PDC cutter will give a benefit of point loading to crack the formation and then improve cutter engagement into hard formation. (Sentanu et al. 2021).

At the beginning of the bit is still new, the bit was run in PX-119 well to drill 815m interval. The bit was pulled out around 100m before TD due to slow down in ROP with resulting final average ROP 9.31 m/hr. On surface, it found that 4 nozzles got plugged (PN) and came out with balled up condition. However, the dull condition or the cutting structure remains 0-1-WT. The reason pulled of PR on the dull grading should not be related to the bit performance as the dull condition also exhibited still very good condition. The bit was then sent to the bit manufacturer facility for refurbishment and conducted cutter placement on the location of worn cutters. Fig-9 shows the bit after the first refurbishment and ready to send back for rerun.

Figure 9: the first refurbishment result.

After first refurbishment, the bit was run in XA-03 well to drill 370m interval of tangent section to TD. The bit achieved high ROP with 14.62 m/hr and came out with still 0-1-WT. the bit was sent back again for refurbishment for replacing the worn cutters. On the second refurbishment finished, the bit was utilized in in XP-117 well to more than 900-meter interval. The result showed the second refurbishment could manage to drill to TD with a total interval of 950m and achieved a final average ROP of 10 m/hr.

The bit set the record as the longest interval drilled by refurbished bit in geothermal drilling. The table-1 summarize all 17.5" PDC Bit (FTKC76) runs for new and refurbished condition.

Table 1: Bit Summary of new and refurbished 17.5" FTKC76.

Condition	Well	Size	Bit Type	SN	Depth In (m)	Depth Out (m)	Interval (m)	ROP (m/hr)	Rig Dull Grading
New	XP-119	17 ½"	FTKC76	A275518	400	1215	815	9.31	0-1-WT-S-X-I-PN-PR*
Refurbished #1	XA-03	17 ½"	FTKC76	A275518	405	775	370	14.62	0-1-WT-S-X-I-NO-TD
Refurbished #2	XP-117	17 ½"	FTKC76	A275518	400	1350	950	10.0	1-4-BT-G-X-1-NO-TD

Performance wise, the refurbished bits are still performing better or even resulting higher ROP compared to the new bit. This proved the highest standard quality and service on refurbishment process has not impact to the lower bit performance. Fig-10 demonstrates the performance comparison between a new bit, refurbished bits dan other bit runs in the nearby offsets. The performance of 17.5" PDC FTKC76 bit could cover 3 TCI runs in two-hole section in offset XP-116 well. In term of average ROP, the new and refurbished bits achieved 36% faster than average ROP offset runs.

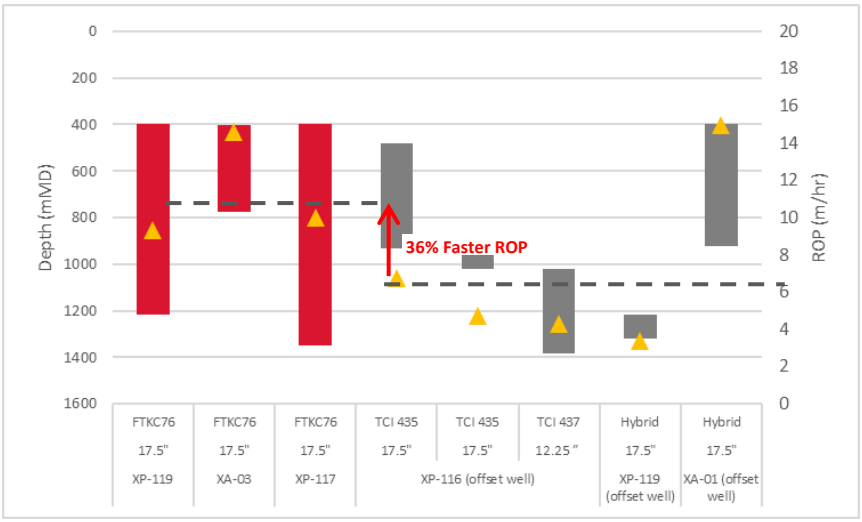


Figure 10: Bit performance comparison against offset runs.

Cost saving of using refurbished bit will depend on how many cutters are replaced. According to the refurbishment of a 17.5" PDC FTKC76 bit, the estimated cost savings were around 55%–64% over purchasing a new one.

5. CONCLUSION

An effective and efficient usage of refurbished bits has added a new capability to improve drilling efficiency and cost-effective in geothermal drilling operations while maintaining performance comparable to a new bit. This is also one way to lower the cost of drilling by using a greater proportion of refurbished bits rather than purchasing a new one.

Performance wise, the refurbished bits are still performing similar or even resulting higher ROP like the new bit. This proved that the highest standard quality and service on refurbishment process did not impact to lower the bit performance. As the bit could perform faster with long interval drilled, the usage of refurbished bits can also reduce costs with lower CPM.

In conclusion, the approach of using refurbished bit delivers effective bit utilization and cost-effective in geothermal drilling operations. Furthermore, by refurbishing drill bits, it will also contribute to protecting environment and decreases the waste generated from the old drill bits.

REFERENCES

Greg L, and Christopher, C.: Guidelines for the repairability of Fixed Cutter Bits, NOV *ReedHycalog internal document*, (2019).

Ryan, H, Christovik, H.S.: The Characteristic of 320˚C Geothermal Wells at Sorik Marapi Geothermal Field, *Proceedings,* The 2nd Digital Indonesia International Geothermal Convention (DIIGC) (2021).

Sentanu, W.R, and Triadi, H.A.: Shaped PDC Cutter With High-Density Impreg's Element Deliver Superior Performance In Sorik Marapi Geothermal Power, Indonesia, *Proceedings,* The 2nd Digital Indonesia International Geothermal Convention (DIIGC) (2021).

Case Study: Field Evaluation of Anti Scalant in The Geothermal Fluid

Arsyan Sasoni[1], Logan Muller[3], Megan Low[2], Michael Bluemle[4], Michael Todd[4], Muhammad Thasril[5], Fajar Mustofa[5], and Efrata Meliala[5]

[1]PT. Solenis Technologies Indonesia, Indonesia
[2]Solenis Singapore Pte Ltd, Singapore
[3]Solenis New Zealand, Auckland, New Zealand
[4]Solenis LLC, Wilmington, DE, USA
[5]PT. Geo Dipa Energi, Indonesia

asasoni@solenis.com

Keywords: Silica Inhibitors, Silica Deposition, Field Evaluation

ABSTRACT

Silica and Metal Silicate deposition remains a prominent challenge to geothermal power plants because severe, costly cleaning of the piping in surface facilities and well can occur. Until recently, many testing methods to mimic the temperature and pressure system were available to mitigate this problem but the result is not describing the real operation.

Generally, a pH modificator (H_2SO_4) has been used to decrease the pH to delay polymerization. However, the addition of sulfuric acid can lead to severe corrosion problems, which decreases pipe diameter and reduces power generation. This led to the development and field evaluation of a new development product of anti-scalant, DPI 920 and Geosol™ GS9310.

This paper documents the results from a series of field tests that were conducted to optimize the silica inhibitor dosing through a side stream test. Delta pressure, comparison of flow control valve, and brine chemistry samples were monitored and analyzed to quantify the performance of this chemical treatment strategy. Additionally, a comparison of the tube's weighting was performed to contrast the treatment versus the blank test. The field trials with this chemical inhibitor resulted in 6.4 fold better than no treatment based on the comparison of initial and final weighting during the treatment.

1. INTRODUCTION

Silica deposition is one of the current drawbacks to developing geothermal resources for electricity generation. A new anti-scalant product has been developed and led to a successful application compared with a conventional method, pH modificator. The silica inhibitor has been used with a result of a stable flow rate and a maintenance cleaning reduction.

Generally, H_2SO_4 is injected to decrease the pH level to maintain the silica saturation at an acceptable rate. However, the control of acid injection must be in sufficient quantities to achieve the desired pH level. Insufficient H_2SO_4 resulted in silica deposition while excessive H_2SO_4 resulted in low pH and may cause corrosion problems. Also decreasing the pH produced another disadvantage which other metal cation co-precipitate with silica.

This paper documented 2 weeks side stream evaluations of Silica inhibitors in which the performance of both chemicals shows the indicative result that works at different temperature parameters based on quantitative weight result, the inhibition percentage, maintaining pH, and the stable delta pressure.

2. BACKGROUND

The side stream test is using a small portion of the geothermal fluid diverted from the main flow or "side-streamed" and analyzed for silica concentration. Silica is a common mineral found in geothermal fluids and can cause scaling issues in the geothermal system. By periodically conducting side stream geothermal silica tests, operators can monitor the silica levels and take necessary measures to prevent scaling. These measures may include adjusting the chemical treatments, implementing scaling

inhibition methods, or modifying the operational parameters to mitigate the scaling effects caused by high silica content. The side stream geothermal silica test plays a crucial role in maintaining the efficiency and productivity of the geothermal power plant by ensuring that the silica levels are within acceptable limits and preventing the formation of scales that can hinder heat transfer and reduce production rates.

The brine was tapped after the separator unit located in one of the Geo Dipa Energi (GDE) fields which have been installed 60MW and operated since 2002. The fluid characteristics of the production field in Dieng geothermal field are water-dominated nature and high silica content of approximately 900 mg/L. The high silica content in the production fluid causes scaling issues in both the geothermal steam production wells and the brine injection lines in the Dieng geothermal field. Scaling in the brine injection lines leads to a reduction in the pipe diameter, disrupting the brine distribution process to the injection wells.

Currently, H_2SO_4 is introduced to mitigate silica scaling in the brine line. However, its effectiveness is still inadequate as it damages surface facility equipment and causes derating or production losses during equipment maintenance. Additionally, maintenance activities for the brine line, pond, and open channels contribute to increased operational costs for Unit Dieng 1. Therefore, side stream using silica inhibitors are needed to mitigate the silica treatment challenge more effectively and efficiently.

3. DATA AND METHODOLOGY

In the 2-week side stream trial were injected silica inhibitors on the Solenis Rig test which simulate the same temperature as GDE's field operation condition. The rig test is installed at the separator vessel below the brine level and continuously sampling the brine for 24/7. The rig test simulates a small heat exchanger or binary plant and hence can determine the type and amounts of deposits that form at different temperatures. It is constructed with 2 lines to compare both chemically treated (line 1) and untreated lines (line 2) simultaneously by using SS304 tank with Swagelok tubing (0.5''), fittings, and control components (Figure 1).

Figure 1: Solenis Rig test tapped in the brine separator at GDE pad.

The trial was divided into 3 temperature parameters. During parameter 1, normal conditions as tested without adding a water cooler system in the rig test which generates outlet temperature around 170^{o} C or mimics the outlet separator system for 4 days. After finishing parameter 1, continue with Parameter 2 with an outlet temperature of 150^{o} C to simulate the dumping line system for 5 days. The final parameter is mimicking the silencer or AFT within 100^{o} C for 4 days.

Table 1: Parameter testing during side stream trial.

Parameter	Adjustment Parameter
Scaling quantity on treated line Vs untreated line	1. Given temperature at outlet separator (4 days)
	2. Dumping Line, 150ºC (5 days)
	3. Silencer/AFT, 100ºC (4 days)
Delta Pressure	Comparison of inlet and outlet, delta pressure.
%Inhibition	Percent silica polymerization inhibition or %SI at three conditions (given outlet temperature, dumping line temperature, and silencer/AFT temperature)
pH brine treated line	pH brine outlet from treated line to prevent metal silicate formation

To monitor the flow, flow meter indicators and flow control valve (FCV) were placed in outlet line 1 and outlet line 2. FCV is designed to control the opening of the valve automatically which is easily operated using Solenis's Onguard™ monitoring. When the scaling occurs, FCV will adapt to increase the valve opening to keep the flow constant as per pre-settings. The Temperature and pressure indicator was monitored in the inlet and both outlets too.

The brine chemistry was checked on-site while the monomeric Silica solubility analyses were monitored routinely on-site to assess the saturation rates. The sample was treated with acid (1.5% HNO3). Any decrease in SiO_2 content in the outlet indicates SiO_2 deposited in the lines. To monitor the inhibitor performance, the percentage of inhibition was calculated based on below table:

Table 2: % Inhibition formula.

% Inhibition =	$\frac{[SiO_2]_{sample} - [SiO_2]_{control}}{[SiO_2]_{initial} - [SiO_2]_{control}}$	x 100

Where the terms above are as follows:

%Inhibition	= Percent silica polymerization inhibition or %SI
[SiO2] sample	= Silica concentration in the presence of inhibitor at 24 hr (treated line)
[SiO2] control	= Silica concentration in the absence of inhibitor at 24 hr (untreated line)
[SiO2] initial	= Silica concentration at the beginning of the test (Inlet sampling)

The weight-gain method was calculated by weighting the series of pipes that can be easily removed and installed in the rig test. The pre-weighed pipes were exposed for several days/weeks and then retrieved for inspection and weighing. The accumulated scaling rate for the exposure period was determined by weight gain. In this trial, the scaling rate was not calculated as the exposure should be at least one month to get the quantitative result.

4. PRE-STUDY

Before the trial program, thermodynamic modeling is conducted using WATCH 2.4 at several pH values over the range of 100 – 180 °C based on the brine chemistry data (Table 1). The modeling shows the behavior of the minerals and the relation between its saturation versus the temperature. This particular pad does not have H_2S concentration analysis but using the nearby pad data that have a significant H_2S concentration (12.9 mg/kg) which combined with the relatively high arsenic concentration, this must be sufficient to cause orpiment (arsenic sulfide) deposition at lower brine temperatures.

Table 3: GDE brine chemistry data.

Parameter	Unit	Result
pH		5.7
TDS	Mg/L	34375
Boron (B)	Mg/L	381
Dissolved Silica (SiO2)	Mg/L	940
Dissolved Sodium (Na)	Mg/L	9265
Dissolved Potassium (K)	Mg/L	2551
Dissolved Calcium (Ca)	Mg/L	664
Dissolved Magnesium (Mg)	Mg/L	0.3
Dissolved Iron (Fe)	Mg/L	1.6
Dissolved Lithium (Li)	Mg/L	48
Bicarbonate (HCO3)	Mg/L	10
Chloride (Cl)	Mg/L	18525
Sulfate (SO4)	Mg/L	18
Dissolved Arsenic (As)	Mg/L	48
Dissolved Aluminum (Al)	Mg/L	0.15

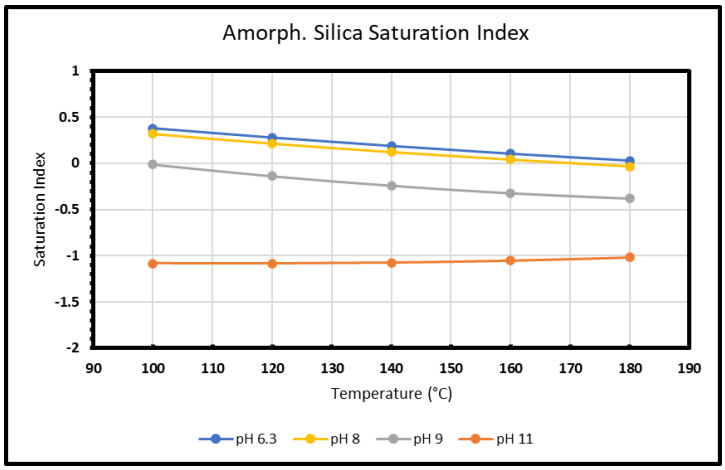


Figure 2: Thermodynamic modeling at pH 6 -11 indicate higher SSI at lower temperature.

In this modeling (Figure 2) saturation indices greater than 0 are thermodynamically supersaturated. Acceptable or low levels of supersaturation are dependent on the mineral and other factors that impact the kinetics of precipitation and deposition. For amorphous silica, polymerization and precipitation are dependent on pH with precipitation slower at lower pH values. An amorphous silica saturation index

greater than 0 often leads to silica and/or silicate deposition geothermal applications, especially under circumneutral or alkaline conditions.

5. TRIAL RESULTS

The primary objective of the trial was to test the efficacy of the inhibitor against the silica and metal silicate deposition in four different indicators mimicking the GDE's system. DPI-920 was evaluated in two adjustment parameters of field tests to find the optimum dosage for 9 days. Firstly, It was injected on the side stream rig with a low dosage for 4 days at 170°C. Then continue to inject DPI920 with a higher dosage for 5 days at 150°C. Finally, Geosol™ GS9310 was injected with a low dosage for 4 days at 100 °C of outlet temperature.

During Parameter 1, we tested normal conditions without adding a water cooler system in the rig test which generates an outlet temperature of around 170° C or mimicking the outlet separator system for 4 days. After finishing parameter 1, continue with Parameter 2 with an outlet temperature of 150° C to simulate the dumping line system for 5 days. The final parameter is mimicking the silencer or AFT within 100° C for 4 days.

5.1 Inhibition %

The percentage of inhibition graph shows the efficacy of the inhibitor. DPI-920 was tested using Parameter 1 which shows the highest % inhibition average of 95% while parameter 2 generates a slight decrease of 94%. GS9310 was only tested with parameter 3 which generates the same efficacy of 94%. In general, outlet 1 which was treated with chemicals shows a slight decrease in dissolved silica compared to outlet 2 (blank test). This indicates that the chemicals are working to delay the silica polymerization and it will be quantified in the pipe weighting discussion.

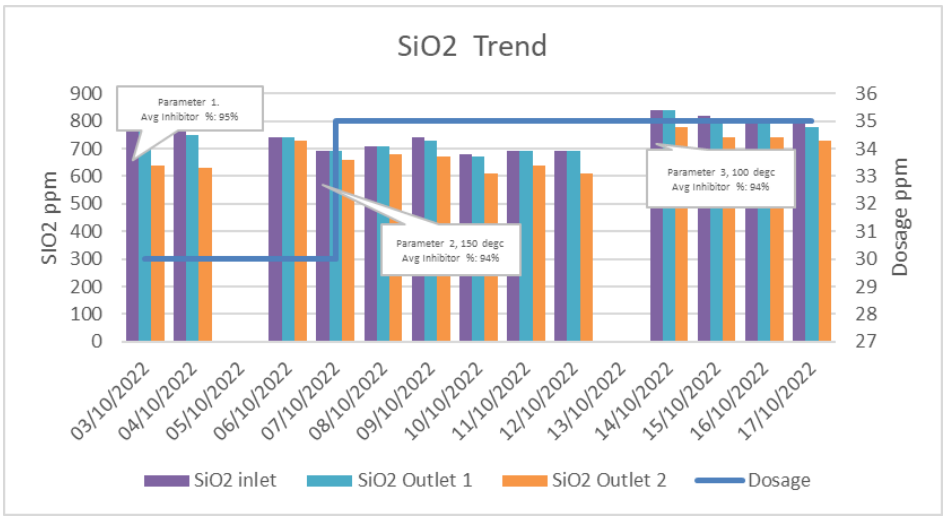


Figure 3: Percentage of inhibition based on comparison of SiO2 inlet vs outlets.

5.2 Delta Pressure and FCV

Delta pressure was measured by comparing the inlet and outlets of pressure gauges. Line 1 showed a stable delta pressure of almost 0 bar while Line 2 displayed a significant increase during the parameter 1 and parameter 2 tests. After testing parameter 2, both the pressure gauge and FCV line 2 were damaged by scaling therefore there is no available data for both measurements in parameter 3.

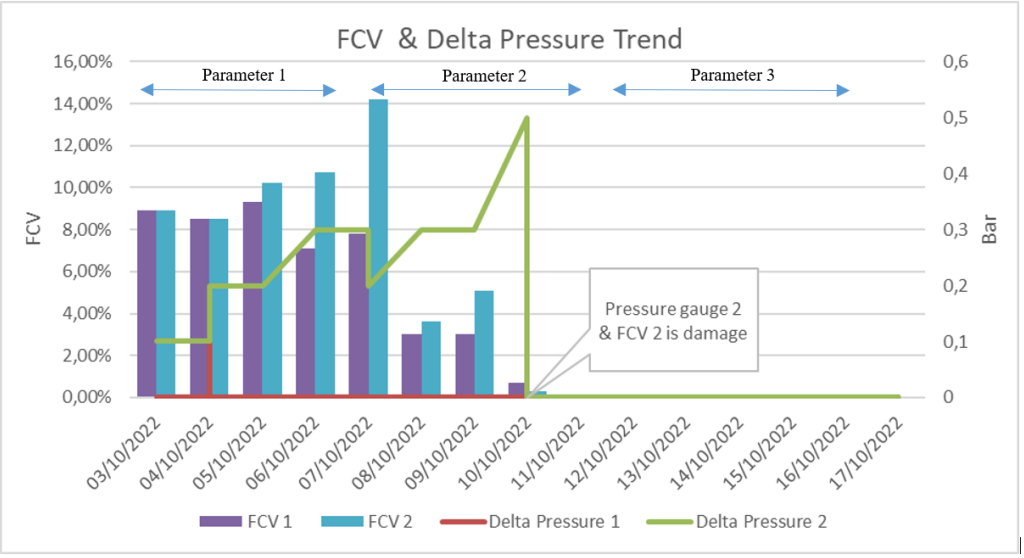


Figure 4: Delta pressure and FCV line 1 and 2.

5.3 Brine pH

pH was monitored both inlet and outlets and the trends are shown below. During the trial, DPI-920 generate pH outlet 1 within 5.8 – 6.3 whereas GS9310 decreased pH outlet to 5,3-5,6. This indicates both chemicals meet GDE's pH target from 5 to 8,3 and are also secure from corrosion issues.

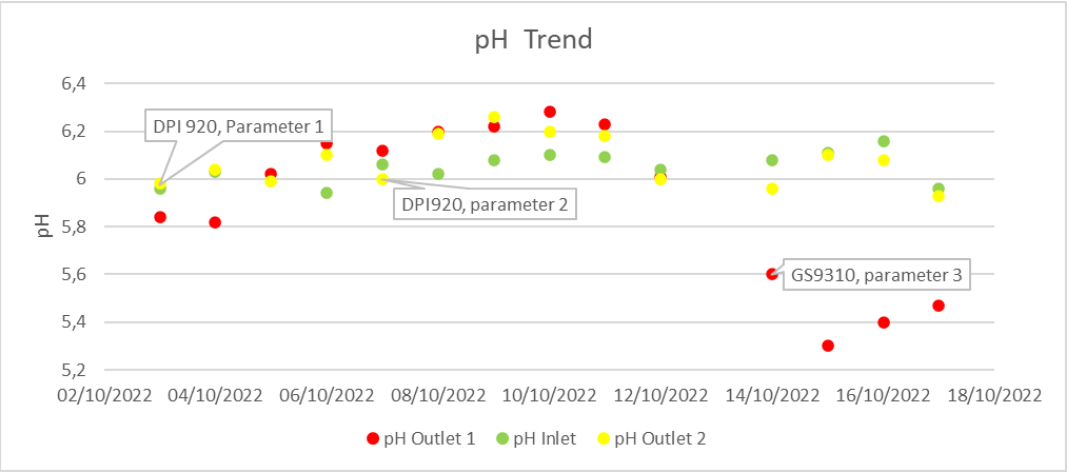


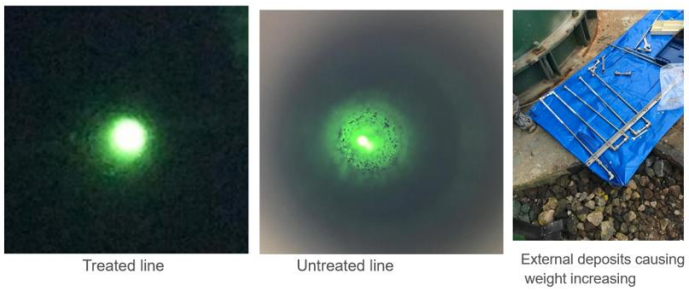
Figure 5: pH trend monitoring.

5.4 Scaling Quantity

5.4.1 Parameter 1 (170^0 C)

After being injected by DPI-920 for 4 days, the tubes were inspected, and the delta weight was then calculated by comparing the initial weight before chemical treatment and after the treatment has finished. In parameter 1, we found external deposits that cause the weight increased in both lines. Qualitatively, we witnessed some deposits inside line 2 but found none in line 1 as pictures below.

Pipe No.	Delta Weight (gr)	
	Treated line	Untreated line
1	1	0,7
2	0,7	1,2
3	0,8	1
4	0,5	1,1
5	0,6	1,2
6	0,7	1,3
7	0,5	1,2
8	0,6	1,3
Total Weight Increasing	**5,4**	**9**



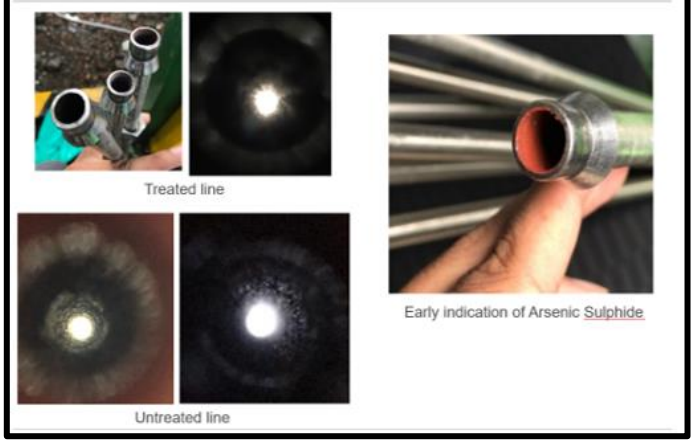
Treated line | Untreated line | External deposits causing weight increasing

Figure 6: The external deposits also contribute to weight increase in both lines. In parameter 2&3 we clean out the external deposits first before the pipes weighting.

5.4.2 Parameter 2 (150^0 C)

DPI-920 was injected for 5 days and the untreated line shows a much higher delta weight than the treated line. An orange-reddish deposit, Arsenic Sulfide, was found in all lines 2 which later was confirmed by lab test in figure 9. Based on the pipe weight comparison, the inhibitor works 6.4 better than untreated.

Pipe No.	Delta Weight (gr)	
	Treated line	Untreated line
1	0,1	0,5
2	0,2	0,4
3	0,3	0,4
4	0	0,4
5	0,1	0,8
6	0,3	0,7
7	0	2,7
8	0,1	1,1
Total Weight Increasing	**1,1**	**7**



Treated line | Early indication of Arsenic Sulphide | Untreated line

Figure 7: Arsenic sulfide was found predominantly in line 2 which cause a higher delta weight compare to line 1.

5.4.3 Parameter 3 (100^0 C)

After being monitored for 4 days, the result shows a similar outcome to previous parameters with the untreated line showing a higher delta weight than the treated line. Arsenic Sulfide is also found not only in line 2 but also in line 1. However, the deposits have a softer character compared to line 2 deposits as described by the picture below.

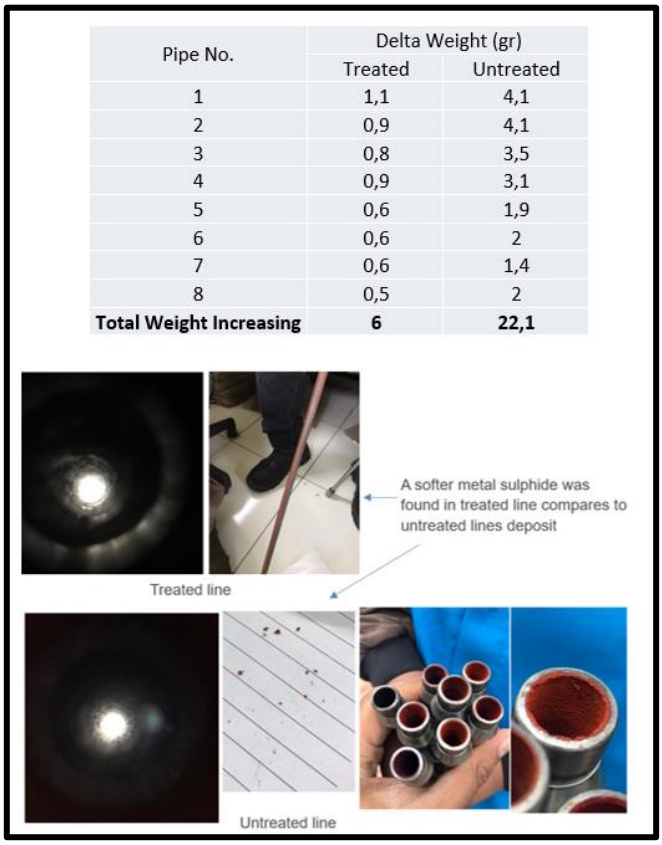


Figure 8: Arsenic Sulfide was found both lines with different characteristic.

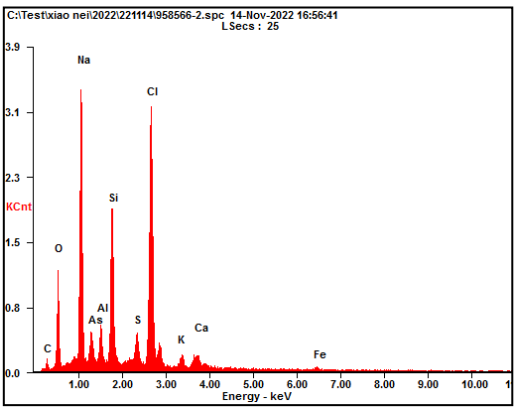


Figure 9: Fourier transform infrared spectroscopy (FTIR) test on scaling deposit indicates major silica, arsenic, and sulfide.

6. CONCLUSION

- The side stream trial show indicative result that the inhibitors work at different temperature based on quantitative weight result, the inhibition percentage (above 94%), and stable delta pressure data.
- The objective to prevent metal silicate and silica deposition has been achieved based on the qualitative and quantitative results. However, based on pre study and lab data, arsenic sulfide still appeared during the lower temperature test. The inhibitor disperses the metal sulfide into smaller colloids which was confirmed during the test found a softer deposit compared to deposit from untreated line.
- It is suggested that a full-flow trial in GDE system with a higher dosage for further validation.

ACKNOWLEDGMENT

The authors thank PT. Geo Dipa Energi and Solenis for supporting this work.

REFERENCES

Gallup D and Hirtz P 2015. Control of Silica-based Scales in Cooling and Geothermal Systems. *(Santa Rosa, California)*

Siahaan, M.N. (2020). Scaling in Two-Phase Pipeline (Study Case: Sarulla Geothermal Field). *ITB International Geothermal Workshop 2020*.

Challenges and Modelling Practices for Low and Medium Temperature Geothermal Resources

Theo Renaud, Joris Popineau, Michael Gravatt, Rony Nugraha, Jeremy Riffault, John O'Sullivan, Ryan Tonkin, Ken Dekkers, and Michael O'Sullivan

Geothermal Institute, University of Auckland, 70 Symonds Street, Grafton, Auckland, 1010, New Zealand

theo.renaud@auckland.ac.nz

Keywords: Geothermal Reservoir, Modelling, AUTOUGH2, Waiwera, Low Temperature

ABSTRACT

The global interest in harnessing low and medium temperature geothermal resources for electricity generation and space heating has been steadily increasing, driven by their substantial potential as sustainable and efficient energy sources. This growing attention stems from the compelling prospects offered by geothermal energy, which presents an environmentally friendly alternative to conventional energy options, supporting the transition towards cleaner and more sustainable energy systems.

The development and utilization of low and medium temperature geothermal resources necessitate accurate reservoir modeling techniques to comprehensively evaluate subsurface thermodynamics and facilitate effective management strategies for future growth. This study presents the recent advancements and associated challenges in modeling approaches specifically tailored for low temperature geothermal resources provide valuable insights, enabling improved understanding and optimization of their utilization potential.

1. INTRODUCTION

Low and medium temperatures for the geothermal resources are largely untapped due to better attractivity to power production and historically cheaper solutions to provide energy for consumers. Undeveloped geothermal resources are often due to high up-front costs to develop viable projects, sparse production of geothermal heat, subsurface geological uncertainties etc.

Modelling ahead work is a crucial tool to better understand the prospects and can be used following the whole development history to refine the understanding and better support the decisions. Other essential aspects raised notably for Indonesia is to raise awareness and public consensus for local communities. to develop geothermal projects. Adityatama et al. 2019 reviewed the geothermal direct-use application with direct benefits during the early geothermal development for the communities. Access to low to medium resources through direct-use is referenced to help increase the social acceptance of geothermal projects. Thanks to small-scale projects, the involvement of local people will sustainably stimulate local economics for tourism or industrial applications. Indonesia shows considerable potential to use low to medium temperature geothermal resources, notably through pumped wells (Febrianto et al. 2019). This work presents the challenges in modelling approaches specifically tailored for low-temperature geothermal resources provide to better optimize their potential.

2. POTENTIAL, APPLICATIONS AND THERMODYNAMICS

2.1 Potential and Applications

Figure 1 shows two maps of the potential for geothermal uses and spatial cooling from aquifers (Limberger et al. 2018). Sedimentary aquifers for direct heat use are estimated to represent a global geothermal resource base around 125 and 1793 EJ yr−1. Figure 1 highlight that cooling using geothermal and subsurface technologies are not to be forgotten in the scope of geothermal development. They represent a significant potential to increase low-carbon emission cooling systems for industries or urban areas.

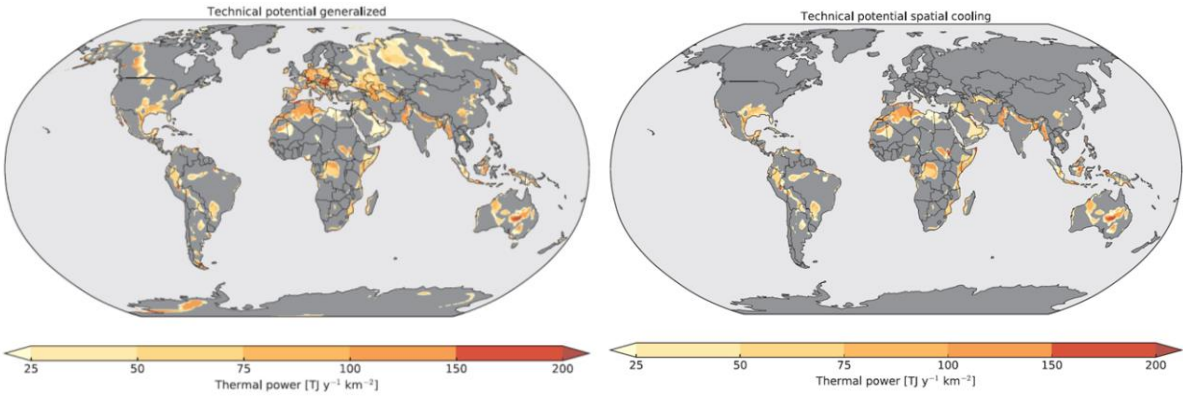


Figure 1: Technical potential generalized for direct use and for spatial cooling (Limberger et al. 2018).

Direct use appears to be the most efficient approach to convert the heat available from low and medium-temperature geothermal systems. In 2020, the geothermal heat pumps were the most represented usage of direct use, followed by bathing and swimming and space heating sectors (Figure 2, Lund and Toth 2021). Many derived applications for industrial uses are shown to be very common to build industrial parks like in New Zealand for Kawerau (McClintock et al. 2021). Reyes 2015 also referenced the low-temperature reserves in New Zealand ranging from temperatures between 30°C and 155°C, or for greenhouse heating or aquaculture. In countries benefiting from high-temperature geothermal resources, cascade mode uses can be developed to access the energy available at a higher efficiency rate than electricity generation only. However, this involves a different sustainable plan than for low and medium-temperature systems, notably for managing reinjection temperature or subsurface resources assessment.

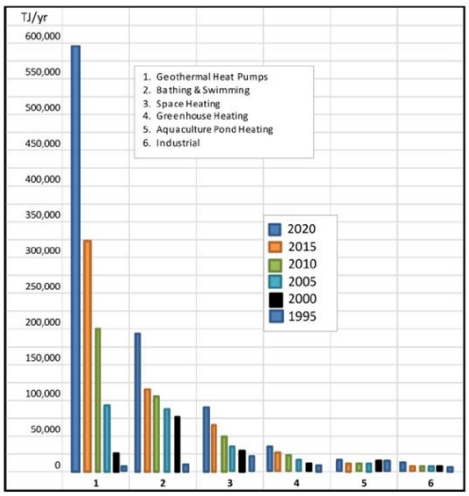


Figure 2: Direct-use energy produced worldwide in 2020, 2015, 2010, 2005, 2000 and 1995 per sector (Lund and Toth 2021).

In Europe, regional aquifers have been used for geothermal direct use. In the Paris basin in France, heat production from several doublets (a combination of one production well and one injection well) has been operational for 50 years with temperatures at the top of the aquifer at depths ranging from 1450 m to 2000 m between 55°C and 80°C and reinjection temperature around 40 °C (Lopez et al. 2010).

In historical mining or hydrocarbon regional contexts, the repurposing of coal mines or oil and gas reservoirs can play an important role in tapping the heat available worldwide, once technical challenges are overcome (Santos et al. 2022, Soldo et al. 2020, Díez and Díaz-Aguado 2014). Thanks to advances

in binary and ORC plants technology (Fiaschi et al. 2014), water at less than 90°C (or possibly lower depending on the atmospheric temperature conditions) can become attractive for power production

2.2 Thermodynamics and structures

Globally, the heat flux varies from 60 to 100 mW/m2 for low to medium-temperature resources in sedimentary basins. The conductive gradient is sufficiently large to produce useful temperatures (50-130°C) at reasonable drilling depths (1-4 km). Conduction is the primary thermal mechanism with minor convective circulation of groundwater. Instead of high temperature resources, no boiling will occur even during the exploitation. Very often, the aquifer boundaries and its internal circulation are controlled by the lithological changes during the sedimentary history. It is very likely to observe horizontal to sub-horizontal layers in unaltered sedimentary basin. The posterior diagenesis processes also affect the sediment properties, leading to sealing processes in the rock matrices. In higher deformed tectonic contexts, local faults or fractures in the sedimentary basins are key to understanding groundwater circulations.

Despite a more extensive interest in high potential temperatures, considering low to medium geothermal temperature prospects must also be considered in volcanic environments. Exploring this alternative can offer various advantages to secure direct uses projects, rather than exploring high risks high temperature fields. Indeed, low to medium temperatures can be found at the outflows of volcanic-hosted geothermal systems (see Figure 3). In the volcanic context, the geothermal system will be governed by either structural or lithological changes, due to alteration or the local and regional tectonics. The early conceptualization of the geothermal systems investigated is crucial to better adapt the modelling strategy required.

3. MODELLING BEST PRACTISE

At every stage of the geothermal development, the modelling is key to storing data, accessing the available volumes and investigating the future of the geothermal field or subsurface aquifer. The ability to design a digital twin of the geothermal environment will convert the knowledge acquired into a real asset. As an operational tool, geological and reservoir models also help to design forecasts or predict uncertainties within the boundaries of the current knowledge and probable developments. One advantage of building the numerical model as early as possible in the geothermal development is to update the conceptual model during the advancement of explorations with new data acquired.

At first, a digital geological model is built to represent the 3D geothermal basin of interest given the information from geophysical surveys, the drilled exploratory wells, the regional and local geology, etc. The 3 D geological model gathers all up-to-date data to numerically construct the current conceptual model. Figure 3 shows two examples of geological settings where low to medium geothermal temperatures can be found.

Figure 4 shows the integrated coupled process to obtain a tight coupling between the scientific data, their interpretation into a conceptual model of the area to achieve the best numerical reservoir representation using 3D modelling software. Utilizing a reservoir simulation and after the calibration process based on field data, the users can test operational strategies to give usable key numbers for stakeholders about the liability of the geothermal field in terms of resource assessment or day-to-day responses to operational decisions. The numerical tools can give extremum of heat and power extraction through uncertainty analysis following the previously discussed strategies. The integrated coupled process is a virtuous cycle where the reservoir simulation reservoir can feed the conceptual model with new insights to improve the understanding of the area.

This process applies to any type of geothermal system, but several different modelling strategies can be performed between sedimentary or volcanic contexts. The modelling strategy will depend highly on the conceptual model drawn, the scale investigated (regional or local) and the simulator capabilities.

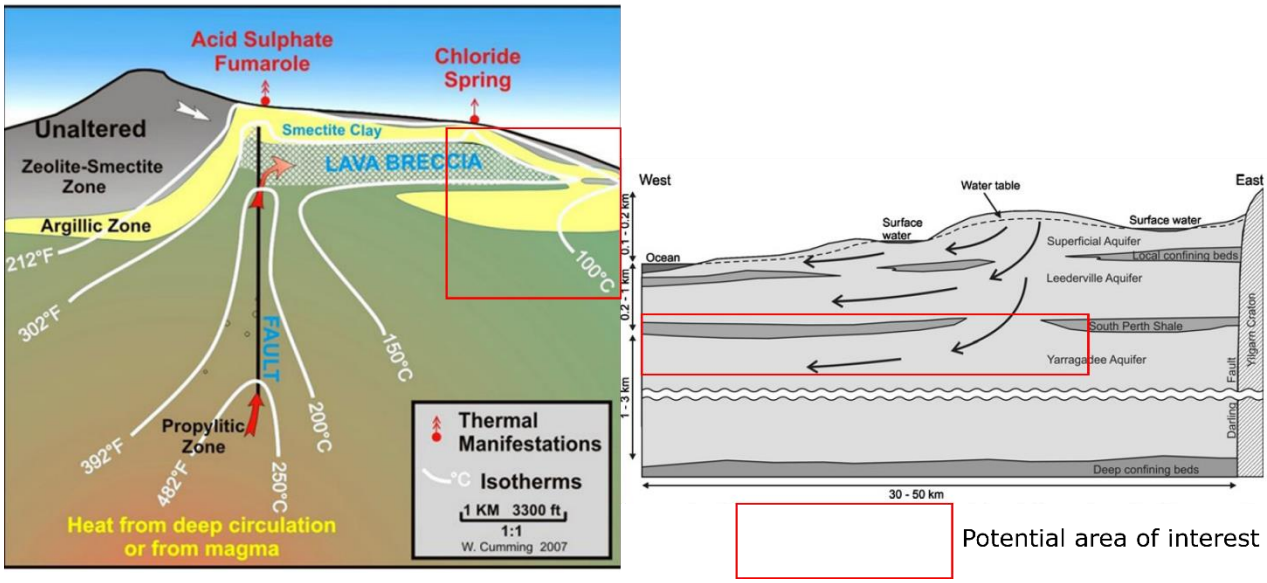


Figure 3: **Left) Potential area of interest for low to medium temperature geothermal resources in volcanic environments and sedimentary basins (right) (Modified from Cumming 2016, Schilling et al. 2013).**

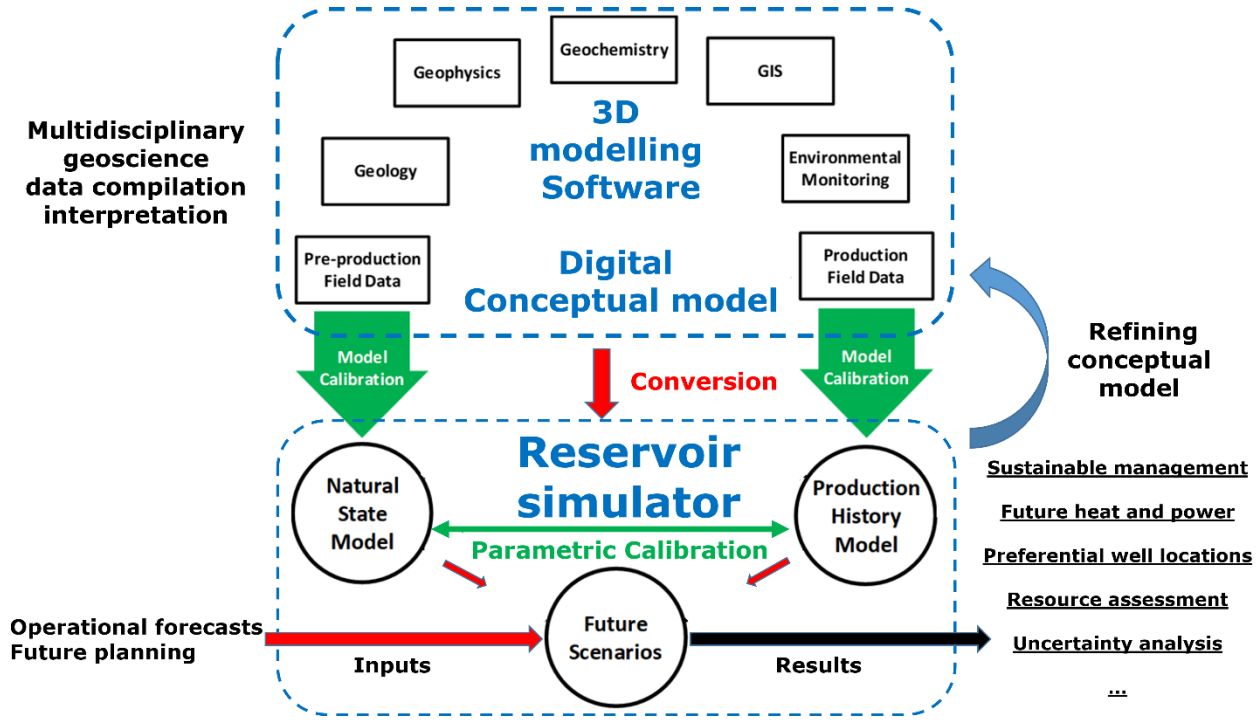


Figure 4: **Integrated Modelling workflow from 3D geological modelling, conceptual model and reservoir simulations.**

4. CHALLENGES

4.1 Boundary conditions and upscaling heterogeneities

Because a numerical model is always a simplified representation of the existing geothermal system, modelling decisions are made based on assumptions and uncertainties around the current geoscientific knowledge.

Reservoir modelling involves setting boundary conditions at the edge of the grid to approximate the natural conditions. For closed lateral boundaries, best practices require extending the border of the reservoir limits far enough to the area of interest to prevent significant influences of the local thermodynamics of the geothermal systems. Depending on the local conditions, cross flows or regional hydrodynamic flow can be considered through recharge or pressure-dependent boundary conditions to better represent the regional hydrogeology (Popineau et al., 2021). At the top, the atmospheric conditions or constant pressure and temperature conditions can be set up whether the model is extended to the surface or not. At the bottom, heat flux bottom conditions are preferred to account for the background heat from the earth.

Initialization in modelling practice can lead to significant differences in long-term simulation. Kriging and other interpolation methods are used to populate the initial thermodynamics conditions of the model prior to any future scenarios or production history. Despite matching the initial field data measurements, this approach may lead to inaccurate forecasting due to wrong boundary conditions applied, missing some key thermodynamic processes in the area. Thus, steady-state converged models are preferred prior to production forecasting scenarios to calibrate the model parameters and potential regional boundary conditions. This approach may lead to larger quantitative differences than fixed initial conditions for the measured data. Still, it will benefit from a better representation of the subsurface processes accounting for the hydrology and heat transfer.

The modellers must also account for the lithology or structural heterogeneities to best represent the hydrodynamic and heat transfer processes. Upscaling processes with various strategies have been applied to balance multiple heterogeneous layers versus homogeneous layering in deep sedimentary aquifers (Mary et al. 2020). Willems et al. (2017) showed that equivalent permeabilities in channelized sedimentary environments can be applied, within a certain threshold of connectivity between the channels. In other terms, if the permeable sediments are highly interconnected, with thick and large channels, this is similar to a homogeneous material with a given equivalent permeability. Thus, the reservoir modelling approach will diverge from the real representation of the sedimentary layers in 3D but with similar hydrodynamic behaviour. Historically, layering methods with homogenous layers as shown in Figure 5, were convenient to create fast models due to limitations of simulators (see section 4.2.).

Among the parameters to calibrate the reservoir models against field data, the permeabilities and the porosities of the reservoir formations. Most volcanic-hosted geothermal systems show predominant convective heat transfer processes due to large permeable pathways in faults or fractured materials. Thus, during the model calibration, the thermal conductivity of the rocks plays a minor role in the overall heat transfer of the entire reservoir model compared to liquid-vapour transports of the geothermal fluids carrying most of the heat available in the reservoir. Choosing the thermal conductivity constant over the field can be a reasonable assumption for highly convective systems.

However, for the geothermal systems with lower geothermal gradients or long circulation residency time, the rock thermal conductivity and specific heat are some parameters to calibrate to replicable the downhole temperature measured. The local background heat flux at the bottom of the reservoir model is also essential for the modeller to best represent the natural conditions.

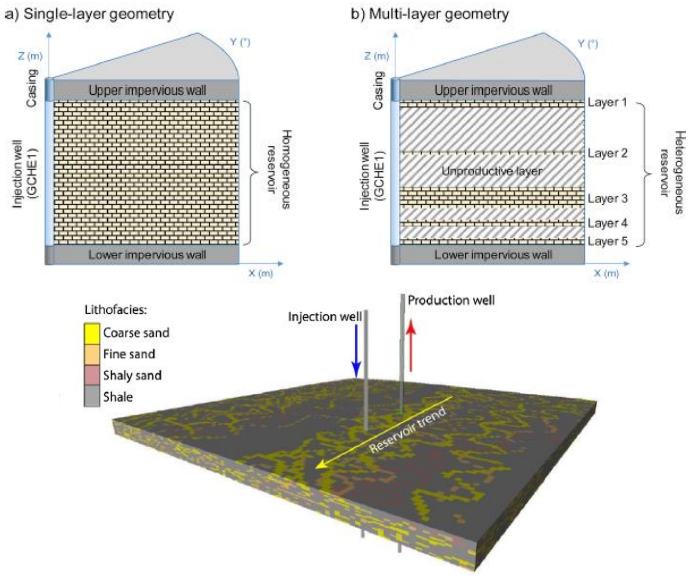


Figure 5: Left, example of two layered model for modelling sedimentary aquifers (Marty et al. 2020). (Right) Channelized sedimentary contexts accounting for the lateral heterogeneities. (Willems et al. 2017).

4.2 Geothermal simulator capabilities

Several differences are observed among the available reservoir simulators for modelling low to medium-temperature geothermal systems. The choice of simulator needs to fit the requirements of the local thermodynamics of the geothermal context investigated, and its ability to answer the modelling objectives knowing the local uncertainties of the conceptual model and the modelling assumptions.

FEFLOW (Poulsen et al. 2015) or MODFLOW (Poulsen et al. 2017) are commonly used for low-medium temperature geothermal resources using density-coupled reservoir flow and heat transport. Usually, the relationship between the fluid density and temperature is given by a polynomial relationship to account for temperature changes or salinity content in the fluid. This relationship to represent the thermodynamic conditions of the fluid properties can be important to account for complex processes, especially for interaction near phase changes. The simulators SHEMAT (Keller et al. 2020), the TOUGH2 suite, AUTOUGH2 or Waiwera (Croucher et al.2020), use formulations to account to the pressure and temperature changes for the properties of water.

Nowadays, the ability to generate thousands of samples is made possible thanks to improvements in numerical simulators with parallel high-performance computation significantly reducing the time required to run the simulations (DARTS or Waiwera). Porosity-permeabilities sampling methods can be used with Sequential Gaussian Simulation, co-kriging methods (Wang et al 2023) or correlated density distribution of the parameters. Dekkers et al. 2022 presented a conditioning method for the clay cap's location and temperature using approximate Bayesian computation. Overall, these methods aim at giving ranges of possible outputs for the operational teams and decision-makers. Figure 6 shows two examples of results for the temperature and power output for geothermal contexts. The P90/p10/P50 numbers are given after the uncertainty quantification analysis.

Modelling sedimentary contexts in low to medium temperature geothermal resources can also lead to thermos-mechanical changes due to the mineral composition of the host rock. Following the modelling objectives, these mechanics cannot be neglected to account for transient changes in the targeted reservoir. Thus, as an example, complex equations of state involving precipitation or dissolution of minerals, inducing permeabilities-porosities changes can be considered (Waiwera, Driesner). Figure 7 shows a conceptual example of a reinjection case of cold pure water into a salty sedimentary formation with an initial solid saturation of 10 % at 70°C.

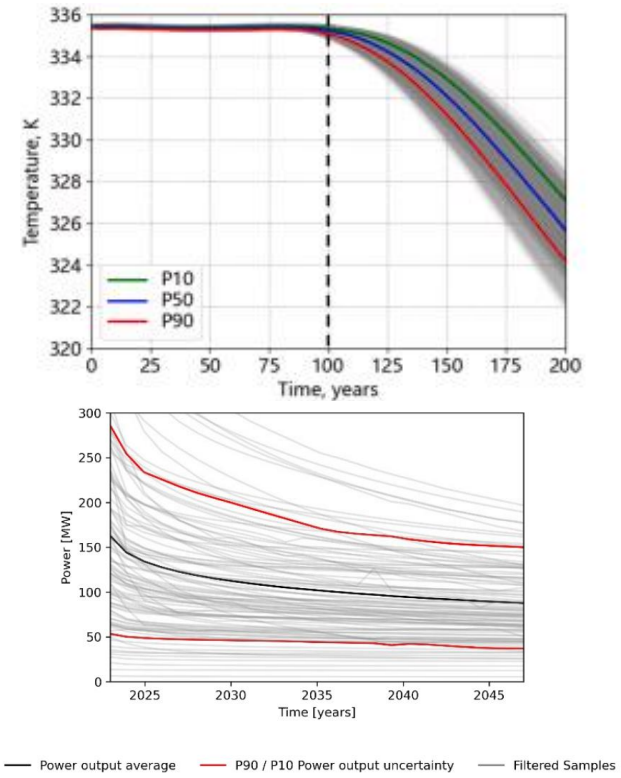


Figure 6: (left) Example of uncertainty analysis for sedimentary contexts (Wang et al. 2023) or (right) volcanics environments for temperature and power outputs (Dekkers et al. 2022).

During the injection, we observe the reduction of the local temperature and solid saturation from 10 %, reaching 9.8 % after 1600 hours of reinjection at 12.5 m of the injection well. This reduction of 2 % involves changes in the local porosity, which will affect the pressure and temperature near the wellbore. At various scales, this dissolution or scaling processes can play an important role to better monitoring production and reinjection strategies for potential reactive reservoirs for heat and cooling interest, mineral extraction or carbon sequestration.

The choice of simulators will highly depend on the users' objectives to better capture the local thermodynamics and complete understanding of the geothermal reservoir to achieve a higher success rate for future development. This may involve various scales of investigations following the scope of the modelling work. Table 1 discusses the differences between the conceptual and reservoir modelling approaches for volcanic and sedimentary contexts for low to medium-temperature geothermal resources. The categories can be discussed through various degrees of variations as sediments and volcanics can exist in the same geothermal systems. While drawing the conceptual model, the origin of the heat anomaly needs to be critically identified.

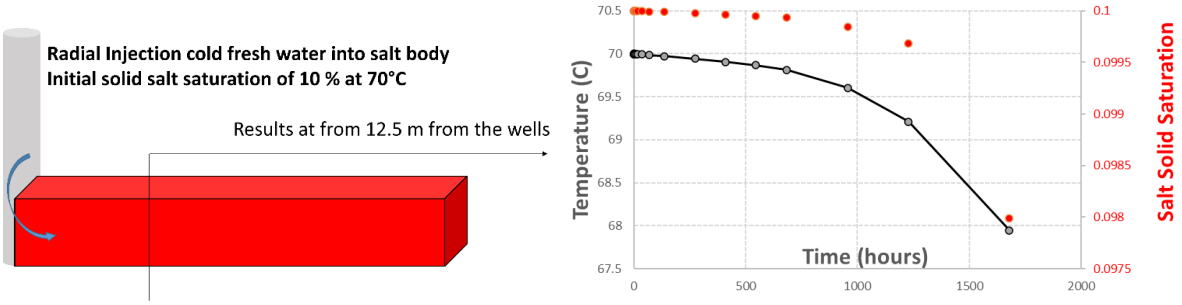


Figure 7: Conceptual simulation results of an injection of pure water into a salt body illustrating dissolution process at a radial distance of 12.5 m of the injection well.

Table 1: Low to Medium temperature geothermal resources summary for modelling practices.

	Volcanic-dominated contexts	**Sedimentary-dominated contexts**
Exploration techniques	Geology, Geophysical, Geochemistry Surface manifestations analysis Magnetotellurics and gravity less accurate than for deep reservoir Electrical tomography can provide useful insights for the main structures	Geology, Geophysical Geochemistry available only from well samples Magnetotellurics and gravity less accurate Seismic profiles
Conceptual model Challenges	Boundary of the systems due to alteration or major structures More easily accessed by users, historical data not available	Detect the impermeable units or structural controlled Heterogeneities management
Thermodynamics characteristics	Outflow of the geothermal systems Hotter two phase systems and High heat fluxes in Young Volcanic areas Lower heat fluxes for old volcanic structures. Mixed Convective-conductive system	Deep aquifers in sedimentary basins Single phase systems at the regional scale Potential influence of dissolved salts or NCs Low-medium heat fluxes Conductive dominated system
Modelling strategies	Derived from high temperature volcanic workflow More detailed representation of the area of interest	Single layers or multi layers options Geostatistical methods
Simulator requirements	Two phases interactions, Complex equations of state Liquid water in old volcanic areas Possibly reactive transport and wellbore coupling	Liquid phase polynomial properties formulation can be sufficient Two phases for magmatic sedimentary contexts Possibly reactive transport and wellbore coupling
Modelling challenges	Lack of sufficient quantitative data Good knowledge of the simulator capabilities and modelling objectives	Equivalent permeability applicable within reasonable interconnectivity factors Boundary conditions and heterogeneity management Good knowledge of the simulator capabilities and modelling objectives

5. CONCLUSION

Low to medium-temperature geothermal fluids are often neglected against higher-temperature resources when available. They represent a large potential resource in sedimentary or volcanics contexts, with various applications for more direct and faster outcomes during geothermal development. Overall, modelling considerations follow similar approaches to high-temperature geothermal systems, using a

detailed analysis of the conceptual digital models based on all geoscience data available. Following the local subsurface conditions and modelling strategies, the conceptual model is then converted into a numerical reservoir model to solve the heat and mass transfer equations. Challenges to account the subsurface heterogeneities arise due to the exploration techniques. Also, complex thermo-hydro-mechanical processes can affect the reservoir behaviour with wellbore effects.

Careful considerations and best practices are required to model accurately low to medium-temperature geothermal systems. The reservoir is a key tool for resource management planning to plan operational surface facilities and help quickly the development of direct users benefitting local communities. Modelling will provide detailed insights of crucial parameters for the stakeholders and decision-makers to minimize risks and delivers ranges of outcomes in the future.

Transdisciplinary approaches are necessary to foster research and applied consortium projects to access the heat better and colling potential of low and medium temperatures through accurate modelling to de-risk investments and assess sustainable energy production.

REFERENCES

Adityatama, D., Umam, M., Purba, D., Muhamma F.: Review on Geothermal Direct Use Application as an Alternative Approach in Community Engagement at Early Exploration Phase in Indonesia. *Proceedings*, Stanford University, Stanford, California, February 11-13, (2019).

Croucher A., O'Sullivan M., John O'Sullivan, J., Yeh, A., Burnell. B., Kissling W. Waiwera: A parallel open-source geothermal flow simulator, *Computers & Geosciences*, **141**, (2020), 104529.

Cumming W.: Resource Conceptual Models of Volcano-Hosted Geothermal Reservoirs for Exploration Well Targeting and Resource Capacity Assessment: Construction, Pitfalls and Challenges, *GRC Transactions*, **40**, (2016).

Dekkers, K., Gravatt, M., Maclaren, O.J., Nicholson, R., Nugraha, R., O'Sullivan, M., Popineau, J., Riffault, J., O'Sullivan J. Resource Assessment: Estimating the Potential of a Geothermal Reservoir. *Proceedings*, 47th Workshop on Geothermal Reservoir Engineering Stanford University, Stanford, California, February 7-9, (2022).

Diez, R.R. and Díaz-Aguado M.B.: Estimating Limits for the Geothermal Energy Potential of Abandoned Underground Coal Mines: A Simple Methodology. *Energies*, **7**, (2014), 4241-4260..

Febrianto, R., Bydder, J., Hochwimmer, A., Ussher, G., Libbey, R: Developing low temperature Geothermal projects in Indonesia using pumped well technology, *Proceedings*, IOP Conf. Ser.: Earth Environ. Sci. 254 012021.

Fiaschi, D., Lifshitz, A., Manfrida, G., Tempesti D.: An innovative ORC power plant layout for heat and power generation from medium- to low-temperature geothermal resources. *Energy Conversion and Management*, **88**, (2014) 883–893.

Keller, J., Rath, V., Bruckmann, J., Mottaghy, D., Clauser, C., Andreas Wolf, A., Seidler, R., H. Martin Bücker, H.M., Norbert Klitzsch, N.: SHEMAT-Suite: An open-source code for simulating flow, heat and species transport in porous media, *SoftwareX*, **12** (2020) 100533

Marty, N.C.M., Hamm, V., Castillo, C., Thiéry, D., Kervévan, C.: Modelling water-rock interactions due to long-term cooled-brine reinjection in the Dogger carbonate aquifer (Paris basin) based on in-situ geothermal well data *Geothermics*, **88**, (2020), 101899

McClintock, S., Robbie Watt R., Quinao, J.: Lookahead from Kawerau, New Zealand: The Largest Geothermal Industrial Direct Use Complex in the World Proceedings, World Geothermal Congress 2020+1 Reykjavik, Iceland, April - October (2021).

Limberger, J., Boxem, T., Pluymaekers, M., Bruhn, D., Manzella, A., Calcagno, P., Beekman, F., Cloetingh, S., Van Wees, J-D.: Geothermal energy in deep aquifers: A global assessment of the resource base for direct heat utilization. *Renewable and Sustainable Energy Reviews*, **82**, (2018), 961-975

Lopez, S., Hamm, V., Le Brun, M., Schaper, L., Boissier, F., Cotiche, C., Giuglaris, E.: 40 years of Dogger aquifer management in Ile-de-France, Paris Basin, France. *Geothermics*, **39**, (2010), 339-356.

Lund, J.W., Toth, A.N.: Direct utilization of geothermal energy 2020 worldwide review, *Geothermics*, **90** (2021) 101915.

O'Sullivan, J., Archer, R., O'Sullivan, M., Krom, T., Williams, B.: A new geothermal modelling workflow using Leapfrog and TOUGH2. *Proceedings*, 6th ITB International Geothermal Workshop. Bandung, (2017).

Popineau, J., Renaud, T., O'Sullivan, J., Gasser Dorado. J.: Production history modelling of a low enthalpy geothermal reservoir used for district heating: example of the Paris sedimentary basin. *Proceedings*, New Zealand Geothermal Workshop 2022 Auckland, New Zealand, (2022).

Poulsen, S.E., Balling, N., Nielsen S.B.: A parametric study of the thermal recharge of low enthalpy geothermal reservoirs *Geothermics*, 53, (2015) 464–478.

Poulsen, S.E., Balling, N., Bording, T.S, Mathiesen, A., Nielsen, S.B: Inverse geothermal modelling applied to Danish sedimentary basins, Geophysical Journal International, 211, (2017), 188–206.

Reyes, A.G.: Low-temperature geothermal reserves in New Zealand, *Geothermics*, **56** (2015) 138–161.

Santos, L., Dahi Taleghani, A., Elsworth, D.: Repurposing abandoned wells for geothermal energy: Current status and future prospects, *Renewable Energy*, **194** (2022) 1288e1302.

Schilling, O., Heather A., Sheldon, H., Lynn B. Reid, L.B., Corbel, S.: Hydrothermal models of the Perth metropolitan area, Western Australia: implications for geothermal energy *Hydrogeology Journal*, **21**, (2013): 605–621

Soldo, E., Alimonti, C., Scrocca D.: Geothermal Repurposing of Depleted Oil and Gas Wells in Italy, *Proceedings*, First World Energies Forum, 14 September–05 October. (2020).

Wang, Y., Voskov, D., Daniilidis, A., Khait, M., Saeid, S., Bruhn D.: Uncertainty quantification in a heterogeneous fluvial sandstone reservoir using GPU-based Monte Carlo simulation, *Geothermics*, **114**, (2023), 102773.

Closed Loop Geothermal Power Generation: Case Study of High Temperature Low Permeability Well

Azaria Haykal Ahmad[1], Daniel Adityatama[2],
M. Rizqi Al Asy'ari[2], Firman Bagja Juangsa[1], and Prihadi Setyo Darmanto[1]

[1]Institut Teknologi Bandung, Bandung, Indonesia
[2]Geoenergi Solusi Indonesia (GEOENERGIS), Jakarta, Indonesia

azariahaykalahmad@gmail.com

Keywords: deep borehole heat exchanger, closed loop, geothermal, computational fluid dynamics, process simulation

ABSTRACT

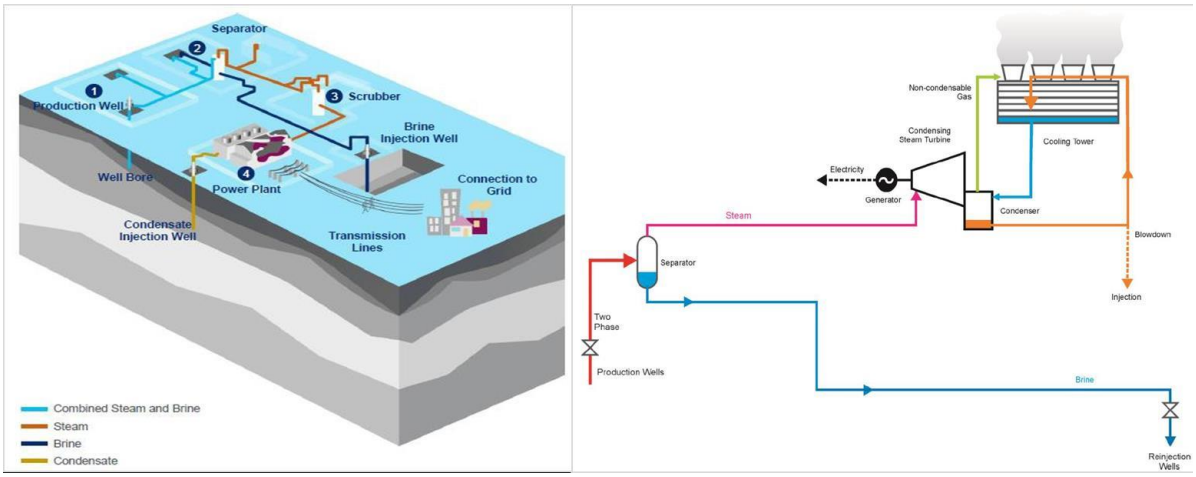
This study investigates the potential of geothermal wells with high bottom-hole temperatures and low permeability, which are typically regarded as non-commercial due to their limited utility as injection wells. Conventional geothermal energy generation depends on the extraction of subsurface geothermal fluid to the surface production facility. However, these non-commercial wells do not satisfy all requirements for conventional use. Using computational fluid dynamics and process engineering, this investigation investigates a novel approach. The focus of this study is on utilizing the closed loop potential of these wells. The concept involves circulating an external fluid through a downhole heat exchanger in order to extract the geothermal fluid's valuable heat. This extracted heat is then transported to the surface, where it is converted into electricity in the most effective way. This study seeks to unlock the untapped energy potential of non-commercial geothermal wells by investigating the viability of this closed loop system. Geothermal resources that were previously deemed inappropriate for conventional geothermal power generation may now be utilized.

The results indicate a declining trend in the outlet water temperature from the deep borehole heat exchanger (DBHE) due to increased flow velocity, resulting in shorter residence times and reduced heat transfer efficiency. To maintain efficient heat exchange, a low circulation flow rate is recommended to allow sufficient residence heating time. Additionally, the polynomial trend in delta pressure emphasizes the importance of flow rate optimization and pressure drop management. Thermal energy availability is positively correlated with mass flow rate, offering opportunities for increased energy extraction. However, a corresponding increase in DBHE pump power necessitates a trade-off between energy extraction and operational costs. The analysis of net work and energy efficiency of the ORC provides valuable insights into the most suitable energy conversion method based on mass flow rate. Striking a balance between pump power and mass flow rate is critical for maximizing net power output and thermal efficiency. To enhance DBHE performance further, experimental validation and the exploration of alternative working fluids, such as water with salinity or supercritical fluids like carbon dioxide or isobutane, are proposed.

1. INTRODUCTION

For hundreds of years, mankind has been incorporating the geothermal energy in their daily life. People have been using geothermal manifestations such as hot springs for bathing, heating, and cooking. Later in the early of twentieth Century, people begin to consider the geothermal as a practical source of energy, marked by the first geothermal energy generator in Larderello, Italy (IGA 2018). From then, the use of geothermal for electricity production started to spread to worldwide, with New Zealand, USA, the Philippines, Indonesia, etc. developed their own geothermal plant for power production.

To utilize geothermal for power production, the heat should be extracted from the subsurface and converted to other forms of energy, i.e., to kinetic energy then to electric energy. The most common geothermal power generation involves extracting the naturally occurring geothermal fluid (can be hot water, steam, or mixture of both in a hydrothermal system) and converting it to into mechanical power to turn the generator and produce electricity (DiPippo 2016; Watson 2013) as illustrated in Figure 1.



a) b)

Figure 1: (a) Illustration of typical geothermal power plant (modified from Liebert, 2019), (b) Simplified diagram of single flash geothermal power generation (modified from Jacobs, 2021).

The geothermal fluid can be naturally discharged from the well or may require artificial pumping, while the geothermal fluid can be directly used to drive the steam turbine (in a dry steam or flash-type power plant) or used to heat other working fluid in the binary or Organic Rankine Cycle power plant (Febrianto et al., 2019; Watson 2013). Regardless of the turbine type, conventional hydrothermal systems require sufficient temperature, benign fluid, and a high level of subsurface permeability in order to be economically used for power generation.

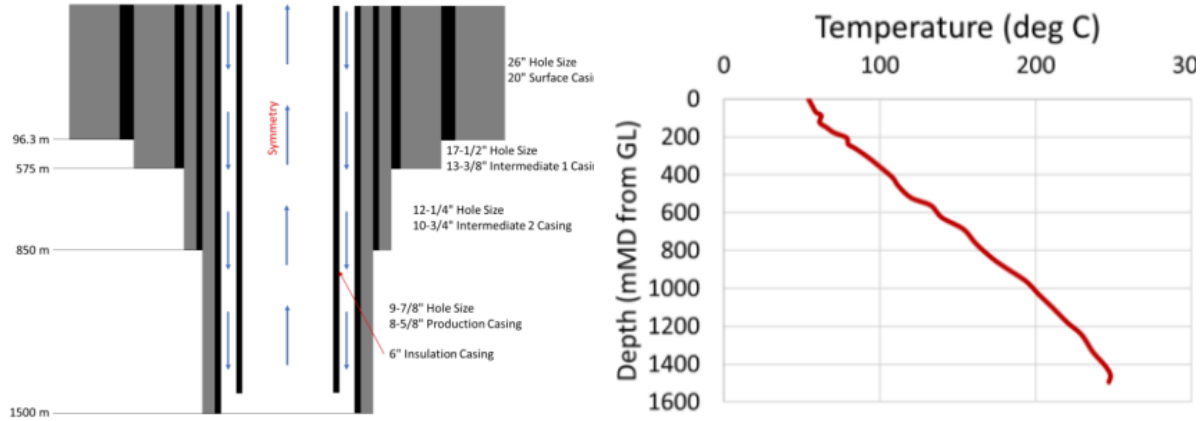
Those aforementioned requirements or constraints make not every place can be used for geothermal power generation, even though the heat beneath the ground exists everywhere on the earth. This has prompted many researchers and companies to develop new ways to extract geothermal energy from the ground. Indonesia has about 3359 GW of enhances geothermal system potential (Aghahosseini and Breyer 2020). Apart from the Engineered Geothermal System (EGS) that wanted to artificially create subsurface permeability in a hot rock, another explored alternatives is the use of closed-loop geothermal system. Closed-loop geothermal systems offer a solution to utilize such a well by extracting the heat only from the wellbore. It introduces external fluid flowing through a downhole heat exchanger to extract the heat to the surface, thus removing the high subsurface permeability requirement (Scherer et al. 2020)

There is lack of research about closed loop power generation in Indonesia. Therefore, the objective of this paper is to explore and elaborate on the performance characteristics of a Deep Borehole Heat Exchanger (DBHE) in a geothermal field, particularly focusing on the outlet water temperature, pump power requirements, available thermal energy, and the analysis of the net work and energy efficiency of the Organic Rankine Cycle (ORC). By understanding and analyzing these aspects, we aim to optimize the design and operation of the DBHE system, achieving a balance between energy efficiency, energy transfer rate, and overall system performance. Additionally, we propose potential future research directions to further enhance the understanding and performance of DBHE systems in geothermal fields.

2. METHODS

2.1. Computational Fluid Dynamics

Several numerical and analytical simulations consider 1D calculations of the borehole fluid flow and heat transfer (Kolo et al. 2014; Næss et al. 2016) or full 3D CFD simulations (Huang et al. 2015; Noorollahi et al., 2015; Sliwa et al., 2012). To reduce the CPU and computing time, 2D axisymmetric approach of the deep bore hole heat exchanger is used. The CFD is carried out with ANSYS Fluent 2020 R2, which is based on the finite volume approximation, and is used in this study to solve the governing equations of fluid. The schematic of DBHE of East Nusa Tenggara Well is shown in Figure 2.



a) b)

Figure 2: (a) DBHE Schematic (b) Temperature of East Nusa Tenggara Well (Adityatama et al., 2023).

The methodology of computational fluid dynamics is shown below. First, slim hole well is simulated with assumption of flowrate 40 lpm (Mackenzie et al. 2017) with boundary condition of temperature based on PT test as shown in Figure 3. Then the heat flux of DBHE well used the approximation of slim hole well. Then the sensitivity analysis of mass flow rate is done.

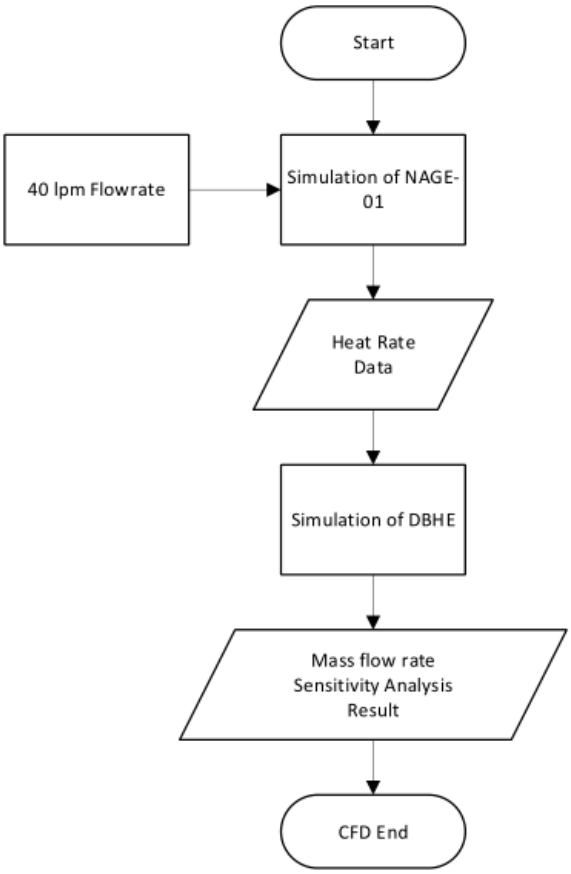


Figure 3: Flow of simulation.

Note that there is no contact between the geothermal fluids (or rocks) and the circulating fluid, as the system is fully independent. The circulating fluid chosen in the present study is liquid water. The choice of constant water properties is a limitation of the current model. However, this study is intended to be

the first step into modelling the complex downhole geothermal environment with a CFD approach, as the heat exchange surface is small (well walls) compared to conventional geothermal extraction (fluids flowing into pores and fractures).

Table 1: Deep Borehole Heat Exchanger parameter.

Parameter	NGE-DBHE	
Insulation pipe (inch) (Falcone et al. 2018)	5	ρ = 2700 kg/m^3 C_p = 470 J/kgC K = 0.01038 W/mK
Casing (inch) (Doran et al. 2021)	8 5/8	ρ = 2700 kg/m^3 C_p = 470 J/kgC K = 46.1W/mK
Cement		ρ = 1830 kg/m^3 C_p = 1900 J/kgC K = 0.99 W/mK

The continuity equation is shown in below.

$$\frac{\partial \rho}{\partial t} + \frac{\partial (\rho v_x)}{\partial x} + \frac{\partial (\rho v_r)}{\partial r} + \frac{v_r}{r} = 0$$

For incompressible flows, the energy equation is calculated as

$$E = \int_{T_{ref}}^{T} cdT + \frac{v^2}{2}$$

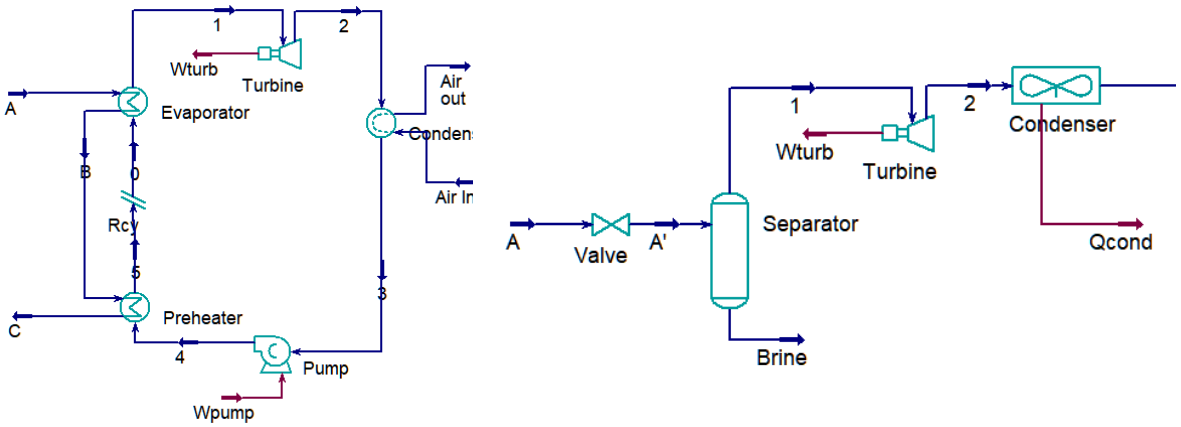
Where c is the heat capacity and v in the fluid velocity. The detail of the equations is available in the ANSYS Fluent Users Guide (ANSYS Inc. 2020)

2.2. Process Simulation

In the paper focused on deep borehole heat exchangers, the process simulation was conducted using ASPEN Hysys V12 Software. The chosen cycle is based on the enthalpy of water, following the methodology proposed by Zarrouk and Moon (2014). Among the available flash options, single flash was preferred over double flash. The schematics of the process simulation is shown in Figure 4. Several key assumptions were made during the analysis:

- Working Fluid: The selected working fluid is n-pentane, based on the operational parameters of the Sarulla Geothermal Power Plant (Sinaga and Saputra 2019).
- Steady State Analysis: The system components were analyzed under steady-state conditions (Moran et al. 2014).
- Fluid Properties: The fluid properties were modeled using the Soave-Redlich-Kwong (SRK) equation of state (Ahmad et al. 2023; Campos Rodríguez et al. 2013).
- Neglecting Energy Changes: Changes in potential and kinetic energy within each system were neglected (Moran et al. 2014).
- Condenser Cooling: The condenser utilizes air as the cooling fluid, with input and output temperatures of 25°C and 40°C (Ahmad et al. 2023).
- Turbine Isentropic Efficiency: The isentropic efficiency of the turbine was assumed to be 85% (DiPippo 2015).

- Pump Adiabatic Efficiency: The adiabatic efficiency of the pump was estimated to be 75% (DiPippo 2015).
- Negligible Pressure Drop: No pressure drop was considered in the piping systems, heat exchanger components, and separators (Moran et al. 2014).
- ORC Condensing Temperature: The condensing temperature for the Organic Rankine Cycle (ORC) was set at 37°C (Campos Rodríguez et al. 2013).
- Fan Power Consumption: The specific power absorbed by the fans of the air-cooled condenser (ACC) was assumed to be 0.15 kW per kg/s of air (Toffolo et al. 2014)
- The pinch point temperature difference (PPTD) of the heat exchanger is 5°C (Ahmad et al. 2023)



a) b)

Figure 4: Schematic of process simulation. (a) Organic Rankine Cycle, (b) Single Flash.

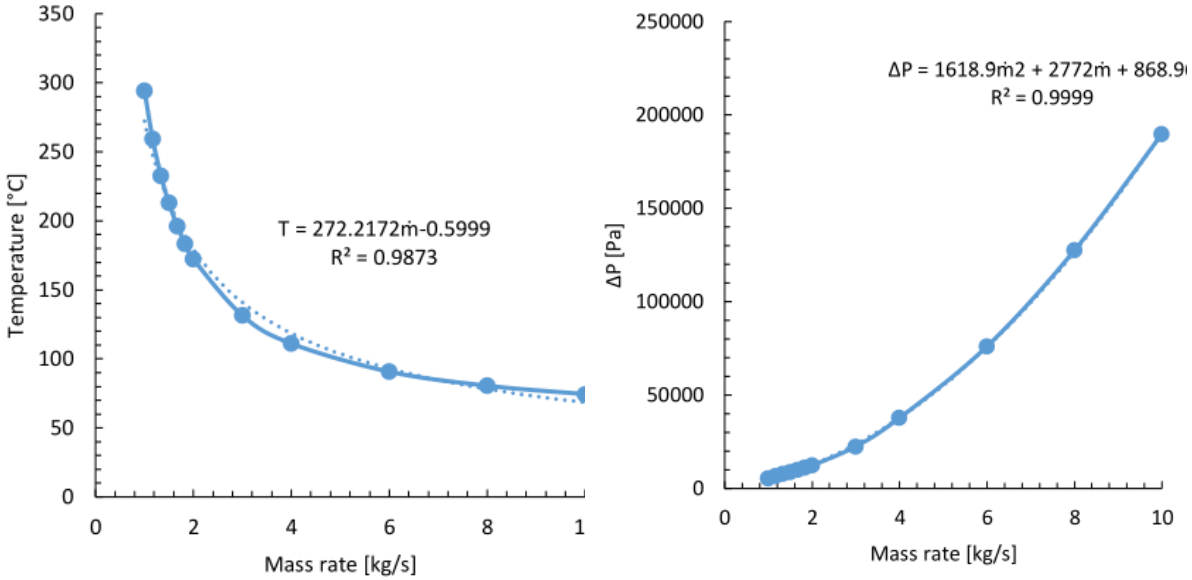
Meanwhile, the work of deep borehole heat exchanger can be calculated with equation below, with dP is pressure different that collected from the computational fluid dynamics, Q as volume flow rate, and ρ is density of water.

$$\dot{W}_{DBHEpump} = dP \cdot Q/\rho$$

3. RESULT AND DISCUSSION

3.1. Analysis of Flow Rate in Deep Borehole Heat Exchanger

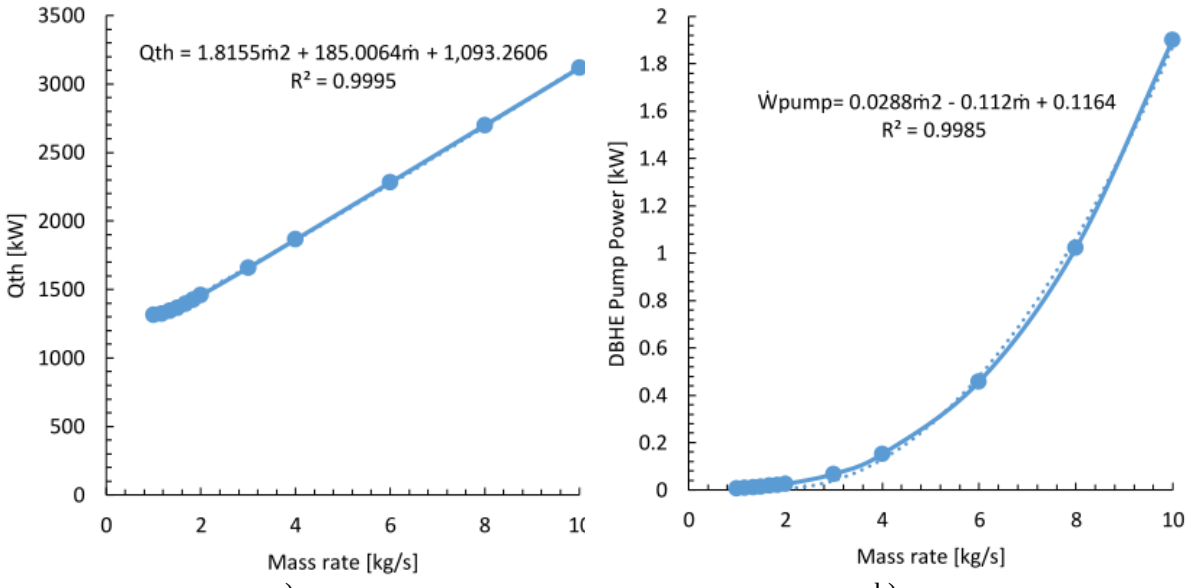
Deep Borehole Heat Exchangers (DBHE) are an essential component of geothermal energy systems that harness the Earth's natural heat for various applications, such as electricity generation and district heating. The temperature of outlet of water from DBHE and the pressure needed is shown in Figure 5. The temperature has a trend of declining as shown in Figure 5(a). This decreases due to responses to increase of velocity, that leads to shorter residences time. The circulation flow rate also suggested to be low to allow a sufficient residence heating time (Renaud et al. 2019). At 1 kg/s, the temperature is above the NAGE-01 well due to more time to heating the water. This result is aligned with GreenFire Energy Inc. report (Scherer et al. 2020), where the wellhead temperature will be lower when the flow increases. Meanwhile the delta pressure needed for the flowing water has polynomial trend as shown in Figure 5(b). Higher the pressure, the pressure drop will be higher and the result is also similar with GreenFire Energy Inc. report (Scherer et al. 2020). Optimally, delta T should be minimized ascending the conduit to improve system efficiency by extracting additional energy from nearby rocks. A balance should be achieved between energy efficiency and energy transfer rate.



a) b)

Figure 5: (a) Temperature outlet in DBHE, (b) pressure drop in DBHE.

The relationship between mass flow rate and thermal energy available is a crucial aspect of the DBHE system's performance. The increase in mass flow rate results in higher available thermal energy, as indicated by Figure 6 (a). This aligned with (Doran et al., 2021) where with the increase of mass flow rate, the available thermal energy. However, it is important to note that as the mass flow rate increases, the DBHE pump power also rises, as shown in Figure 6 (b). his is an essential consideration for system designers and operators as higher pump power requirements can result in increased operational costs. Finding the optimum mass flow rate that balances thermal energy extraction with acceptable pump power requirements is crucial for maximizing the system's overall efficiency.



a) b)

Figure 6: (a) Thermal energy available, (b) DBHE Pump Power.

3.2. Analysis of Net Work and Energy Efficiency of Organic Rankine Cycle

The analysis of net work and energy efficiency of the Organic Rankine Cycle (ORC) is critical in determining the optimum operating conditions for the DBHE system. Figure 7 shows the enthalpy variation with mass rate, indicating that a mass rate below 1.33 kg/s would be best suited for single

flash utilization, while higher mass rates warrant the use of the ORC for energy conversion based on Zarrouk and Moon (2014). This information provides valuable insights into the appropriate energy conversion method based on the mass flow rate, enabling efficient energy extraction from the geothermal source. The net power is evaluated to determine the optimum operation of DBHE East Nusa Tenggara well.

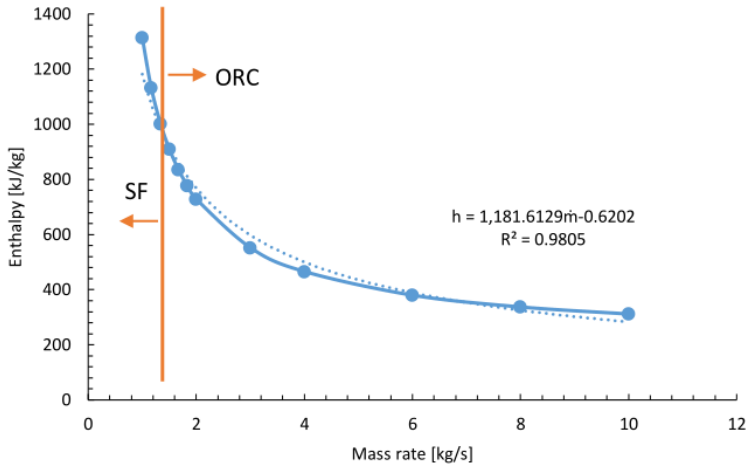
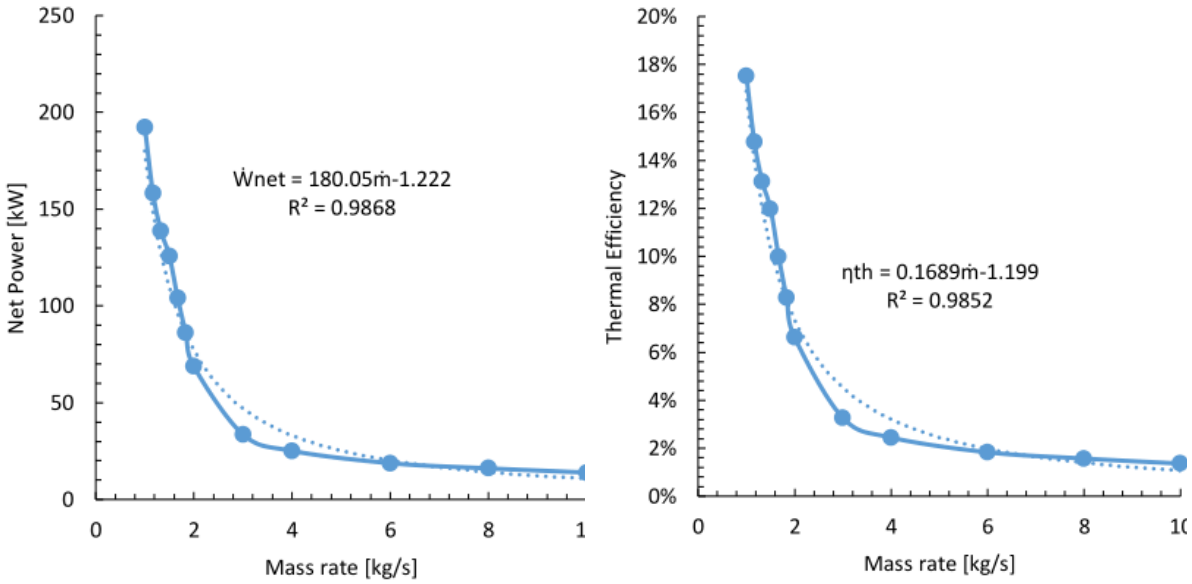


Figure 7: Enthalpy outlet in DBHE. SF=Single Flash, ORC=Organic Rankine Cycle.

Figure 8 illustrates the relationship between net power, thermal efficiency, and mass rate. A noteworthy observation is the decrease in net power and thermal efficiency as the pump power increases, while the outlet temperature of the DBHE decreases. This indicates that the higher pump power requirements at elevated mass rates can negatively impact the overall performance of the DBHE system. Therefore, striking a balance between pump power and mass flow rate is crucial for optimizing net power output and thermal efficiency.



a) b)

Figure 8: (a) Net power, (b) Thermal efficiency.

4. CONCLUSION AND WAY FORWARD

In conclusion, the performance analysis of a Deep Borehole Heat Exchanger (DBHE) in a geothermal field is a multi-faceted process that requires a thorough understanding and careful consideration of several key factors. The declining trend in the outlet water temperature and the polynomial trend in delta pressure underscore the importance of optimizing the flow rate and managing pressure drops to ensure efficient heat exchange within the system. By implementing appropriate flow rate control and pressure drop management strategies, it is possible to maintain the desired outlet water temperature while maximizing the system's overall performance.

One of the critical aspects to consider is the positive correlation between the mass flow rate and the availability of thermal energy. As the mass flow rate increases, the DBHE can extract more thermal energy from the geothermal source. However, this comes at the cost of an increase in the DBHE pump power. Therefore, system designers and operators must carefully balance the desire for higher thermal energy extraction with the associated operational costs due to increased pump power requirements. Striking this balance is essential to ensure the long-term economic viability and sustainability of the DBHE system.

Furthermore, the analysis of the net work and energy efficiency of the Organic Rankine Cycle (ORC) provides valuable insights into the most suitable energy conversion method based on the mass flow rate. Understanding the optimal energy conversion approach is critical for achieving the maximum net power output and thermal efficiency from the DBHE system. By carefully selecting the appropriate energy conversion method, the system can effectively harness the available thermal energy and convert it into usable power with minimal losses.

Moving forward, to enhance the understanding and performance of DBHE systems in geothermal fields, further research and experimentation are crucial. Validating the DBHE's performance with experimental studies can provide real-world data to support and refine the theoretical analysis. Conducting controlled experiments under varying conditions will offer valuable insights into the system's behavior and aid in optimizing its design and operation.

Additionally, exploring a wider range of working fluids represents a promising avenue for improving DBHE efficiency. Investigating alternative working fluids, such as water with salinity, carbon dioxide (Sun et al. 2019) or isobutane as a supercritical fluid (Wang et al., 2019), can have a significant impact on the system's performance. Different working fluids may offer unique thermodynamic properties that can be harnessed to enhance energy extraction and conversion processes, leading to increased overall efficiency.

5. REFERENCES

Adityatama, D.W., Asyari, M.R. Al, Ahmad, A.H., Riyanto, N., Purba, D., and Erichatama, N.: Potential Closed-loop Geothermal Power Generation Application for Non-commercial Well in Indonesia: A Preliminary Study. (2023);1–9.

Aghahosseini, A., and Breyer, C.: From hot rock to useful energy: A global estimate of enhanced geothermal systems potential. Appl. Energy. (2020);279.

Ahmad, A.H., Darmanto, P.S., Juangsa, F.B., Al, M.R., and Adityatama, D.: Thermodynamic and Economic Comparison of Organic Rankine Cycle and Kalina Cycle as Bottoming Unit to Utilize Exhaust Steam from Back Pressure Turbine Geothermal Power Plant. PROCEEDINGS, 48th Work. Geotherm. Reserv. Eng. California; (2023).

ANSYS Inc.: ANSYS® Academic Research CFD, Release 2020 R2, Fluent User’s Guide. Canonsburg, PA 15317; (2020).

Campos Rodríguez, C.E., Escobar Palacio, J.C., Venturini, O.J., Silva Lora, E.E., Cobas, V.M., Marques Dos Santos, D., et al.: Exergetic and economic comparison of ORC and Kalina cycle for low

temperature enhanced geothermal system in Brazil. Appl. Therm. Eng. [Internet]. Elsevier Ltd; (2013);52(1):109–19. Available from: http://dx.doi.org/10.1016/j.applthermaleng.2012.11.012

DiPippo, R.: Geothermal Power Plants: Principles, Applications, Case Studies and Environmental Impact: Fourth Edition. Geotherm. Power Plants Princ. Appl. Case Stud. Environ. Impact Fourth Ed. (2015).

DiPippo, R.: Geothermal Power Generation: Developments and Innovation. Geotherm. Power Gener. Dev. Innov. (2016).

Doran, H.R., Renaud, T., Falcone, G., Pan, L., and Verdin, P.G.: Modelling an unconventional closed - loop deep borehole heat exchanger (DBHE): sensitivity analysis on the Newberry volcanic setting. Geotherm. Energy [Internet]. Springer Berlin Heidelberg; (2021); Available from: https://doi.org/10.1186/s40517-021-00185-0

Falcone, G., Liu, X., Okech, R.R., Seyidov, F., and Teodoriu, C.: Assessment of deep geothermal energy exploitation methods: The need for novel single-well solutions. Energy. Pergamon; (2018); 160:54–63.

Febrianto, R., Bydder, J., Hochwimmer, A., Ussher, G., and Libbey, R.: Developing low temperature Geothermal projects in Indonesia using pumped well technology. IOP Conf. Ser. Earth Environ. Sci. (2019);254(1).

Huang, X., Zhu, J., and Li, J.: On Wellbore Heat Transfer and Fluid Flow in the Doublet of Enhanced Geothermal System. Energy Procedia [Internet]. Elsevier B.V.; (2015); 75:946–55. Available from: http://dx.doi.org/10.1016/j.egypro.2015.07.277

IGA.: Geothermal Quick Guide [Internet]. Int. Geotherm. Assoc. (2018). Available from: https://www.lovegeothermal.org/wp-content/uploads/dlm_uploads/IGA-Geothermal-Quick-Guide-0618.pdf

Jacobs.: Types of System and Differences Indonesia - NZ. (2021).

Kolo, I., Sousa, R., and Zhang, T.: Heat Transmission in a Geothermal Wellbore: Modelling and Application. (2014); (December).

Liebert, F.: Geothermal Reservoir Management Training Material. (2019).

Mackenzie, K.M., Ussher, G.N.H., Libbey, R.B., Quinlivan, P.F., Dacanay, J.U., and Bogie, I.: Use of Deep Slimhole Drilling for Geothermal Exploration. 5th Indones. Int. Geotherm. Conv. Exhib. 2017. (2017). p. 12–6.

Moran, M.J., Saphiro, H.N., Boettner, D.D., and Bailey, M.B.: Fundamental of Engineering Thermodynamics. Wiley. (2014).

Næss, E., Sønju, O.K., and Holmberg, H.: Thermal evaluation of coaxial deep borehole heat exchangers Acu n. (2016);97:65–76.

Noorollahi, Y., Pourarshad, M., Jalilinasrabady, S., and Yousefi, H.: Numerical simulation of power production from abandoned oil wells in Ahwaz oil field in southern Iran. Geothermics [Internet]. CNR-Istituto di Geoscienze e Georisorse; (2015); 55:16–23. Available from: http://dx.doi.org/10.1016/j.geothermics.2015.01.008

Renaud, T., Verdin, P., and Falcone, G.: Numerical simulation of a Deep Borehole Heat Exchanger in the Krafla geothermal system. Int. J. Heat Mass Transf. [Internet]. The Authors; (2019); 143:118496. Available from: https://doi.org/10.1016/j.ijheatmasstransfer.2019.118496

Scherer, J.A., Higgins, B., Muir, J.R., and Amaya, A.: Closed-Loop Geothermal Demonstration Project. Consult. Rep. Emeryville, CA 94608: California Energy Commission; (2020).

Sinaga, R.H.M., and Saputra, D.W.: Performance Investigation of Geothermal Power Plant Based on Exergy and Exergoeconomic Analyses (Case Study: Sarulla Geothermal Power Plant). IOP Conf. Ser. Mater. Sci. Eng. (2019);546(7).

Sliwa, T., Gołas, A., Wołoszyn, J., and Gonet, A.: Numerical model of borehole heat exchanger in ansys CFX software. Arch. Min. Sci. (2012);57(2):375–90.

Sun, X., Wang, Z., Liao, Y., Sun, B., and Gao, Y.: Geothermal energy production utilizing a U-shaped well in combination with supercritical CO2 circulation. Appl. Therm. Eng. [Internet]. Elsevier; (2019);151(December 2018):523–35. Available from: https://doi.org/10.1016/j.applthermaleng.2019.02.048

Toffolo, A., Lazzaretto, A., Manente, G., and Paci, M.: A multi-criteria approach for the optimal selection of working fluid and design parameters in Organic Rankine Cycle systems. Appl. Energy [Internet]. Elsevier Ltd; (2014); 121:219–32. Available from: http://dx.doi.org/10.1016/j.apenergy.2014.01.089

Wang, Y., Zhang, L., Cui, G., Kang, J., and Ren, S.: Geothermal development and power generation by circulating water and isobutane via a closed-loop horizontal well from hot dry rocks. Renew. Energy [Internet]. Elsevier Ltd; (2019); 136:909–22. Available from: https://doi.org/10.1016/j.renene.2019.01.042

Watson, A.: Geothermal engineering: Fundamentals and applications. Geotherm. Eng. Fundam. Appl. (2013).

Zarrouk, S.J., and Moon, H.: Efficiency of geothermal power plants: A worldwide review. Geothermics [Internet]. CNR-Istituto di Geoscienze e Georisorse; (2014); 51:142–53. Available from: http://dx.doi.org/10.1016/j.geothermics.2013.11.001.

Collapse Challenges in High-Temperature Geothermal Wells

François Penven, Khaled Hamdani, Beatriz Yabarra, and Jean-Guillaume Besse

Vallourec

francois.penven@vallourec.com

Keywords: Geothermal wells, High temperature, Casing failure, High Collapse Grades

ABSTRACT

High-temperature geothermal wells (temperature above 250°C) result in specific load cases induced by the temperature or by the well design itself. Several high-temperature geothermal well failures have been observed and reported in the literature in different parts of the globe due to collapse loads. The consequences for the operator are very severe, as in most cases, the well needs to be abandoned, resulting in both a huge financial impact due to the loss of the well and an immediate and unpredictable drop in energy supply. The purpose of this paper is to review and analyze the possible root causes of casing collapse based on well design approach and lessons learned from the literature and to propose possible technical solutions to mitigate and avoid casing collapse failures in high- temperature geothermal wells. In most geothermal wells, casing design has historically been based on classical API standard or low standards pipe sizes in material grades such as K55 or L80 fitted with buttress or semi1premium connections. The usage of these grades provides limited resistance to collapse, which can, in some cases, be insufficient to sustain the collapse loads induced by the temperature or related to the well environment and life cycle. The paper includes a literature review of casing failures and well design evaluations to understand and quantify the main load cases that can generate collapse, such as cementing phase or "annulus" fluid pocket expansion due to high temperature changes during well production. The higher collapse performances are achieved thanks to a tighter control of the manufacturing processes and the key geometrical and mechanical parameters of the pipe such as wall thickness, ovality, eccentricity, yield strength and residual stress. The control and the consistency of these parameters are the key drivers to achieve these enhanced collapse performances. Pipe collapse resistance can be increased up to 50% without adding extra weight to the pipe string. As OCTG manufacturer, Vallourec, has developed a comprehensive range of High Collapse and Extreme Collapse grades which provide enhanced resistance compared to classical OCTG grades. High Collapse and Extreme Collapse grades have already been successfully used in oil and gas applications such as drilling through salt domes or to cope with annulus pressure buildup in some High Pressure and High Temperature and deep-water wells. A thorough well design in partnership with the OCTG pipe manufacturer and the use of High Collapse grades in High Temperature geothermal wells can be a solution to prevent casing collapse and therefore ensure well reliability, longer-lasting wells, and a steady energy supply.

1. INTRODUCTION

From a thermodynamic perspective, Geothermal plants operating at higher temperatures and beyond 350°C, could generate significantly more power with the same flow of water / vapor. The ratio between a plant operating at 200°C and a plant operating at 400°C could be up to 8 or 10 (increase of +700 to 900%). Evidence from a test well drilled by the Iceland Deep Drilling Project (IDDP) suggests that an estimated 36 megawatts (MW) of energy could be produced from one well, approximately five to ten times that of a typical 3-5 MW commercial geothermal well today. (Bruce Hill et al., 2022).

High temperature Geothermal Energy production is already developed in several countries around the world with the aim to generate power based on Geothermal resource exploitation up to around 350°C.

Operating Geothermal plants at higher temperatures is possible considering that the power plant steam turbines used with other energy sources (Nuclear, Coal, …) are operating up to ca. 600°C.

However, drilling and installing wells with bottom hole temperatures up to 350°C and beyond implies several technical challenges related to the material behavior (steel and others) at such elevated temperatures as well as technology readiness of several components required to execute reliable installations and avoid well failures faced in pilot projects executed with this very high level of temperatures.

One of the main casing failure modes observed in Geothermal well is related to collapse of the casing either during well installation or during well flowing. The purpose of this paper is to review the mechanisms involved in this failure mode and to propose solutions which can contribute to prevent such failures.

2. REVIEW OF THE LITERATURE AND CASING FAILURE DUE TO CASING COLLAPSE

Several Geothermal operators have already drilled Geothermal wells at significantly high temperatures and in Iceland, Indonesia, the

Philippines as indicated in the graph below.

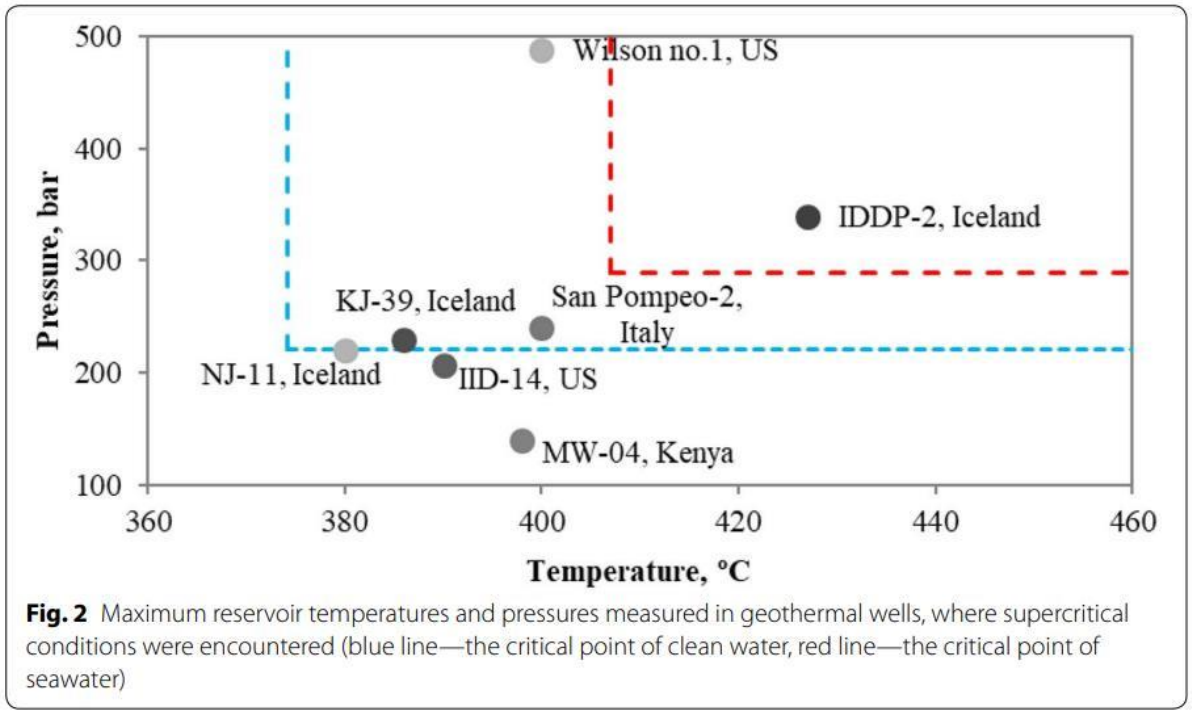


Fig. 2 Maximum reservoir temperatures and pressures measured in geothermal wells, where supercritical conditions were encountered (blue line—the critical point of clean water, red line—the critical point of seawater)

Figure 1: Maximum reservoir temperatures and pressures in geothermal wells (Source: Kruszewski and Wittig, 2018).

High-Temperature geothermal wells (temperature above 250°C) result in specific load cases induced by the temperature or by the well design itself. Several high-temperature geothermal well failures have been observed and reported in the literature (Kruszewski and Wittig, 2018) in different parts of the globe due to collapse loads (external pressure loads) on the casing. The consequences for the operator are very severe, as in most cases, the well needs to be abandoned or the collapsed pipe leads to a severe flow reduction, resulting in both a huge financial impact due to the loss of the well and an immediate and unpredictable drop in energy supply.

3. ROOT-CAUSE ANALYSIS OF THE COLLAPSE

3.1 Cementing phase

During the cementing of the casing, there is a pressure difference between the inside of the casing (full of water / density =1) and the outside of the casing (density = 1,9) since the density of both fluids (water and cement) are different. In the specific case of a Geothermal well with a fully cemented casing, the hydrostatic pressure difference between the inside and the outside of the casing can be significant (especially for deep wells) which induces collapse pressures on the pipe and in particular in the bottom section of the well (BLADE Advanced Casing Design Course, 2013).

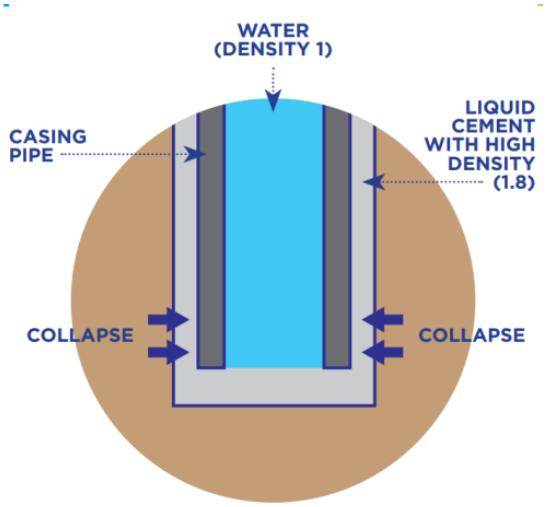


Figure 2: Collapse-loads during cementing phase (Source: Vallourec).

3.2 Annulus fluid pocket expansion due to high temperature changes during well production

The second main cause which can generate external pressure loads on the casing is the presence of water pockets outside the casing or flows in the cement filled with water (either in the annulus between two casing pipes or between the casing pipe and the formation). When the well is flowing, the hot geothermal fluid circulating inside the casing heats up the casing and consequently the water pocket outside the casing is also heated up. The temperature increase of the water involves a change in volume which generate collapse loads on the casing in case the water trapped cannot escape in the formation (Ragnarsdóttir et al., 2023).

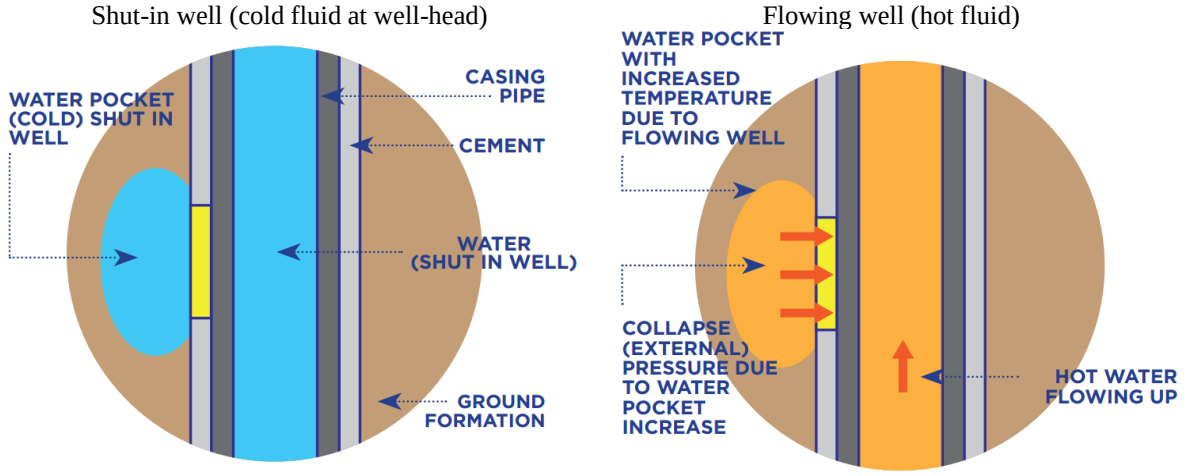


Figure 3: Collapse-loads during production phase (Source: Vallourec).

4. HIGH COLLAPSE GRADES, HOW DO WE ACHIEVE HIGHER COLLAPSE RATING

Collapse loads in wells are found when the external pressure (po) exerted on the tubular exceeds the internal pressure (pi). The pipe must withstand all loads applied during drilling and well service, thus representing a major factor of well design not only in OCTG industry, but also on new applications, such as geothermal wells.

4.1 Increasing the collapse resistance of a tubular

The collapse resistance of a tubular is governed by a series of mechanical (yield strength, residual stress) and geometrical (wall thickness, ovality, eccentricity) parameters. In order to enhance its resistance, these parameters must be strictly controlled at several stages of the production process (Performance Baskets: An Alternative Solution to Challenging Collapse Pressures. Ybarra, M. B., Filgueiras, P., Kubla, G., Thomas, T., Daly, D., Oliveira, J. Houston: Offshore Technology Conference, 2022 (Ybarra et al., 2022)) while still remaining within the tolerances (Diameter, wall thickness, drift* and mass) of tubular specification such as API 5CT. Generally speaking, the tighter the control of these parameters, the higher the final collapse resistance of the tubular will be.

4.2 Calculating the collapse rating of an individual pipe

In the industry, there are different models used to accurately predict the collapse or external resistance of a tubular based on its mechanical and geometrical parameters. This external resistance is referred to as design collapse rating i.e., the minimum guaranteed collapse pressure for a given tubular.

The international standard API 5C3 (American Petrol Institute, 2018) proposes on its Clause 8 four different regions based on the D/t ratio (yield, plastic, transition and elastic collapse) and proposes historical equations for calculating the collapse design rating of an API product based on the parameters mentioned above. Furthermore, statistical methods to calculate non-API proprietary collapse ratings are proposed on its Annexes G (direct method, statistics) and H (indirect method, based on production data). However, both analyses are limited to the analysis of historical data. (Adams, A.J., Moore, P.W. and Payne, M.L. Houston: SPE Drilling & Completion, 2003).

To address these limitations, Vallourec has developed a proprietary model to calculate the collapse resistance of each individual pipe to a Target Reliability Level with a given level of confidence (Calculation of The Collapse Rating of Individual Pipe Joints for OCTG Casing and Tubing. Filgueiras et al., 2022). The proprietary model accounts for mechanical properties and residual stresses, based on physical tests; and the geometry of each pipe (wall thickness, ovality, eccentricity), obtained by automated non-destructive inspection to 100% surface coverage. Pipe traceability assures the link between shop floor and data. Actual collapse tests confirm ratings and model assumptions.

4.3 Vallourec's offer

The combination of the proprietary model and the application of a tighter production control results on enhanced collapse ratings when compared to API products; not only increasing the safety margin on well designs, but also allowing for slimmer, more cost effective well designs.

Additionally, tubulars with high collapse resistance can also be proposed on metallurgies that offer sour service or sweet corrosion resistance, and on non-standard products, such as odd-ball sizes and special drifts.

*Drift diameter is an internal diameter, smaller than the nominal inside diameter d of the tubular, that is guaranteed by the pipe manufacturer. It is a critical well design input used to determine what size tools or subsequent strings can later be run through that given tubular. As a result, each released product shall be tested by pulling a calibrated mandrel, with a given length, through the tubular [API 5CT Clause 8.10] (API Spec, 2018) to prove conformance to the drift requirement.

Nominal outside diameter of tubular

t: Nominal wall thickness of tubular

d = D-2 t Nominal inside diameter of tubular

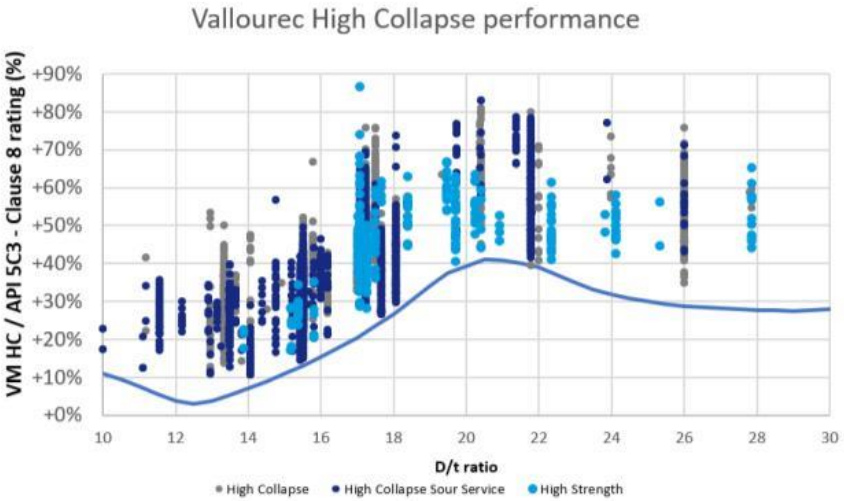


Figure 4: Vallourec High Collapse pipe performances (Source: Vallourec).

4.4 Numerical example

The table below summarizes the gain in collapse performances for two classical pipes sizes used in the Geothermal industry.

Table 1: Collapse ratings of pipes depending on size and material grades (Source: Vallourec).

Size	K55	L80	VM 80HC	VM 110HC
9 5/8 47.00#	3890 psi	4760 psi (+22,30%)	6740 psi (+73.2%)	7570 psi (+94%)
13 3/8 68#	1950 psi	2270 psi (+16.50%)	2980 psi (+52.8%)	2980 psi (+52.8%)

5. WELL DESIGN CONSIDERATIONS

Some industry papers based on case studies have described the challenges faced during the installation and while operating Geothermal wells at elevated temperatures.

It appears that no international standard specifically related to the well design of Geothermal wells operated at very high temperature (above 350°C) is available.

Regarding the casing pipe failure mode, some key additional aspects need to be considered (in addition to classical load cases considered in well design) during the well design phase of the Geothermal wells operated at very high temperature.

As described in the previous section, collapse loads can occur either during the cementation phase or during production phase due to the temperature increase of “trapped water pockets” outside of the production casing. The accurate assessment of the possible level of collapse pressure appears to be complex in some case (using classical well design software such as WellCat® or StressCheck®). In order to avoid the casing collapse, the following strategies / guidelines can be considered:

5.1 For casing sections cemented in the formation

Ensure that the casing collapse rating is higher than the fracture pressure of the formation. Doing so, any trapped water pressure increase would escape in a fracture in the formation rather than inducing casing collapse.

5.2 For casing sections overlapped with surface casing (The load in this case is an APB (Annulus Pressure Build Up)

Ensure either that the burst rating of the outside casing is lower than the collapse rating of the production casing or integrate “sacrificial elements” in the outer casing such as “burst discs” rated at a lower value as the collapse rating of the Production casing.

REFERENCES

Adams, A.J., Moore, P.W. and Payne, M.L. Houston: SPE Drilling & Completion, 2003

American Petrol Institute, 2018. API TECHNICAL REPORT 5C3 - Calculating Performance Properties of Pipe Used as Casing or Tubing.

API SPECIFICATION 5CT TENTH EDITION, JUNE 2018 – Casing and Tubing.

BLADE Advanced Casing Design Course, 2013

Filgueiras, P., Klever, F., Bellani, L., Compare, M., Almeida, G., Ybarra, M.B., Oliveira, J., Zio, E. Calculation of The Collapse Rating of Individual Pipe Joints for OCTG Casing and Tubing. Houston: Offshore Technology Conference, 2022

Kolbrún Ragna Ragnarsdóttir, K.R., Gunnar Gunnarsson, Þráinn Friðriksson, Helen Ósk Haraldsdóttir, Gunnar S. Kaldal, Hieu-Nguyen Hoang, Terence Coudert, Emily Davison, Tomaso Maccio, Axel-Pierre Bois, 2023, Challenges and possible solutions in superhot/supercritical drilling: Planning the IDDP-3 well, Proceedings World Geothermal Congress 2023.

L. Bruce Hill, Ph.D., Chief Geoscientist, 2022, Superhot Rock Energy, A vision for Firm, Global Zero-Carbon Energy, Clean Air Task Force (CATF).

Maria Beatriz Ybarra, Pedro Filgueiras, Guido Kubla, Thimothy Thomas, Daly Daly, Jonathas Oliveira, Performance Baskets: An Alternative Solution to Challenging Collapse Pressures, 2023, OTC-32009-MS, Offshore Technology Conference.

Michal Kruszewski and Volker Wittig, Review of failure modes in supercritical geothermal drilling projects, 2018.

Comprehensive Analysis and Mitigation Strategies for Slim Hole Drilling Challenges in Geothermal Exploration: A Case Study in Cisolok, Indonesia

Geofri W. O. Sairdola[1], Huda Nahrudi Ilham[1], Redha Bhawika Putra[1], Sentanu W. Reksalegora[1], Rizki Davidtri[2], Lano Aditya[3], Dikdik Risdianto[3], and Dudi Hermawan[3]

[1]Arka Data Pratama, Gandaria Utara, Kebayoran Baru, Jakarta Selatan
[2]Lemigas, Cipulir, Jakarta Selatan 12230, Indonesia
[3]PSDMBP, Regol, Kota Bandung, Jawa Barat 40254

geofri.sairdola@arkadata.net

Keywords: geothermal, drilling performance, slim hole well

ABSTRACT

In the current geothermal development in Indonesia, geothermal operators are trying to verify subsurface potentials by drilling new geothermal fields. Drilling a slim hole well is considered a cheaper option than drilling big bore or standard hole wells.

Previous publications on slim hole operations in Indonesia have discussed the benefits of slim hole drilling in theory. However, few geothermal operators in Indonesia have drilled slim-hole wells Indonesia, and there a very few publications discussing the evaluation of the actual operations. This kind of discussion and publication is critical of slim hole drilling knowledge in Indonesia, as it will provide deeper insight into the best practices for drilling the next geothermal slim hole well.

This paper will review the actual operation of geothermal slim hole drilling in the field Cisolok-Cisukarame (CKK) in Java Island. The operations were not able to reach the planned target depth and this paper tries to identify the problems and provide recommendations to avoid the same problems in the next slim hole drilling project.

1. INTRODUCTION

Indonesia possesses a significant potential for geothermal energy, which is recognized as a renewable and sustainable alternative to fossil fuels. To fully exploit this potential, geothermal operators in the country are continuously searching for new ways to explore subsurface potentials through the drilling of new geothermal fields. One method that has been suggested is slim hole drilling, which involves the use of smaller diameter drill bits to reduce drilling costs and time required to reach the desired depth.

In theory, slim hole drilling is a promising option for geothermal operators in Indonesia, as it can lower overall drilling costs and reduce the environmental impact of drilling operations. However, the slim hole does not have the advantages of a big hole and a standard hole. However, few geothermal operators in Indonesia have implemented slim hole drilling, and there is a lack of published evaluations on the actual operations of the method. This paper aims to fill the knowledge gap by providing deeper insights into the actual operations and challenges of slim-hole drilling in Indonesia. The study's findings and recommendations can guide geothermal operators interested in slim-hole drilling, enhancing the efficiency and effectiveness of the drilling process.

The slim hole wells CKK-1 and CKK-1A were drilled as exploration wells. CKK-1 was the first well drilled, but it encountered a stuck pipe problem and only reached a depth of 223 mMD. As a result, the drilling team decided to drill a new well, CKK-1A. But, the CKK-1A also got stuck at 806 mMD and the well was abandoned.

The two wells experienced the same problem, i.e., stuck pipe. However, the pipes stuck in thetwo wells occurred at different depths and hole sections as can be seen in Figure 1.

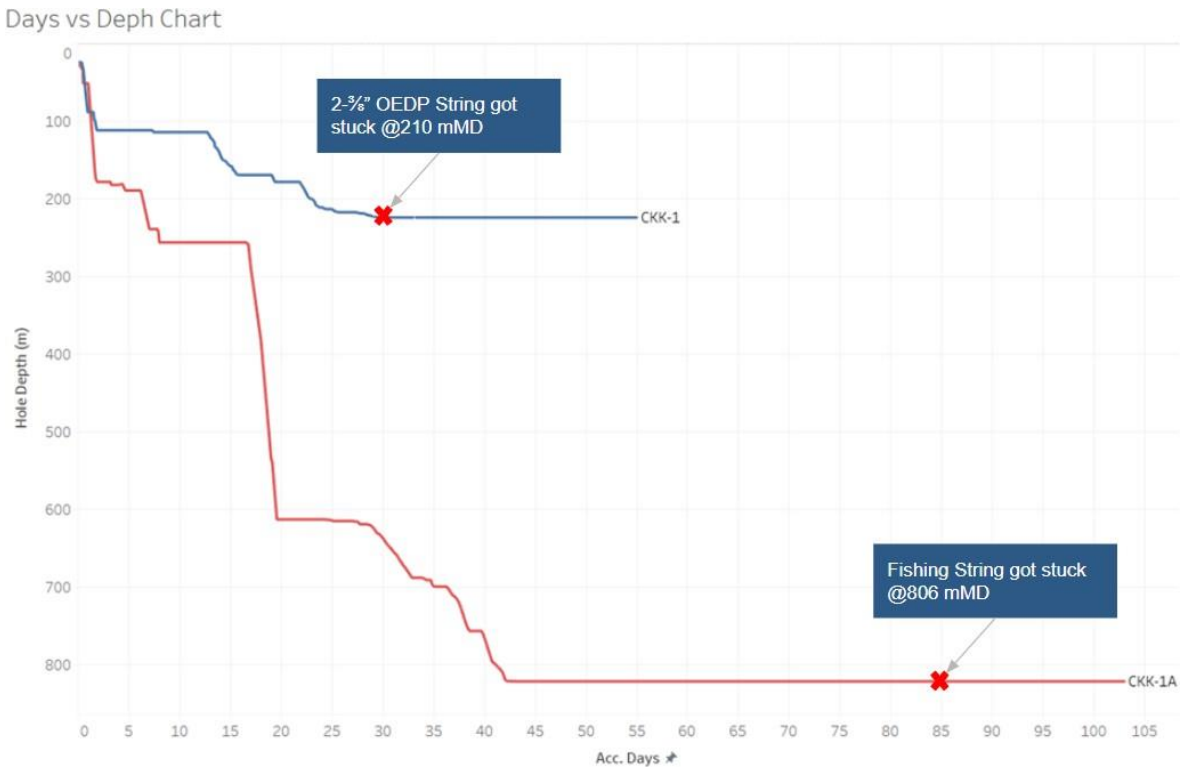


Figure 1: The actual days vs. depth chart of the well CKK-1 (blue line) and CKK-1A (red line).

2. SLIMHOLE DRILLING OPERATIONS

2.1 Definition

According to the Schlumberger Glossary (2023), slimhole drilling is an imprecise term used todescribe a borehole (and associated casing program) that is significantly smaller than a standard approach, typically a wellbore with a diameter of less than 6 inches.

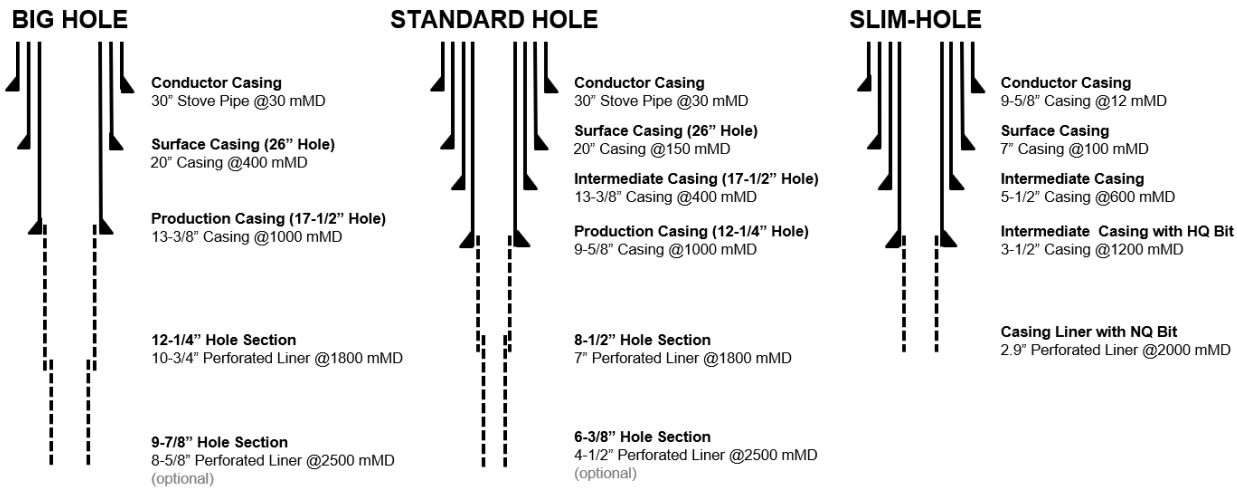


Figure 2: Configuration of common well types used in geothermal exploration drilling in Indonesia modified by Adityatama et al (2020).

2.2 Typical Slim Hole Drilling Depth in the World

In 2022, Sumardi et al. stated that slim hole drilling operations are widely used for exploration programs in Indonesia with drilling depths reaching up to 2000 mMD. Mackenzie et al. (2017) reported that from 45 slim hole projects in 14 countries, slim hole wells can be drilled up to 2300 m (Figure 3). Based on Figure 2, two wells were successfully drilled to a depth of 2000 m, namely slim hole wells in the Oguni (Japan) and Blawan-Ijen (Indonesia) fields. Additionally,two other wells were successfully drilled to reach the reservoir at a depth of approximately 2300 m. These slim hole wells were drilled in the Sarulla and Darajat fields in Indonesia.

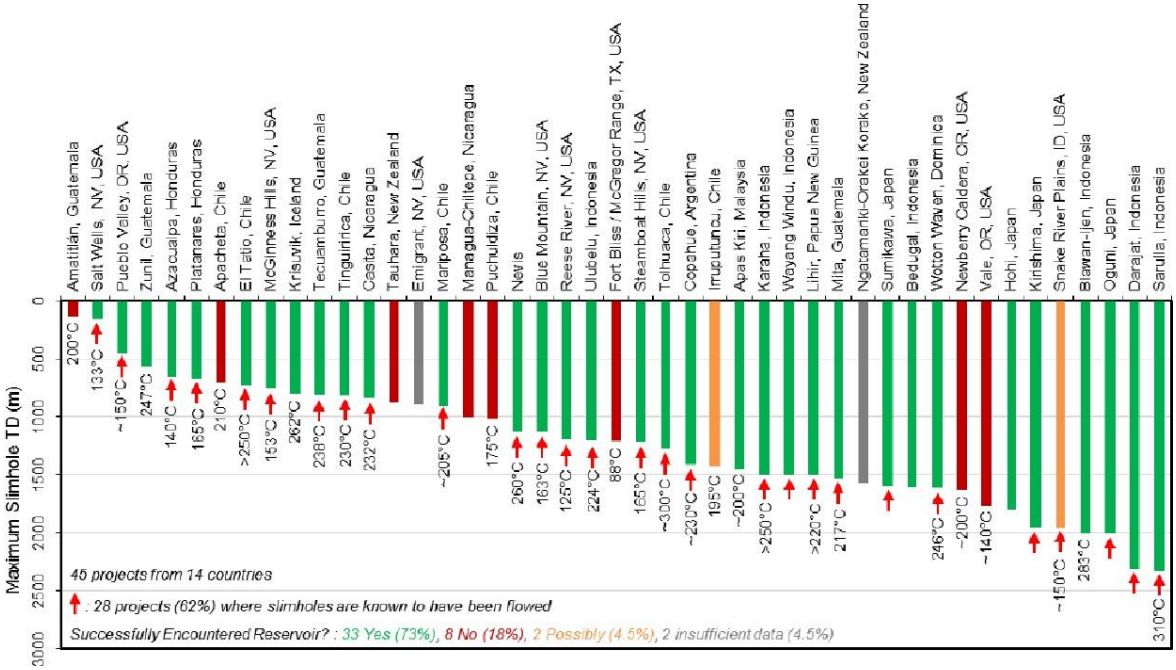


Figure 3: Maximum depth and temperature of slim holes utilized at geothermal projects. (Mackenzie, K.M., et al., 2017).

2.3 Slim Hole Drilling Challenges

Challenges can be found when trying to drill a deep slim hole well approximately from 1500 mMD until 2000 mMD such as the long time consumed (±60-65 days for 1500 mMD). This long time is needed to complete drilling a well due to the low rate of penetrations. Smaller diameter drilling equipment used for the drilling and casing of slim holes increased the risk of formation related to drilling difficulties if compared to big holes and standard holes, which utilize larger and more powerful equipment, and can run a greater number of casing strings to overcome the challenging conditions if these are encountered (White et al., 2010).

3. METHODOLOGY

This paper is divided into three stages: literature study, data processing, and analysis and evaluation of slim hole drilling operations. In the literature study stage, the authors conducted research on previous publications related to slim hole drilling operations and drilling improvement and performance, focusing on non-productive time (NPT).

During the data processing stage, the authors processed the daily report data on the in-house Arka Dashboard to identify and visualize the main factors that caused the slim hole drilling operation on wells CKK-1 and CKK-1A not to reach the target depth. Subsequently, the authors performed an analysis and evaluation of the slim hole drilling problems.

The analysis and evaluation stage involved the development of analytical methods to identify and solve problems related to slim-hole drilling operations. Table 1 displays the problem formulations utilized in this study. The discussion of drilling problems that occurred during the slim hole drilling operation will primarily focus on well CKK-1A since both CKK-1 and CKK-1A wells encountered similar drilling problems, but CKK-1A was drilled deeper. This paper will provide an overview of the two slim hole drilling operations and conduct a detailed investigation of well CKK-1A.

Table 1: Problem Formulation Methods.

No	Problem Formulation	Objective	Method
1	What are the planning and actual slim hole drilling in the wells CKK-1 and CKK-1A?	Knowing the actual vs plan on the wells CKK-1and CKK-1A	Perform analysis on the drilling program, final report, and dailyreport
2.	What problems caused to not reaching the target depth of well CKK-1A?	Determine the main factors that cause not reaching the target depth ofwell CKK-1A	Analyze the chronology to know the main cause of well CKK-1A not reaching target depth
3.	How to mitigate the main problems in slim hole drilling operations in the well CKK-1A?	Providing lessons learned to minimize the same problems in future slim hole drilling	Based on direct experience in other fields in providing alternative solutions to the problems discussed

4. OVERVIEW OF TWO ACTUAL SLIM HOLE OPERATIONS

4.1 Overview of the Well CKK-1

Drilling for well CKK-1 was planned to reach a depth of 2000 mMD. However, during the drilling process, the well could only reach a depth of 223 mMD, as seen in Table 2. This was due to the stuck pipe problem that occurred at a depth of 210 mMD, which ultimately caused the well to be abandoned. On day 30, to overcome the total loss circulation (TLC) problem, 2-3/8” OEDP + 3-1/2” DP was inserted into a 222 mMD to perform cement plug #3. Unfortunately, the drill string was stuck at a depth of 210 mMD (Figure 4) while pulling out of the hole (POOH) after completing the third cement plug operation.

Apart from the stuck pipe problem, there were other non-productive time (NPT) drilling problems encountered in well CKK-1. Figure 5 shows that these problems include rig repair, waiting on equipment, loss of circulation, coring, plug and abandonment, and tripping, and hole cleaning. The biggest NPT problem at CKK-1 was the rig's repair, which took 413 hours. This issue occurred due to several problems with the drilling equipment, resulting in delays in drilling operations.

Several attempts were made to free the stuck pipe using a top drive system and rock cranes, but all efforts were unsuccessful. Finally, it was decided to perform a back-off string to release a 2-3/8” OEDP of 9 joints and a 3-1/2” drill pipe. The fish left in the hole were 2-3/8” drill pipes with a length of 103.67 mMD, and the top of the fish was at a depth of 105.39 mMD.

Fishing operations were carried out to retrieve the fish left in the drilled hole. The 2-7/8” + 2- 3/8” OEDP was inserted from the surface to the top of the fish, and it was successfully carried out with an indication of rising torque and getting overpull when the drill string was lifted. However, attempts to lift the string out of the borehole were unsuccessful. Efforts to free the stuck pipe continued to be carried out by lifting and lowering the string while turning to the right without success. The string was lifted again with 2400 psi hydraulic pressure and gradually increased to 3000 psi, but there was a reverse rotation of the pipe, and the top drive could not hold the pipe rotation. Therefore, it was decided to back off the strings and pull out to the surface. After that, preparations were made for rig down.

Table 2: Plan vs. Actual Slim Hole Operations of CKK-1.

Description	Plan	Actual
Location	Java Island	Java Island
Well Name	CKK-1	CKK-1
Drilling Rig	Hydraulic Rig 440 HP	Hydraulic Rig 440 HP
Classification	Exploration Well	Exploration Well
Drilling Type	Slim Hole	Slim Hole
Last Depth	2000 mMD	223.8 mMD
Total Days	78	55 (plug and abandoned)
Hole Data:		
Piling Casing 9-5/8”	22 mMD	24 mMD
8-1/2” Hole Section	100 mMD	111.5 mMD
5-1/2” Hole Section	600 mMD	223.8 mMD (stuck pipe)
3-7/8” Hole Section (HQ)	1200 mMD	-
2.98” Hole Section (NQ)	2000 mMD	-

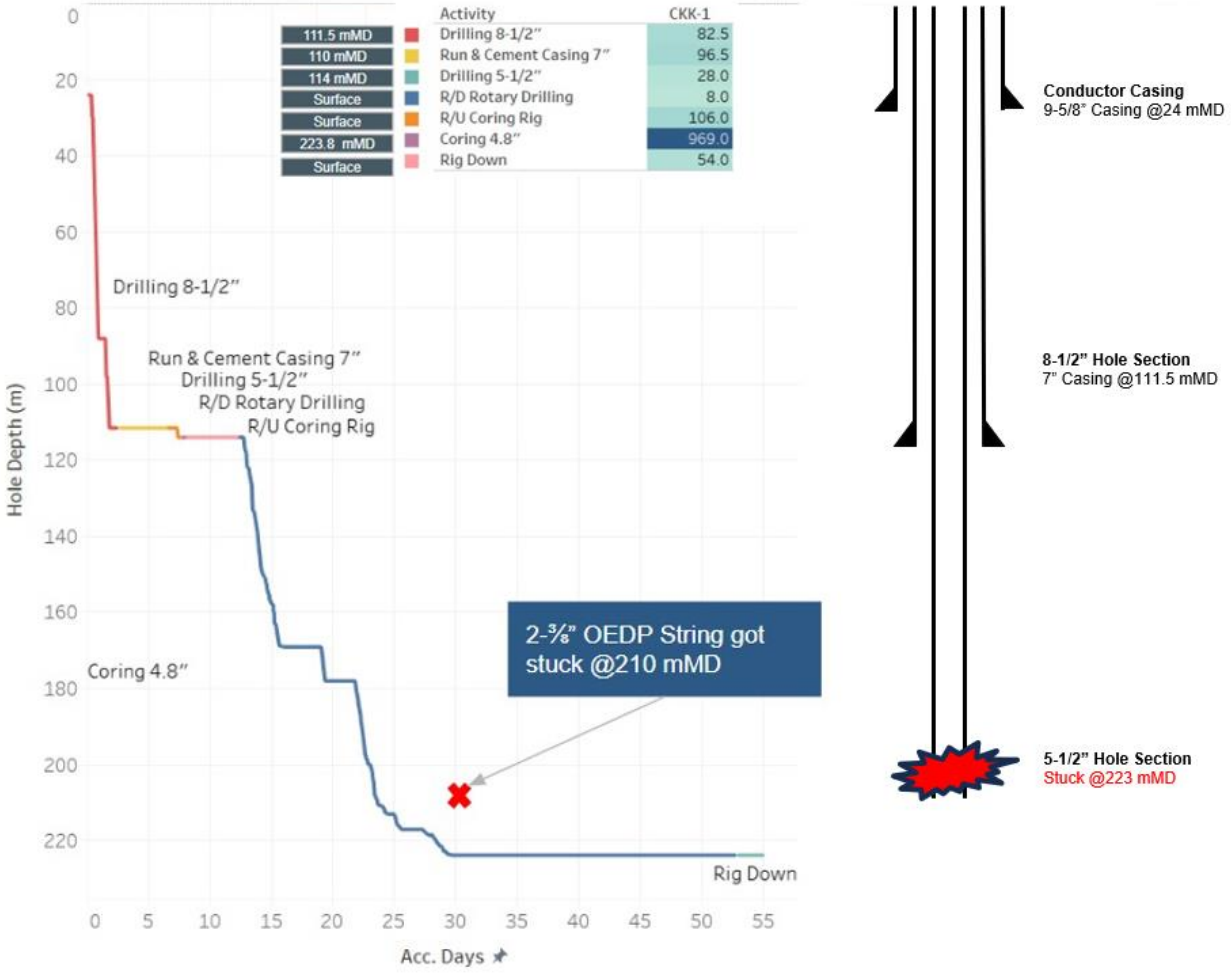


Figure 4: Days Vs Depth Chart of the Well CKK-1.

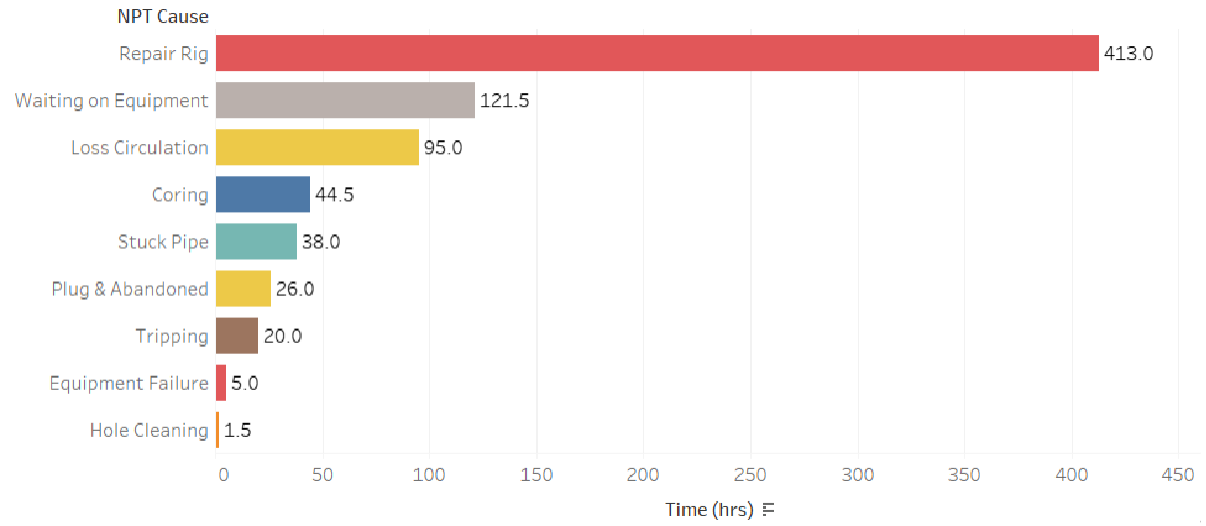


Figure 5: NPT Factors in the Well CKK-1.

4.2 Overview of the Well CKK-1A

The well CKK-1A was drilled after abandoning CKK-1. Based on its purpose, this well utilized the slim hole drilling method with a target depth of 2000 mMD, as shown in Table 3.

The actual slim hole drilling operation took approximately 105 days, but the well only reacheda depth of 821 mMD. Ultimately, the well was abandoned due to a stuck pipe problem at a depth of approximately 806 mMD (Figure 6). The stuck pipe occurred during a fishing operation to retrieve the coring outer tube that had fallen into the drill hole. Additionally, several other problems arose, leading to an increase in non-productive time for the well. An analysis of NPT will be conducted to determine the factors contributing to this increase.

Table 3: Plan vs. Actual Slim Hole Operations of the Well CKK-1A.

Description	Plan	Actual
Location	Java Island	Java Island
Well Name	CKK-1A	CKK-1A
Drilling Rig	Hydraulic Rig 440 HP	Hydraulic Rig 440 HP
Classification	Exploration Well	Exploration Well
Drilling Type	Slim Hole	Slim Hole
Last Depth	2000 mMD	821 mMD
Total Days	76	105 (plug and abandoned)
Hole Data:		
Piling Casing 9-5/8”	20 mMD	28.7 mMD
8-1/2” Hole Section	250 mMD	256 mMD
6-1/8” Hole Section	600 mMD	613 mMD
3-7/8” Hole Section (HQ)	1200 mMD	821 mMD (stuck pipe)
2.98” Hole Section (NQ)	2000 mMD	-

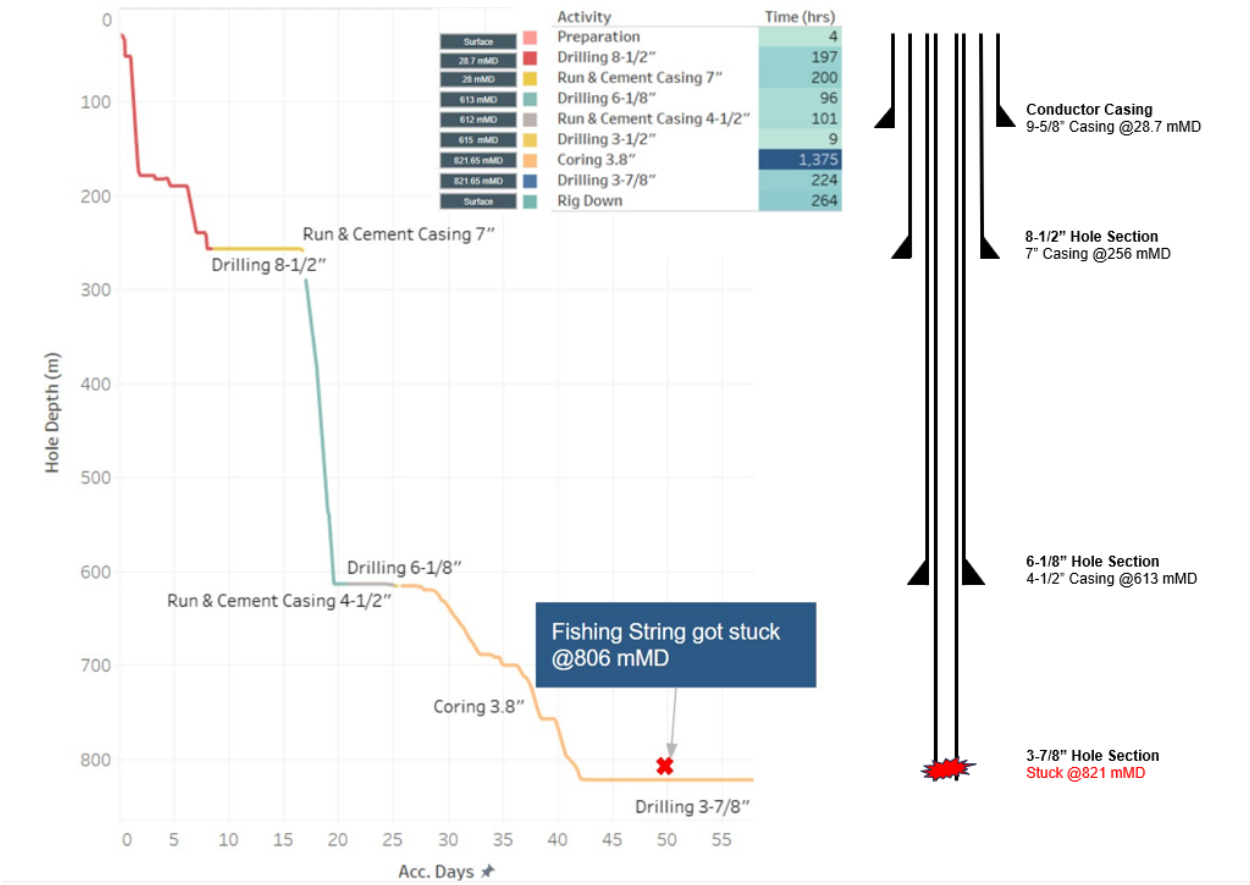


Figure 6: Days Vs Depth Chart of the Well CKK-1A.

5. INVESTIGATIONS OF SLIM HOLE DRILLING PROBLEMS IN WELL CKK-1A

The investigation of the slim hole drilling problems that occurred in the well CKK-1A is divided into two categories of problems: drilling problems which are categorized as NPT and drilling problems which are not categorized as NPT i.e., stuck pipe problems in the well CKK-1A. The first discussion will be aimed at stuck pipe investigations and the second discussion will focus on problems that are categorized as NPT.

5.1 Stuck Pipe Investigations

As mentioned in the previous section, the well CKK-1A was abandoned due to a stuck pipe problem that could not be released from the hole. Therefore, further investigations were carriedout into the problems that caused the drilling not to reach the target depth in this well.

Stuck pipe chronology

When the coring bit reached a depth of 821 mMD, the condition of the wellbore was not very good, as the walls of the formation hole continued to collapse. This was caused by the altered tuff formation located at that depth, which was not compact and easily collapsed, according tothe wellsite geologist's data (Table 4). The collapse of the drill hole was evident from the tag, which always went up every time the string was inserted into the drill hole.

A reaming operation was then carried out when the coring of the formation could not go furtherto penetrate the last depth at 821 mMD. This operation was carried out in stages, and the first stage took about a week, but the string tags remained at the same depth. Thus, it was decidedto clean out the hole using 3–7/8" PDC bits, aimed at cleaning out the rubble of the formationin the hole. After cleaning out the hole, cement plug jobs had to be performed seven times to stabilize and strengthen the wellbore. The details of the cement plug jobs are as follows:

- Cement plug job #1
  A cement slurry with a density of 15.8 ppg and 1.8 bbl was mixed and pumped. The top of cement (TOC) was calculated, and it showed that the TOC would be 782 mMD. However, the actual TOC was at 776 mMD, which might indicate that the bottom of the cement was not in the bottom hole at 821.65 mMD.

- Cement plug job #2
  Cement plug job #2 was conducted due to hard reaming and lost circulation issues. But before that, the 3-7/8" bit was run into the hole to clean out the cuttings. After that, a cement slurry of 15.8 ppg and 3 bbls was pumped through the drill pipe, followed by waiting on cement. The string was run in the hole and tagged TOC at 767.55 mMD. Based on the calculations, 2.57 bbls of cement were lost in the hole.

- Cement plug job #3
  three barrels of cement slurry with a density of 13.3 ppg was pumped into the borehole. After waiting on cement, the string was run into the hole and tagged TOC at 767 mMD, which remained the same as the previous cement plug job. This indicated that 3 bbls were lost in the hole.

- Cement plug job #4
  The density of the cement slurry was increased to 15.8 ppg, and 2% fracseal medium was added to the 10 bbls of cement slurry. Based on the calculation results, the TOC should be at 312 mMD, but the actual TOC showed a different depth at 758 mMD. It was only an increase of 9 m from the previous TOC.

- Cement plug job #5
  Eight barrels of cement slurry were pumped into the borehole, and it still showed a different TOC from what we had calculated. The actual TOC was at 637 mMD, which was different from the calculated TOC at 492 mMD, indicating an increase of 121 m from the previous TOC. However, we still lost 6 bbls of cement in the hole.

- Cement plug job #6
  The string was pulled out to 583, and we conducted cement plug job #6 with 15.8 ppg +4 ppb fracseal coarse 2 bbls. Again, the top of the cement remained at the same TOC as the previous cement plug job. The cement plug was drilled to 795 mMD, and always spotted LCM to cure losses. The string was pulled out to 602 mMD and run back in the hole (RBIH) to 791 mMD. We decided to conduct cement plug job #7.

- Cement plug job #7
  Cement plugs #7 were finally conducted, and the actual TOC was at 795 mMD, indicating that 1.8 bbls were lost in the hole.

However, these cement plug jobs were considered unsuccessful because the cement could notstrengthen the wellbore that had collapsed to the bottom. So, it was decided to continue the operation with the coring job.

The coring operation was carried out with the final condition of the well being cemented. So, we proceeded with coring cement until it was finished. This coring operation succeeded in penetrating the formation ruins to a depth of 820 mMD. At that depth, there was no additionaldepth, based on the absence of recorded ROP parameters. It was then decided to pull the stringout from the hole up to the surface. The condition of the string indicated that there were fish left in the drilled hole, i.e., the inner tube, outer tube, reamer, and bit. The next step was to carry out the #1 fishing job to retrieve the fish left in the hole.

#1 Fishing operations were also carried out and succeeded in lifting the inner tube out of the drill hole. Then #2 fishing jobs were conducted to fish the outer tube, reamer, and bit that werestill left in the hole. When fishing attempts were made, the fishing BHA got stuck at a depth of

±806 mMD. Efforts to free the stuck pipe were made but failed the string pulled with high tension then caused the string to break. This resulted in a ±350 m length of fish with the top ofthe fish at 456 mMD. The fishing job was then conducted to lift the stuck string, but it still failed. This was also caused by the limitation of fishing tools. Finally, the well was abandoned,and the rig was released.

Table 4: Lost circulation depth in section 3-7/8" well CKK-1A.

3-7/8 HS	Lithology	Depth, mMD	Problem Events
	Altered Andesite Breccia	673.8	TLC @628-634 mMD
	Altered Dacite	682.1	
	Altered Andesite Breccia	699.5	
	Altered Tuff Breccia	682	PLC, 0.2-0.4 bpm
	Altered Tuff	753.5	
	Altered Tuff Breccia	762.5	TLC
	Altered Andesite Breccia	768.5	TLC
	Altered Andesite	775.1	
	Altered Tuff Breccia	794.3	
	Altered Tuff	803.6	TLC
	Altered Tuff Breccia	804.3	TLC
	Altered Tuff	806.6	TLC
	Altered Tuff Breccia	808.1	TLC
	Altered Tuff	809.6	TLC
	Altered Tuff Breccia	820.2	TLC
	Altered Tuff	821	TLC

5.2 Non-Productive Time Analysis

In this section, an analysis is conducted to find out what problems are causing the non-productive time in the well CKK-1A. The analysis will be carried out to find out the top activities that have the largest NPT. When drilling well CKK-1A, there are several problems occurred and delayed the drilling operation. As shown in Figure 7 below, there are two biggest NPT in well CKK-1A which are repair rig, inner tube stuck, waiting on water supply, waiting on equipment, loss circulation, trips, monitoring well, and equipment failure.

The repair rig is the top one of the non-productive time in CKK-1A. This problem often causes drilling operations to be stopped for a moment to make repairs to the rig equipment that is experiencing disturbances. Most of the problems are due to damage to the drilling rig system that requires repair.

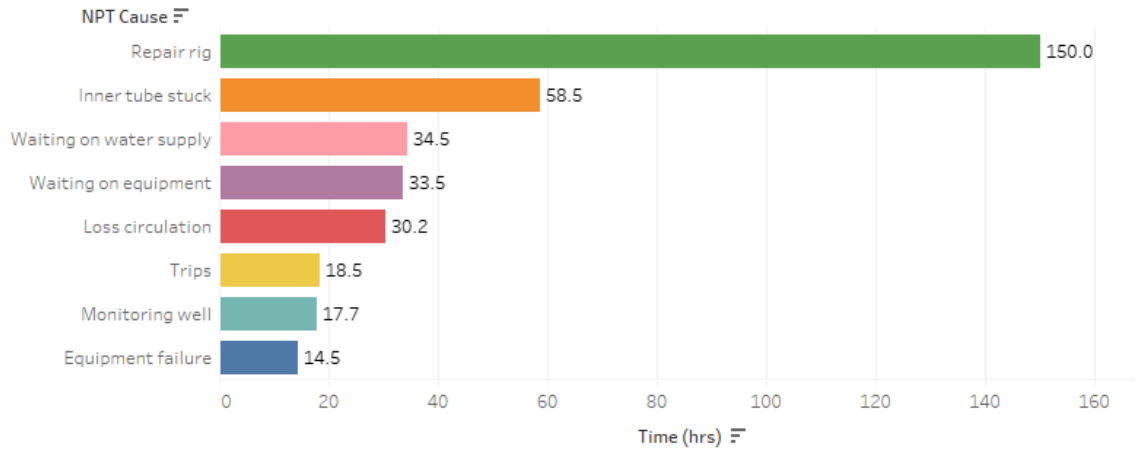


Figure 7: NPT factors in the well CKK-1A.

6. LESSON LEARNED

6.1 Repair rig

The inhibiting factor for rig operations is damage to the main equipment such as prime mover equipment, lifting equipment, rotary equipment, blowout prevention equipment, and circulation equipment. As was the case with the well CKK-1A where there were several problems with the rig equipment. Most of the problems that are categorized as repair rigs are repairing the top drive system tools.

This repair rig will result in a long waiting time due to repairs to the damaged rig equipment until the tool can be used again. An alternative solution that can be offered in resolving or avoiding the inhibiting factors for this rig's operations is to provide enough equipment spare parts so that when there is equipment damage, it can be replaced with available spare parts while the damaged equipment can be repaired without causing sufficient waiting time. In addition, this equipment must continue to be checked for quality and continue to be evaluatedperiodically. Maintenance of the rig equipment must also be carried out continuously, especially for equipment that has been used for a long time.

The main challenge in fulfilling this solution is related to the relatively large costs incurred toprovide sufficient equipment spare parts and the costs related to rig maintenance which are quite expensive. Therefore, a large investment is also needed to deal with this problem becauseit most commonly occurs when rigs are operating in the field.

6.2 Wellbore Instability

Wellbore instability is a critical factor to consider, particularly in the case of well CKK-1A. The collapse of the wellbore wall can cause the pipe to get stuck in the well, making it essential to have a mitigation plan for this problem. To address the issue of wellbore instability, a thorough analysis of the geological and geo-mechanical characteristics of the formation must be carried out. The drilling parameters, especially those related to drilling fluid, which supports the wellbore wall and prevents it from collapsing and falling into the hole, must also be evaluated. Using polyamine is an option to consider. According to Redha et al. (2022), adding polyamine to the mud system enhances the inhibition property and improves wellbore stability.

To drill through the collapse formation safely, further studies are required, even though this is an exploration well. It is important to carefully consider the borehole and selectthe proper casing point, as well as assess the potential for reactive or problematic formation. Ifwe come across such a formation that can't be controlled, it is recommended to set the casing at an earlier stage and drill with a smaller diameter. By taking these measures, we can ensure the safety of the drilling operation and minimize the potential for any unexpected incidents.

If the well still getting stuck like in CKK-1A during the #1 fishing job. These strategies can be used. In this well, the fishing BHA got stuck and needed to be pulled with high tension to release the pipe. As a result, the string twisted, and 350 meters of pipe were left in the hole. Apart from pulling with high tension, there are other alternatives for pipe recovery, such as using RCT or explosives. These methods can recover the pipe with a determined depth of cut,making it possible to recover more pipe.

7. CONCLUSION

This study was conducted to review the drilling process of two slim hole wells on Cisolok-Cisukarame, Java Island, to provide lessons learned to improve future slim hole drilling. The wells were not drilled successfully to their planned total depth and CKK-1 and CKK-1A became stuck and had to be abandoned.

Further studies are required to mitigate and prevent future stuck pipe incidents. Several strategies can be employed, such as selecting proper casing points and setting casing to cover problematic formations, then continuing drilling with a smaller hole size. If the pipe still gets stuck, it is recommended to have a plan for pipe recovery to salvage more of the bottomhole assembly (BHA).

REFERENCES

Finger, J., & Jacobson, R. (2000). Slimhole Drilling, Logging, And Completion Technology- An Update. *Proceedings*, World Geothermal Congress 2000.

Jacobson Cha, T., Laboratories, J. A., Polk, G., & Goransa, C. (1999). Slimhole Handbook: Procedures and Recommendations for Slimhole Drilling and Testing in Geothermal Exploration.

Mackenzie, K. M., Ussher, G. N. H., Libbey, R. B., Quinlivan, P. F., Dacanay, J. U., & Jacobs, I. B. (2017). Use Of Deep Slimhole Drilling for Geothermal Exploration. *Proceedings,* The 5th Indonesia International Geothermal Convention & Exhibition.

Mackenzie, K., Ussher, G., & Quinlivan, P. (n.d.). Applications of Slimholes for Geothermal Exploration.

Ng'ang', S. I. (2018). Wellbore Stability-Principles and Analysis in Geothermal Well Drilling.

Schlumberger Glossary. (2023).Slimhole Well.

Sumardi, J. A., Wigati, T. S., Sumardi, J. A., Rizqi, M., Asy'ari, A. L., Pinandito, F. S., Adityatama, D. W., & Purba, D. (2022). Summary of Geothermal Slimhole DrillingOperation in the Last 10 Years: Lessons Learned for Geothermal Exploration in Indonesia. *Proceedings,* 47th Workshop on Geothermal Reservoir Engineering.

Wigati, T. S., Sumardi, J. A., Wilhelmus Adityatama, D., Rizqi, M., Asy'ari, A.L., Pinandito, F. S., & Purba, D. (2022). Slimhole Drilling Design and Operation in Indonesia: What Can We Learn? *Proceedings,* 47th Workshop on Geothermal Reservoir Engineering.

Development of A Coupled Wellbore-Reservoir Simulator

Ryan Tonkin, Michael Gravatt, Theo Renaud,
Rony Nugraha, John O'Sullivan, and Michael O'Sullivan

Department of Engineering Science, University of Auckland, Auckland, New Zealand

ryan.tonkin@auckland.ac.nz

Keywords: Wellbore, reservoir, coupling, AUTOUGH2, loose-lagged

ABSTRACT

Simulation of transient flow in geothermal wells is an important reservoir engineering task. Previously, we discussed the development of a wellbore simulator capable of modelling complex transient flows of water and non-condensable gases in geothermal wells. However, this simulator used productivity models to represent the reservoir. While this representation is simple to implement and quick to run, it cannot capture changes in reservoir conditions that result due to wellbore flow.

A wellbore model must be coupled to a reservoir model to represent changes in the conditions of the fluid flowing into a well. This paper discusses coupling our existing simulator to the numerical reservoir simulator AUTOUGH2. The wellbore model is coupled to the reservoir model using a loose-lagged method. We demonstrate the capability of the simulator to represent flow in both the well and reservoir using a simple two-phase production test case.

1. INTRODUCTION

Transient wellbore simulators are of interest to the geothermal community as they are used to gain insight into phenomena that are hard to observe. Flow within geothermal wells is strongly affected by reservoir conditions. Additionally, conditions in the reservoir will change due to production (or injection) through wells. Therefore, coupled simulations, in which the wellbore and reservoir are represented numerically, are required to accurately simulate some processes. For example, coupled simulations are required to accurately model completion testing procedures (heat-up, injection and production testing) and discharge stimulation methods (air-injection, gas-lifting and well-to-well stimulation).

The following four categories, ordered in terms of increasing complexity, can be used to broadly classify different methods of coupling numerical simulators.

Indirect coupling involves running wellbore (or reservoir) simulations for a wide range of scenarios before the main simulation work. Murray and Gunn (1993) presented simulations using an indirect coupling between the reservoir simulator TETRAD and the wellbore simulator WELLSIM (Hadgu and Freeston, 1990). In this work, wellbore simulations were run for different inflow conditions to generate a table relating mass flow rate, enthalpy and bottomhole pressure. This table was used in reservoir simulations to estimate the mass flow from a reservoir block given its pressure and enthalpy. Rivera Ayala (2010) applied a similar approach when coupling the wellbore simulator HOLA (Bjornsson, 1987) to the TOUGH2 reservoir simulator (Pruess et al., 1999).

In **explicit coupling**, the wellbore and reservoir are treated as different domains, which are solved using different numerical simulators. Information is exchanged between the reservoir and wellbore models at user-defined timesteps. Hadgu et al. (1995) presented an explicit coupling between the TOUGH reservoir simulator (Pruess, 1987) and the steady-state wellbore simulator WFSA (the predecessor of WELLSIM) (Hadgu and Freeston, 1990). Bhat et al. (2005) used a similar method to couple the TOUGH2 reservoir simulator with the steady-state wellbore simulator, HOLA.

Semi-implicit coupling methods also treat the well and reservoir as separate computational domains that are solved using different numerical simulators. However, unlike explicit coupling, information is

passed between the simulator multiple times for a single timestep to converge a shared flow parameter iteratively.

A **fully-implicit coupling** of the wellbore and reservoir involves treating the wellbore and reservoir as a single computational domain, meaning the conservation equations describing mass, momentum and energy transfer in both the well and the reservoir are solved simultaneously for each time step. Fully implicit couplings between the wellbore and reservoir have been presented by Pan et al. (2011) and Korzani et al. (2019).

Recently, we developed a simulator capable of modelling complex flows of water and non-condensable gases (e.g. air and CO_2) in geothermal wells with multiple feed-zones (Tonkin, 2022; Tonkin et al., 2023a). Test cases modelled with our simulator include discharge stimulation using air-lifting and air-injection, counter-flow processes (gas flows up the well while liquid flow down), rapid processes during the start-up and shut-in of wells, and CO_2 re-injection (Tonkin et al., 2023b). This body of work focused on developing a robust numerical simulator that could model a wide range of complex wellbore processes.

In this paper, we discuss the coupling of the reservoir simulator AUTOUGH2 with our in-house wellbore simulator using an explicit coupling method and present an example of coupled wellbore-reservoir simulation. Sections 2 and 3 will briefly outline the numerical wellbore and reservoir models. Section 4 will explain the coupling methodology. Finally, Section 5 will discuss the results of a coupled simulation of a two-phase production scenario.

2. GEOTHERMAL WELLBORE MODEL

This investigation of coupled wellbore-reservoir flow makes use of our in-house transient wellbore simulator, the development of which is discussed in detail elsewhere (Tonkin, 2022; Tonkin et al., 2023a). Section 2.1 below briefly discusses the governing conservation equations and highlights the terms used to couple the reservoir simulator to the wellbore. Section 2.2 outlines the model setup of the wellbore used in this investigation.

2.1 Governing Equations

Transient flow in geothermal wells is modelled by considering the conservation of mass, momentum and energy. The conservation of mass equation is:

$$\frac{\partial}{\partial t}[\rho_l S_l + \rho_v S_v] + \frac{1}{A}\frac{\partial}{\partial s}[A\rho_l S_l u_l + A\rho_v S_v u_v] - q_{mass} = 0. \quad (1)$$

Here, ρ_l and ρ_v are the densities of the liquid and vapour phases. The saturation and velocity of phase β are given by S_β and u_β, respectively. Mass exchange with the reservoir is modelled using q_{mass}.

The conservation of momentum for a two-phase mixture is:

$$\frac{\partial}{\partial t}[\rho_l S_l u_l + \rho_v S_v u_v] + \frac{1}{A}\frac{\partial}{\partial s}\left[A\rho_l S_l u_l^2 + A\rho_v S_v u_v^2\right] + \frac{\partial P}{\partial s} + \frac{2}{r}\tau + (\rho_l S_l + \rho_v S_v) g \frac{\partial z}{\partial s} - q_{mom} = 0. \quad (2)$$

Here, P is pressure, g is gravitational acceleration (equal to 9.81 m/s^2), z is vertical depth, and s is the distance along the wellbore. Wellbore friction, τ, is defined by a constitutive model discussed elsewhere (Tonkin, 2022). We assume that fluid from a feed enters the well perpendicular to the flow direction as was done by Bendiksen et al. (1991). This means the in-flowing fluid does not add momentum to the well, and q_{mom} is zero.

The conservation of energy for a two-phase mixture is:

$$\frac{\partial}{\partial t}\left[\rho_l S_l\left(h_l+\frac{u_l^2}{2}\right)+\rho_v S_v\left(h_v+\frac{u_v^2}{2}\right)-P\right] + \frac{1}{A}\frac{\partial}{\partial s}\left[A\rho_l S_l u_l\left(h_l+\frac{u_l^2}{2}\right)+A\rho_v S_v u_v\left(h_v+\frac{u_v^2}{2}\right)\right] + (\rho_l S_l u_l+\rho_v S_v u_v) g\frac{\partial z}{\partial s}+q_{heat}-q_{ener}=0. \quad (3)$$

Here, h_l and h_v are the enthalpies of the liquid and vapour phases. Finally, q_{heat} models heat transfer between the wellbore and the surrounding reservoir and q_{ener} models energy transfer due to fluid exchange with the reservoir.

Sources and sinks of mass and energy in the well are modelled in (1) and (3) using the terms q_{mass} and q_{ener}. In our previous work, we have approximated these terms using simple deliverability models, such as:

$$q_{mass}=\frac{1}{A}\left(\frac{k_{rl}\rho_l}{\mu_l}+\frac{k_{rv}\rho_v}{\mu_v}\right)\left(\frac{\mathrm{PI}}{h}\right)\left(P_{feed}-P_{wb}\right), \quad (4)$$

and

$$q_{ener}=q_{mass}h_{f_{feed}} \quad (5)$$

for sources of mass and energy. In (4), $k_{r\beta}$, ρ_β and μ_β are the relative permeability, density and dynamic viscosity of phase β. The feed is described by its pressure, P_{feed}, productivity index, PI, and thickness h. Finally, A is the wellbore cross-sectional area and P_{wb} is the pressure in the well at the depth of the feed. In (5), q_{mass} is given in (4), and $h_{f_{feed}}$ is the flowing enthalpy of the feed.

In (4) and (5), the mass and energy exchange between the well and reservoir is proportional to the difference in pressure between the well and the reservoir at the elevation of the feed. Modelling sources in this way allows the flow within the well to vary based on changes that occur within the well. However, it does not consider the change in pressure and enthalpy within the reservoir resulting from production (or injection) through the well.

In this work, we couple our wellbore simulator to the AUTOUGH2 reservoir model to estimate q_{mass} and $h_{f_{feed}}$. The coupling procedure is discussed further in Section 4 below.

2.1 Numerical Model Setup

The simulations presented in this work use a 1000 m vertical well with a constant production diameter of 0.2 m. Additional simulation parameters are given in Table 1, and the well is shown diagrammatically in Figure 3.

The test case presented in this work, discussed in Section 5, simulates the opening of a wellbore to flow and the resulting production from the reservoir. Flow in the well is controlled using the wellhead pressure boundary condition. The wellhead pressure begins at 14 bara and is dropped to atmospheric conditions (1.01325 bara) to induce flow. The well is initialized as a static column of fluid with a linearly increasing temperature from 25 and 200 °C and a linearly increasing pressure from 14 bara to 100 bara between 0 mRL and -1000 mRL. These initial conditions are shown by the dashed profiles in Figure 5.

The well is connected to a single feed-zone between -990 and -1000 mRL. The feed is modelled using a single layer reservoir model discussed in Section 3.1 below.

Table 1: Wellbore parameters for simulations.

Wellhead elevation	0 mRL
Length	1000 m
Inclination	0°
Diameter	0.2 m
Completion diameter	0.3 m
Discretization	Uniform, 100 elements
Heat flux model	Analytical: Ramey (1962)
Slip model	Drift-flux model by Shi et al. (2005)
Overall heat transfer coefficient	35 W/m^2/K
Feed-zone	AUTOUGH2 reservoir model
Pipe roughness	9 E-05 m
Wellhead boundary	Transient pressure condition
Bottomhole boundary	Closed
Formation temperature	Linear from 25 – 200 °C between 0 – -1000 mRL

3. GEOTHERMAL RESERVOIR MODEL

Flow within the reservoir is simulated using AUTOUGH2, the University of Auckland's version of TOUGH2 (Yeh et al., 2012). The parameters for the reservoir model used in this investigation are discussed in Section 3.1 below.

Numerical Model Setup

This investigation uses a simple single layer, radially symmetric model shown diagrammatically in Figure 1. The reservoir has a radius of 1000 m and a thickness of 10 m. The reservoir model consists of 22 blocks, which increase in size by a factor of 1.5 for each block starting at 0.1 m. Constant pressure and temperature (or saturation) conditions are specified at both reservoir boundaries. The furthest block of the wedge represents the far-field reservoir conditions beyond 1000 m. These conditions remain constant throughout the simulation. The far-field conditions in this test problem correspond to liquid water at 100 bara and 250 °C. The boundary condition applied to the inner-most block represents the conditions within the well at the elevation of the feed. These are updated at the start of every reservoir timestep using the coupling procedure described in Section 4 below. In AUTOUGH2, constant boundary conditions are specified by setting the volume of a block as an arbitrarily high value, in this case, 1×10^{50} m^3. The reservoir is initialized as single-phase water at 100 bara and 250 °C.

The reservoir permeability is 1×10^{-13} m^2, density is 2600 kg/m^3, porosity is 0.1, thermal conductivity (wet) is 1.5 W/m/°C, and the specific heat capacity is 900 J/kg/°C.

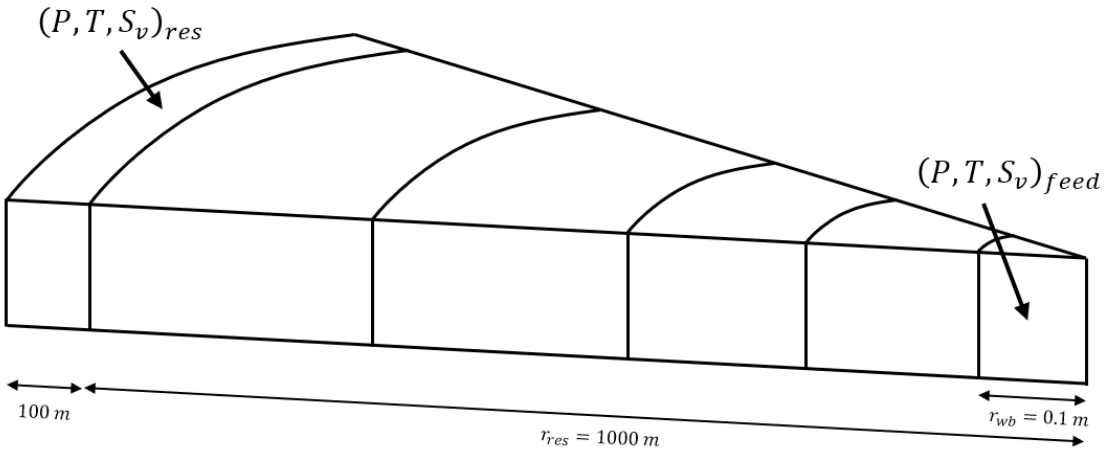


Figure 5: Diagrammatic representation of the numerical grid for the reservoir used in this investigation. The blocks on either end of the reservoir model have constant thermodynamic conditions. These blocks represent the far field reservoir conditions (constant for the entire simulation) and the conditions in the well at the feed (constant for a timestep).

4. LOOSE-LAGGED WELLBORE-RESERVOIR COUPLING

This work implements an explicit coupling method commonly called *loose-lagged* coupling. The method is *loose* because the wellbore and reservoir simulators only exchange information once during a timestep and is *lagged* because the wellbore model solves for timestep *n+1* using reservoir information from timestep *n*.

Explicit coupling methods have multiple advantages over more tightly coupled methods. Specifically, explicit coupling methods are typically easier to implement, less expensive computationally, more flexible and require less complex meshing than tightly coupled methods. The modular nature of explicit coupling means that different wellbore or reservoir simulators can be used with minimal modification to their code. Additionally, poor numerical performance (e.g., slow or failed convergence of the residual equations), which is commonplace in both wellbore and reservoir simulation, is easier to identify and manage when the two systems are solved separately rather than as a single fully-coupled system.

The loose-lagged coupling procedure for a generic time step *n+1* is as follows:

1. Solve wellbore model for timestep *n+1* using reservoir information $\left(Q_m, h_{fm}\right)_{feed}^{res}$ from timestep *n*
2. Pass $(P, T, S_v)_{feed}^{well}$ to reservoir and specify as constant boundary conditions in the inner-most block of the reservoir model
3. Solve reservoir model for timestep *n+1* using the wellbore information $(P, T, S_v)_{feed}^{well}$ from timestep *n+1*
4. Pass $\left(Q_m, h_{fm}\right)_{feed}^{res}$ to the wellbore solver and specify as a constant mass and energy source (q_{mass} and q_{ener})
5. Solve the wellbore model for timestep *n+2* using reservoir information $\left(Q_m, h_{fm}\right)_{feed}^{res}$ from timestep *n+1*
6. Repeat from (2) for timestep *n+2*

This coupling procedure is represented with a flow diagram in Figure 2 below. In Figure 2, W_n indicated the solution to a wellbore simulation at timestep *n* and R_n represents the solution to a reservoir

simulation at timestep n. The arrows represent the progression of the coupled simulation where the numeric labels correspond to the steps outlined above. Figure 3 shows a diagrammatic representation of the coupling of the two numerical models. In Figure 3, the information that is passed between the wellbore and reservoir simulators is highlighted in red.

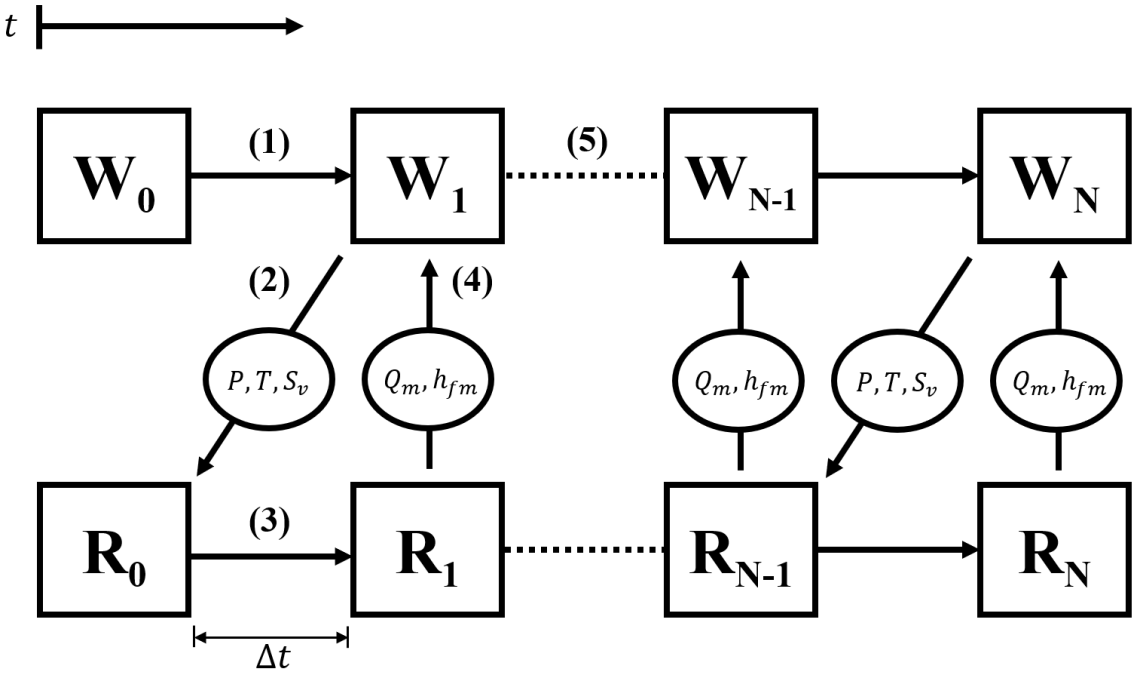


Figure 6: **Flow diagram of the loose-lagged coupling method implemented in this work. Here, W_n is the solution of a wellbore simulation at time step n, R_n is the solution of a reservoir simulation at time step n, and t is time.**

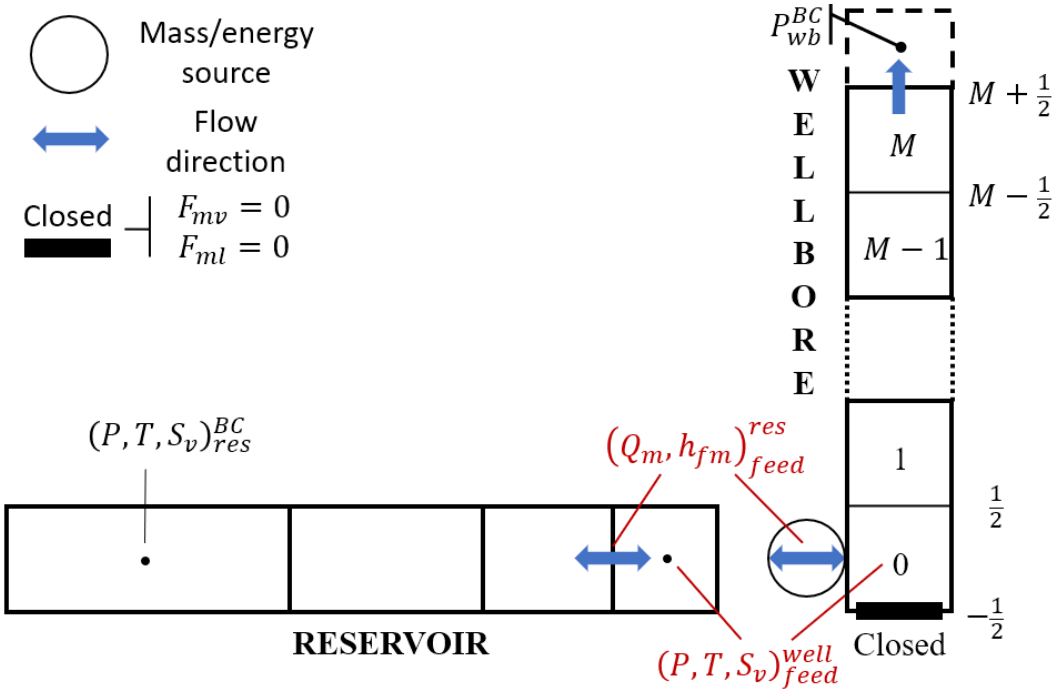


Figure 7: **Diagrammatic representation of the numerical models for the wellbore and reservoir. The information exchanged between the simulators at each time step is highlighted in red. The superscript BC indicates boundary conditions.**

5. RESULTS AND DISCUSSION

Simulation results are shown in Figures 4 and 5 below. Figure 4 shows the conditions in the reservoir at increasing distances from the well vs. time. Figure 5 shows conditions in the well vs. elevation at different times. Flow is initiated by dropping the wellhead pressure boundary condition from 14 bara to 1.01325 bara over 50 seconds. Figures 5 B) and C) indicate that after 10 minutes, the well is flowing at approximately 5-6 kg/s and is heating up due to the influx of hotter reservoir fluid. Figure 4 A) indicates a linear drop in pressure in the reservoir blocks near the well, which continues until flashing occurs in the well. This change in reservoir pressure is caused by the drop in bottomhole pressure due to the influx of hot fluid from the reservoir, which results in a decrease in the hydrostatic head within the well. However, the reservoir pressure remains undisturbed at radial distances beyond 70 m throughout this period.

After approximately 45 minutes of production, higher enthalpy fluid has reached the wellhead, and flashing begins in the well. After 50 minutes (red in Figure 5), the top 200 m of the well has flashed, causing the bottomhole pressure to drop by approximately 20 bar. Over the next 10 minutes, flashing progresses rapidly down the well. Figure 4 A) indicates that the drop in bottomhole pressure due to flashing causes a significant drop in pressure within 150 m of the well. The pressure in the reservoir at a distance of 164 m from the well has dropped to approximately 85 bara after 2 hours of production.

Figure 4 C) indicates that flashing begins in the reservoir after approximately 1 hour of production. This flashing is localized to the reservoir close to the well and does not extend more than 0.5 m away from the well during this simulation.

After 2 hours of production, flow in the well has reached a pseudo-steady state. As production continues beyond 2 hours, there is a gradual decline in reservoir pressure, which causes additional flashing within the reservoir and a small reduction in the flow rate of the well.

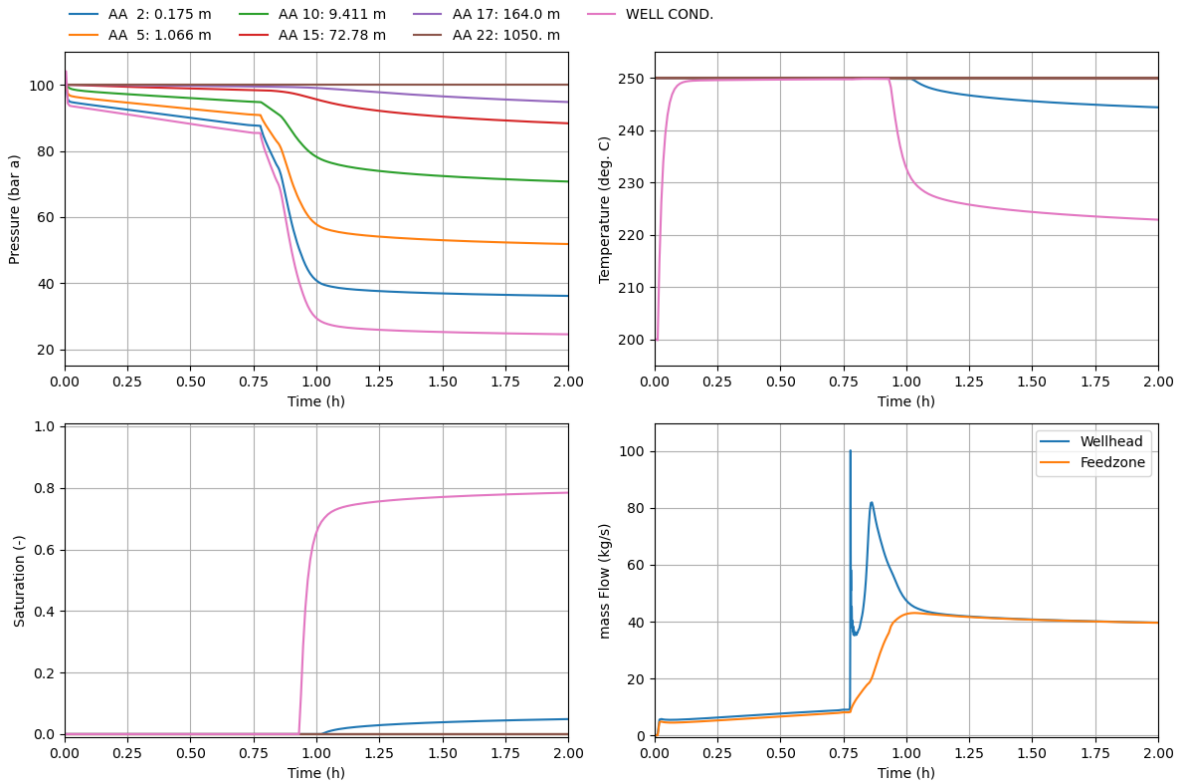


Figure 8: Plots of a) pressure, b) temperature, c) vapour saturation and d) mass flow vs. time within the reservoir at various distances from the well. Bottomhole conditions in the well are also plotted in pink.

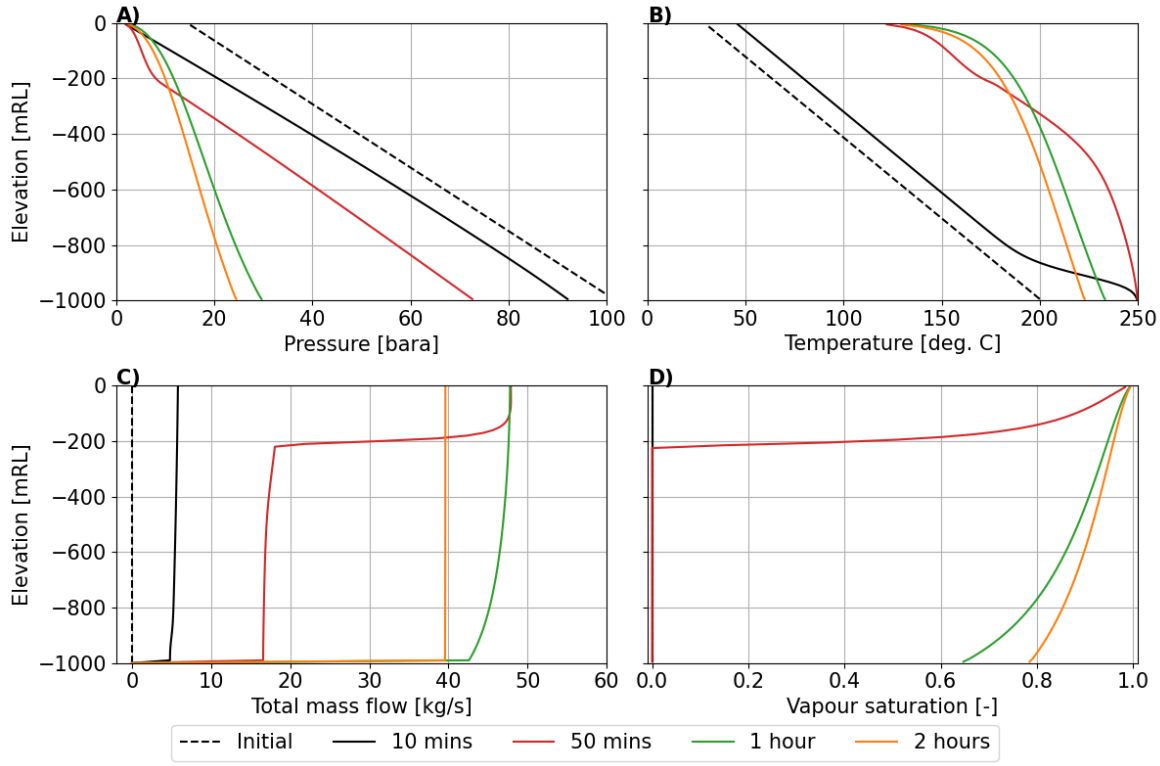


Figure 9: Plots of a) pressure, b) temperature, c) mass flow rate and d) vapour saturation vs. depth in the well at various times.

Although simple, this test case demonstrates the ability of our coupled simulator to model transient processes in both the well and reservoir that evolve over different time scales. In this case, we modelled fast transients in pressure, temperature and saturation in the well caused by the onset of flashing. We were also able to simulate the gradual pressure decline that occurred in the reservoir due to production.

6. CONCLUSIONS

This work discussed coupling our in-house transient geothermal wellbore simulator with the AUTOUGH2 reservoir simulator. The method implemented in this work was an explicit coupling between the well and reservoir. This relatively simple method of coupling was chosen because of its computational efficiency, flexibility and modularity, ease of implementation, and the ability to manage convergence issues in either the well or reservoir more easily.

In this work, we presented a simulation of coupled wellbore-reservoir flow during two-phase production. Although simple, this test case demonstrated the ability of our coupled model to resolve transient processes in the well and the reservoir that occur on different timescales. This included fast transients in the well caused by the onset of flashing and slower reservoir transients caused by production from the well.

Further testing of this coupled model is required. This testing will include comparisons of the coupled model with transient wellbore simulations that use simple productivity relationships to approximate the reservoir and with transient reservoir simulations that use simple deliverability relationships to approximate the well. This work aims to quantify the differences in simulation results when using a coupled model for different flow scenarios. This will help to determine the combination of reservoir conditions and timescales in which coupled simulations are required to represent geothermal systems accurately. Finally, future coupled simulations will investigate completion testing for geothermal wells (heat-up, injection and production testing) and discharge stimulation methods (air-injection, gas-lifting and well-to-well stimulation).

REFERENCES

Bendiksen, K. H., Maines, D., Moe, R. and Nuland, S.: 'The Dynamic Two-Fluid Model OLGA: Theory and Application', *SPE Production Engineering* **6**(02), (1991), 171–180.

Bhat, A., Swenson, D. and Gosavi, S.: Coupling the HOLA Wellbore Simulator with TOUGH2, *Proceedings*, 30th Workshop on Geothermal Reservoir Engineering, Stanford, California, (1987).

Bjornsson, G.: A Multi-Feedzone Geothermal Wellbore Simulator, Master's thesis, University of California, Berkeley, (1987).

Hadgu, T. and Freeston, D. H.: A Multipurpose Wellbore Simulator, Geothermal Resources Council Transactions, 14, (1990), 1279–1286.

Hadgu, T., Zimmerman, R. W., & Bodvarsson, G. S.: Coupling of a reservoir simulator and a wellbore simulator for geothermal applications, *Geothermics*, **24**(2), (1995), 145-166.

Korzani, M. G., Nitschke, F., Held, S., & Kohl, T.: The development of a fully coupled wellbore-reservoir simulator for geothermal application. GRC Transactions, 43, (2019).

Murray, L. and Gunn, C.: Toward Integrating Geothermal Reservoir and Wellbore Simulation: Tetrad and WELLSIM, *Proceedings*, 15th New Zealand Geothermal Workshop, New Zealand, (1993).

Pan, L., Oldenburg, C. M., Wu, Y.-S. and Pruess, K.: T2Well/ECO2N Version 1.0: Multiphase and Non-Isothermal Model for Coupled Wellbore-Reservoir Flow of Carbon Dioxide and Variable Salinity Water, Technical report, Lawrence Berkeley National Laboratory, Berkeley, California, (2011).

Pruess, K., Oldenburg, C. M. and Moridis, G.: TOUGH2 User's Guide, Version 2, Technical report, Lawrence Berkeley National Laboratory, Berkeley, California, (2012).

Ramey, H. J.: Wellbore Heat Transmission, Journal of Petroleum Technology, 14(04), (1962), 427–435.

Rivera Ayala (2010

Shi, H., Holmes, J. A., Durlofsky, L. J., Aziz, K., Diaz, L. R., Alkaya, B. and Oddie, G.: Drift-Flux Modeling of Two-Phase Flow in Wellbores, SPE Journal, 10(01), (2005), 24–33.

Tonkin, R.A.: Transient Two-Phase Modelling of Multi-Feed Geothermal Wells. PhD Thesis, University of Auckland, (2022).

Tonkin, R. A., O'Sullivan, M. J., O'Sullivan, J. P.: A review of mathematical models for geothermal wellbore simulation, Geothermics, 97, (2021).

Tonkin R., O'Sullivan, J., Gravatt, M., O'Sullivan M.: A transient geothermal wellbore simulator, Geothermics, 110, (2023a).

Tonkin R., O'Sullivan, J., Gravatt, M., O'Sullivan M.: Simulation of complex flows in geothermal wells, Geothermics, 108 (2023b).

Yeh, A., Croucher, A. E., & O'Sullivan, M. J.: Recent developments in the AUTOUGH2 simulator, *Proceedings*, TOUGH Symposium, Lawrence Berkeley National Laboratory, Berkeley, California (2012).

Drilling Rig Selection for Geothermal Exploration: Evaluating Factors and Decision-making Criteria

Dorman P. Purba[1,2], Daniel W. Adityatama[2], M. Rizqi Al Asyari[2], Brian Christiantoro[2], Vincentius A. Brilian[2], and Nadya Erichatama[1,2]

[1]ENERKA Bhumi Pratama, Cibis Park, Jakarta, Indonesia
[2]PT Geoenergi Solusi Indonesia (GEOENERGIS), Cibis Nine 11th Floor, Jakarta, Indonesia

dorman.purba@enerklaz.com

Keywords: geothermal, drilling, rig, cost, capacity, horsepower, sizing, load, hoisting, drawwork, rating, exploration, Indonesia

ABSTRACT

The selection of an appropriate drilling rig plays a critical role in the success of geothermal exploration projects. This paper aims to provide insights into the factors and decision-making criteria involved in drilling rig selection for geothermal exploration. The introduction highlights the importance of rig selection in achieving efficient and cost-effective drilling operations. It establishes the objectives of the paper, which are to identify key factors and criteria that influence rig selection decisions and to provide a simple framework for evaluating and comparing drilling rigs.

The paper first examines the geological considerations that impact rig selection, including drilling depth, formation characteristics, and temperature conditions. It emphasizes the significance of understanding the specific geothermal field's geological parameters to ensure compatibility with the selected drilling rig.

Next, the technical aspects of drilling rigs are explored, encompassing mobility, power requirements, rig size, and equipment capabilities. The interplay between rig specifications and project requirements is analyzed, emphasizing the need for rigs that can efficiently handle the anticipated drilling challenges.

Furthermore, the economic considerations are discussed, including rig availability, rental costs, and operational expenses. The paper addresses the importance of aligning rig selection with the project's budget constraints and financial viability.

To aid decision-making, a framework for evaluating and comparing drilling rigs is proposed. This framework incorporates a comprehensive set of criteria, including technical specifications, performance history, safety records, environmental certifications, and cost-effectiveness. The findings highlight that a systematic approach to drilling rig selection, considering geological, technical, economic, safety, and environmental factors, can contribute to the success of geothermal exploration projects. The paper underscores the significance of collaboration among geoscientists, drilling engineers, and project managers in the rig selection process.

By understanding the factors and decision-making criteria outlined in this paper, stakeholders involved in geothermal exploration can make informed choices in selecting drilling rigs that align with project requirements, optimize operational efficiency, and mitigate risks, ultimately leading to successful exploration outcomes.

1. INTRODUCTION

Indonesia is one of the countries that is estimated to have the most considerable geothermal energy potential in the world, with an estimated potential of approximately 18,000-megawatt electricity (MWe). However, from that vast potential, currently, Indonesia only utilizes approximately 13% of the total potential, which is 2,356 MW installed capacity (ThinkGeoEnergy, 2023). This utilization rate is low compared to New Zealand, which used 38% of its total potential, while the United States used 21% of its total potential (Asokawaty et al., 2020). To increase geothermal energy utilization in electricity,

the Government of Indonesia (GoI) is currently targeting 5,486 MWe of geothermal power plant installations by 2030 (Direktorat Panas Bumi, 2022).

Many published studies and papers have discussed the challenges the Indonesian government and the geothermal developers will face in developing geothermal projects in Indonesia (Ibrahim et al., 2005; IGA, 2014; Poernomo, 2015; Darma, 2016; Purba, 2018; Umam et al., 2018; Purba et al., 2019; Purba et al., 2020). Despite those challenges, the exploration phase is currently the most critical phase that Indonesia needs to take into action to seriously achieve the national geothermal target. Figure 1 shows that Indonesia has only been developing a few geothermal areas for geothermal power generation despite Indonesia's vast potential.

Figure 1 (Pusdatin ESDM, 2020) also shows Indonesia's distribution of geothermal areas according to each area's progress. Areas colored green, light green, and yellow indicate areas that have been through a preliminary survey, commonly the 3G survey. In some areas, the government, academic institutions, and geothermal developers have conducted surveys such as the temperature gradient hole or deep slim hole. Pink indicates the areas ready for development, whereas red indicates areas that have already been developed.

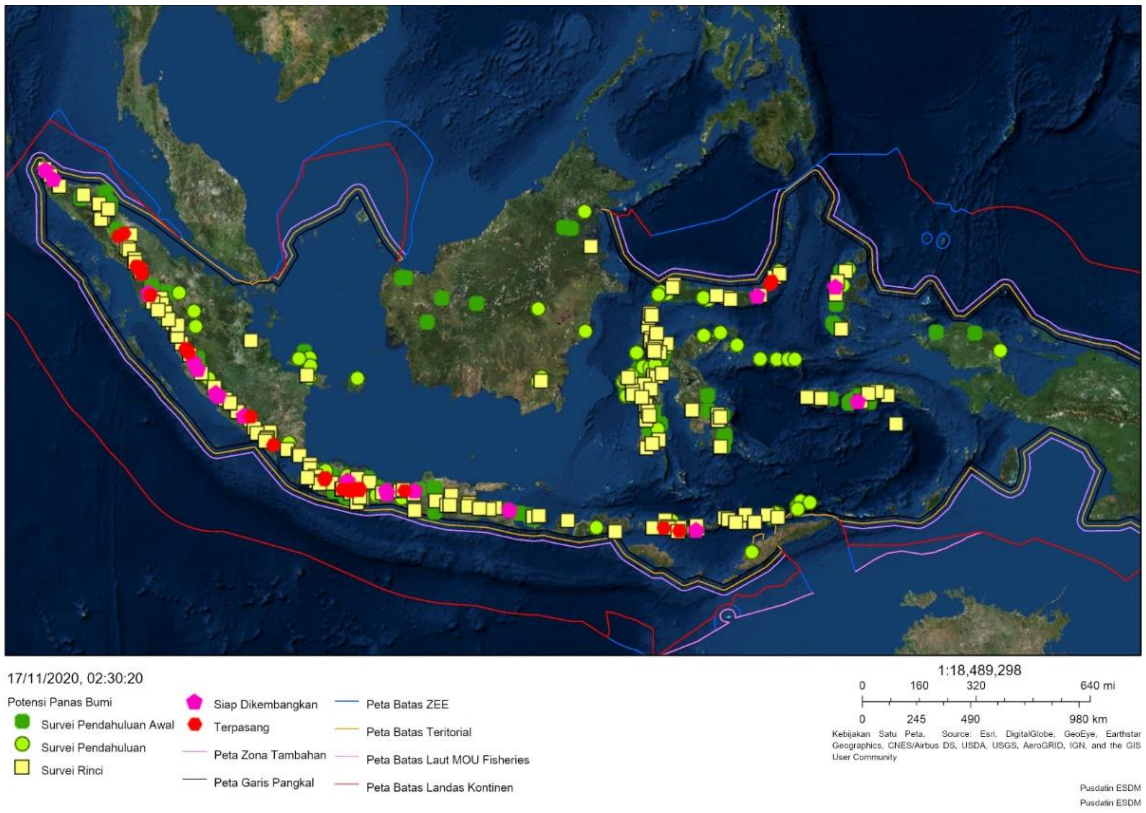


Figure 1: Maps of geothermal potential area in Indonesia with its status (Pusdatin ESDM, 2020).

Table 1 shows the list of the 22 geothermal prospect areas or concession areas still in the exploration stage and is expected to contribute in achieving the aforementioned national geothermal target.

Table 1: List of Indonesia's Geothermal Prospect Areas/ Concession Areas in the Exploration Stage (modified from Direktorat Panas Bumi, 2022; Siahaan et al., 2023).

No.	Name of the Prospect Area / Concession Area	Location	Estimated Potential Capacity (MWe)	Developer
1.	Tulehu	Maluku	31	PT PLN (Persero)
2.	Gn. Ungaran	Central Java	150	PT PLN (Persero)
3.	Atadei	East Nusa Tenggara	40	PT PLN (Persero)
4.	Songa Wayaua	North Maluku	42	PT PLN (Persero)
5.	Danau Ranau	South Sumatera	210	PT PLN (Persero)
6.	Oka Ile Ange	East Nusa Tenggara	50	PT PLN (Persero)
7.	Kepahiang	Bengkulu	254	PT PLN (Persero)
8.	Gn. Sirung	East Nusa Tenggara	152	PT PLN (Persero)
9.	Tangkuban Perahu	West Java	375	PT PLN (Persero)
10.	North Patuha (WKP Patuha)	West Java	55	PT Geo Dipa Energi
11.	Candradimuka (WKP Dieng)	Central Java	50	PT Geo Dipa Energi
12.	Candi Umbul Telomoyo	Central Java	92	PT Geo Dipa Energi
13.	Gn. Arjuno Welirang	East Java	302	PT Geo Dipa Energi
14.	Gn. Rajabasa	Lampung	283	PT Supreme Energy Rajabasa
15.	Rawa Dano	Banten	385	PT Sintesa Banten Geothermal
16.	Baturaden	Central Java	258	PT Sejahtera Alam Energy
17.	Telaga Ngebel	East Java	120	PT Bakrie Darmakarya Energi
18.	Seulawah Agam	Aceh	223	PT Geothermal Energi Seulawah
19.	Gn. Lawu	Central Java & East Java	332	PT Pertamina Geothermal Energy
20.	Kotamobagu	North Sulawesi	410	PT Pertamina Geothermal Energy
21.	Jaboi	Aceh	107	PT Sabang Geothermal Energy
22.	Gn. Talang – Bukit Kili	West Sumatera	90	PT Hitay Daya Energy
		TOTAL	**4,011**	

Indonesia's geothermal energy target certainly requires collaborative efforts from all stakeholders, including the government, geothermal development companies, investors, off-taker, academics, researchers, affected local communities, and various institutions and companies involved in geothermal development projects. Looking at the geothermal prospects and fields map in Indonesia (Figure 1 and Table 1), the collaboration of these stakeholders should be focused primarily on efforts to complete the exploration phase in various prospect areas in Indonesia. Indonesia cannot achieve the national geothermal target without going through the exportation stage, which is the most crucial stage and has many challenges.

The level of difficulty and risk of Indonesia's geothermal exploration phase is mainly due to a combination of 2 (two) primary factors:

1. The high level of uncertainty regarding the existence of economically viable geothermal resources underneath the ground (resource risk) and,

2. The high cost of drilling activity to prove the existence of these geothermal resources.

Some additional factors that intensify the geothermal exploration challenges (Utami, 2010; Chandra et al., 2021a; Umam et al., 2018; Adityatama et al., 2020; Poernomo, 2015; Purba, 2018; Purba et al., 2019) are as follows:

1. Geothermal prospect/exploration areas are usually in a volcanic setting with many geohazards, minimal road access, and hilly terrain.

2. There still needs to be a greater understanding of the local community living around the geothermal prospect area regarding geothermal projects. The low awareness often results in a higher level of community rejection of geothermal exploration projects.

3. Number of geothermal exploration experts in Indonesia from all disciplines (e.g., geoscience, drilling, environmental, social) is less than the number of exploration projects to be completed. When combining this situation with the absence of a certification program for geothermal exploration experts, many personnel with inadequate competence have the chance to run geothermal exploration projects in Indonesia.

4. In the exploration phase, there is usually not yet the certainty of the electricity prices, which creates difficulties for investors in deciding to spend the exploration budget.

Therefore, stakeholders in Indonesia need to be able to collaborate to solve the main challenges of geothermal exploration projects that have been discussed in various publications and forums to achieve the national geothermal target finally. Discussion of the challenges of geothermal exploration will be discussed in more detail in the next section.

2. EXPLORATION DRILLING PROJECT

2.1 Exploration Drilling Objective: The Only Method to Prove the Geothermal Resources in the Subsurface

Geothermal exploration activities are generally carried out in stages starting from activities that require the least cost and effort, then increasing to higher-cost activities as the confidence level in the project's feasibility increases.

The exploration activities can be divided into three main activity groups as follow:

1. *Surface surveys/studies* – This activity mainly includes collecting subsurface data from the surface. The assigned team performs the surveys on the surface; therefore, the cost is much cheaper than the cost of drilling a well. However, the team needs to interpret the obtained data since it does not come directly from the subsurface. The typical surface studies may include geological mapping, geochemical sampling, magnetotelluric, gravity, other geophysical data collection, LiDAR, topographic surveys, and hydrogeological surveys. It is common to conduct social mapping and environmental baseline preliminary studies to support project decisions.

2. *Data interpretation and integration, conceptual modeling, and resource assessment* – These are the activities of integrating and interpreting the data obtained through the surface survey described above. These activities include laboratory analysis, data cleansing, interpretation, and integration. Integrating all relevant data will produce a final product called a conceptual model. It is a common practice in the industry to use the conceptual model to estimate the amount of commercial geothermal reserves in the prospective area. Based on the assessment, if the geothermal developer considers the geothermal resource attractive for further research, the project will proceed to more complex and expensive activities, drilling deep wells. Drilling deep wells into predicted reservoir depth can prove the existence of geothermal resources but require high capital expenses and involve higher risks.

3. *Deep well exploration drilling* – Drilling is commonly becoming the final activity in a geothermal exploration project because, with a deep well, the geothermal developer expects to prove the existence or the absence of a commercial geothermal system below the surface.

Geothermal developers will only decide to perform deep well drilling if they already have various supporting information considering the high cost and difficulty of drilling.

As the only way to prove the existence of a commercial geothermal system underneath the ground, the geothermal developer must plan and execute an exploration drilling project carefully. Exploration well(s) will only be valuable if they can reach the planned depth target and acquire the targeted subsurface data. The subsurface data includes formation characteristics, rock properties, fluid characteristics, rock permeability, and reservoir temperature (Chandra et al., 2021a). It can be acquired directly through various methods such as coring, cutting sampling, measurement while drilling (MWD), and wireline downhole logging.

2.2 Exploration Drilling Challenges and Learning Curve

Geothermal drilling in Indonesia has been carried out significantly on several prospects since the 1970s where exploration drilling was carried out in the Kamojang, Dieng, and Darajat field (Hochstein and Sudarman, 2008). Drilling activities continued intensively since the 1980s to the late 1990s, this was related to exploration activities and to fulfill steam supply in supporting the generation capacity in Kamojang, Salak, Darajat, and Sibayak fields which commercially operated within that period with total installed capacity of 778 MW by the end of 2000 (Purwanto,2021). Drilling activity was slowed in the early 2000s as a result of the government's decision to postpone state-owned enterprise, private, and government-related projects due to the country's monetary and fiscal condition, as enacted by Presidential Decree Number 39 of 1997. From 2002 to the present, drilling activities have continued.

Theoretically, all personnel involved in a geothermal project should know that the exploration wells are crucial for the decision-making process toward the next stage. As explained earlier, the primary objective of exploration drilling in geothermal energy development is to locate, assess, and determine the size, temperature, and quality of geothermal resources in a specific area. However, not all personnel involved in a geothermal exploration drilling project may have the same understanding of the objectives of drilling exploration wells.

Therefore, the geothermal company might need to ensure their personnel has received sufficient information and training to deal with technical and non-technical challenges, such as regulation/legal, social, and environmental. Some of the challenges in geothermal exploration drilling in Indonesia can be summarized as follows (summarized from Purba et al, 2019; Chandra et al., 2021a; Utami, 2010; Chandra et al., 2021b; IGA, 2014; GeothermEx, 2010; Purwanto et al., 2018; Purba et al., 2020; Adityatama, 2020; Purba et al., 2021):

1. *Low accuracy of subsurface data* - at the exploration stage, the available subsurface data are generally still generated based upon surface studies' interpretations, so drilling planning will be carried out based on data with very low accuracy and low reliability. The drilling team may expect various surprises from formations at unexpected depths, such as massive lost zones, reactive formations, unconsolidated formations, shallow steam pockets, deeper top of reservoirs, and troublesome paleosol formations. Realizing that the geoscientific prognosis provided by the geoscience team may not match actual conditions, the drilling team must make a mitigation plan for these various scenarios or potential subsurface hazards. Failure to make a proper mitigation plan will significantly increase drilling costs and might stop the drilling team from completing the well as planned.

2. *Newly formed exploration team* – currently, in Indonesia, companies conducting geothermal exploration activities are generally newly formed with a combination of several sponsoring companies. A new company implies that the team combines several key personnel who might be their first time working together and are unfamiliar with each other's working methods and communication styles. Furthermore, due to the shortage of geothermal personnel, geothermal companies often recruit personnel from similar industries such as oil and gas or mining. Although similar, drilling challenges in the geothermal environment are significantly different compared to the oil and gas and mining environments. The failure of geothermal companies to

build a competent, experienced, professional, and coherent exploration team will cause the exploration projects to run slower and ultimately increase project costs.

3. *Higher project costs compared to development stage drilling* – despite the explanation of the two points above regarding the lack of subsurface data and the exploration team being generally newly formed, the cost of exploration drilling itself is generally higher than the cost of drilling at the development stage. The higher cost is because of the project scale. In terms of scale, the number of wells drilled in the exploration stage is usually less than those drilled in the development stage. The number of these wells affects the unit prices proposed by rigs and support services providers. The more wells drilled, the lower the unit price for all drilling services, equipment, and materials.

4. *Low acceptance of local communities* – not only from the technical side but exploration challenges also come from the non-technical aspect, especially those related to local communities. In the exploration stage, people living in Indonesia's geothermal prospect areas are generally not adequately educated about the benefits of geothermal projects for their livelihood. Often, geothermal companies focus too much on planning from the technical aspect and forget about engagement with local communities, resulting in community rejection.

5. *Indonesia does not yet have a geothermal drilling database* – Indonesia does not currently have a database that collects and integrates data and lessons learned from geothermal drilling activities from all geothermal development companies in Indonesia. If Indonesia has established this kind of database, geothermal developers in Indonesia can easily take advantage by learning from other geothermal projects and avoiding the same mistakes. Without this database, each geothermal developers can only learn from its respective projects, isolated from each other.

6. *Geohazards related to volcanic area* - Indonesia, located on the Pacific Ring of Fire, faces various geohazards that pose challenges to developing geothermal projects. These include earthquakes, volcanic eruptions, landslides, flood, phreatic eruption, and tsunamis, which can disrupt or damage power plants and infrastructure, leading to production losses and environmental impacts. Moreover, active, and potentially active volcanic systems add to the uncertainty of siting and drilling for geothermal resources. Therefore, proper assessment and management of geohazards are critical for the successful implementation and operation of geothermal projects in Indonesia and demand robust risk mitigation and response strategies to minimize their impacts.

7. *Being an archipelago country and poor infrastructures* - Indonesia faces several challenges in developing its geothermal resources as an archipelago country. The country's geography, with its numerous islands spread across vast distances, presents logistical difficulties in transporting equipment and personnel to remote locations. Additionally, the lack of infrastructure and limited access to resources such as water and power can impede the development of geothermal projects. Furthermore, diverse cultures and languages across the islands can also create challenges in gaining local community support for geothermal projects. To overcome these challenges, effective collaboration and communication with local communities and investment in infrastructure and resources are essential for the successful development of geothermal energy in Indonesia.

"Learning curve" might be suitable to describe all the challenges above. It means the team is still learning and gathering information in the exploration stage, which is the beginning of a geothermal development project. Along with the increase in information, data, experience, skills, and communication quality within the exploration team, the drilling success rate will generally increase, as Sanyal (2011) shows in Figure 2.

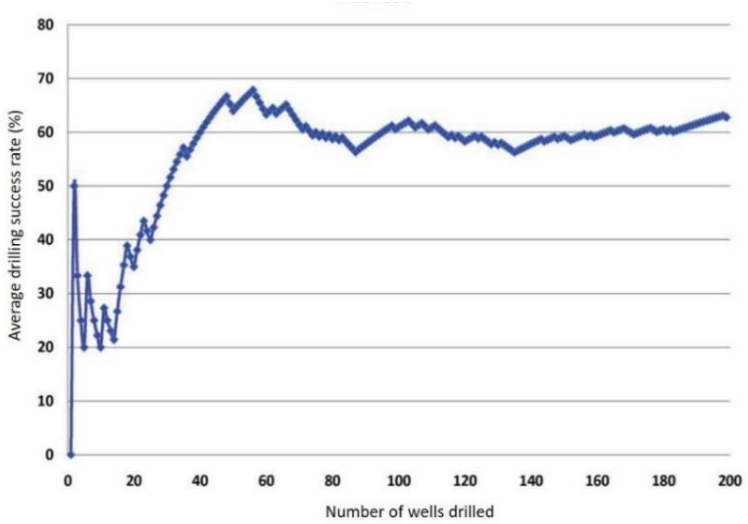


Figure 2: Average drilling success rate versus number of wells using data from Indonesia (Sanyal et al., 2011).

Geothermal developers or exploration teams need to address and mitigate the various exploration challenges outlined above to avoid an increase in the cost of exploration projects that leads to an increase in the overall cost of geothermal development projects. A significant increase in overall project costs can eventually cause the project to become uneconomical and may stop the project. The cost of geothermal exploration projects in Indonesia currently ranges from USD 15-50 million, with drilling costs as the most significant cost component (Direktorat Panas Bumi, 2022; GeothermEx, 2010; Purwanto et al., 2018; Purba et al., 2020; Siahaan et al., 2023). Based on the authors' observations, many geothermal companies in Indonesia have spent more than 50 million USD for geothermal exploration in a prospective area with inconclusive results.

In addition to project cost overruns, another factor that can cause an exploration project to stop is work incidents. If not managed properly, some work incidents may impact the environment and residents around the project. Recent incidents in geothermal drilling projects in Indonesia (DPR RI, 2022a; DPR RI, 2022b; MCG, 2022; MCG, 2020; SOL, 2019) indicate the difficulty of geothermal drilling activities in Indonesia. Like other energy development projects, human and environmental safety must be the top priority for any geothermal drilling exploration project in Indonesia.

2.3 Drilling Cost Component in a Geothermal Project

Geothermal drilling project is complex since it involves multiple stakeholders, organizations, and equipment (Bodley, 2018; Gul and Aslanoglu, 2018). Inadequate project management could spin a project out of control (Discenza and Forman, 2007). Southon and Gorbachev (2003), Kipsang (2015), Bodley (2018), and Otieno (2016) clearly mentioned the paramount of planning phase and understanding of all drilling activities to control the drilling cost. Additionally, Hole (2008) mentioned that there are two categories of influences that are driving up the cost of drilling, the one that we have little or no control over and the one that we can control. Thus, the authors use this section to discuss several aspects that play crucial roles in a geothermal drilling project to understand the wide variation of drilling cost observed in Indonesia.

In any geothermal project, drilling activities are performed in the exploration and development phase. The purpose of drilling activities in each of these phases is different, which can be described as follows:

1. In the exploration phase: the aim is to answer the question of the presences, size and viability of a conventional geothermal system in the area with drilling cost as low as possible.
2. In the development phase: the aim is to meet the number and size of the production and injection wells required to exploit the geothermal resources as economically and sustainably as possible.

One of the challenges that is often discussed in the geothermal community in Indonesia is the high cost of drilling activities. Worldwide, including Indonesia, shows that every geothermal project cost mainly dominated by two major components, which are power plant construction and drilling. In addition to that, Purwanto et al. (2018) mentioned that for a 55 MW geothermal project in Indonesia, drilling cost accounts for 58% of total project cost. Therefore, it is important for Indonesia to find ways in optimizing its drilling cost to increase the economics of the overall geothermal project.

The drilling project complexity, as an implication of multiple parties involved, must be managed by the geothermal company by legally translate the verbal agreements, with all related parties, into a written contract document formulating the collaboration mechanism. Typically, in a geothermal drilling project in Indonesia, there are about 18-25 contracts required if each service and materials are treated individually (Purba et al., 2020a), including tangible such as casing, wellhead, and master valves. Figure 3 shows the example of actual cost distribution based on drilling services. The chart summarizes actual drilling cost from two geothermal fields in Indonesia that authors have on hand at the time of this study.

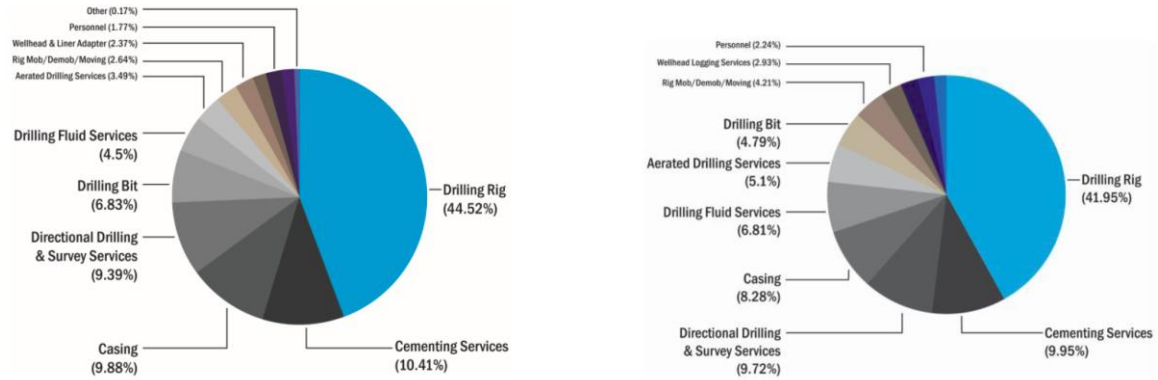


Figure 3: Summary of actual drilling cost from two geothermal fields in Indonesia. One field is in Central Java (left) and the other is in West Java (right).

The chart shows that both fields have relatively similar drilling cost allocation. The top contributors are drilling rig, cementing, directional drilling, casing, drill bit, and drilling fluid/mud, which in total contribute to roughly 80% of total drilling cost. This is consistent with Pareto law stating that "80% of the effects come from 20% of the causes". If the pattern of this cost distribution is always consistent throughout all geothermal drilling operation in Indonesia, then the drilling team should focus more on managing these six drilling service contracts that influence more than 80% of drilling costs instead of invest equal portion of time and effort to all 25 contracts.

Cost wise, same rules apply for the drilling project, as in any project, that the total cost incurred is the result of multiplication of unit price with quantity. The higher the unit price that we agreed in the contract with our drilling partners, the higher the total cost that will occur. Similarly, with quantity, the more drilling days, tools, equipment, drilling materials, consumables, and personnel we consume or utilize, the higher the total drilling cost appears in our project. In this study the authors chose to discuss the top four drilling cost contributors, which is drilling rig.

2.4 Why Selecting Fit-for-Purpose Rig is Important?

Since the rig accountable for the largest portion, 40-45% of total drilling cost (Figure 3), it become the priority in this discussion. With limited access to actual geothermal project cost in Indonesia, the authors decide to conduct simple mapping on various factors that might influence the rig cost. The mapping process always start with one question in mind: "what are the factors that influence unit price and quantity?". In the case of rig cost, the price is the rig operation daily rate (ODR) agreed in the contract while the quantity is the number of drilling days.

Drilling rig is the main equipment in any drilling operation. It is important that the drilling engineer in charge properly calculates the maximum anticipated load and pressure to avoid procuring over-

specification rig and eventually lead to higher overall drilling cost. Generally, in terms of load and pressure rating, the 1,500 HP and 2,000 HP rigs are considered to have more than enough capacity to drill standard wells/big holes to the depth of 2,000 - 2,500 meters in Indonesia. But those capabilities require higher fuel consumption, larger footprint and higher ODR compared to a 1,000 HP rigs. Table 3 shows a comparison of several types of drilling rigs used in Indonesia, based on their capacity, which are commonly expressed in horsepower (HP).

Table 2: General comparison of conventional rotary drilling rig capacity (land operation) that typically available in Indonesia.

Comparison Items	750 HP	1,000 HP	1,500 HP	2,000 HP
Hookload	410,000 lbs	550,000 lbs	750,000 lbs	1,000,000 lbs
Hoisting capacity	10 Lines - 300,000 lbs	10 Lines - 400,000 lbs	12 lines - 750,000 lbs 10 Lines - 640,000 lbs 8 Lines - 530,000 lbs	12 lines - 840,000 lbs 10 Lines - 700,000 lbs 8 Lines - 560,000 lbs
Setback capacity	200,000 lbs	250,000 lbs	500,000 lbs	600,000 lbs
Mast standing	1 stand - 2 joints	1 stand - 2 jts or 3 jts	1 stand - 3 joints	1 stand - 3 joints
Rotary table opening	27.5"	27.5"	37.5"	37.5"
Clearance height under rotary table	16 feet	20 - 24 feet	27 - 29 feet	27 - 29 feet
Mud pump size	2 x 800 HP	2 x 1,000 HP	3 x 1,300 HP	3 x 1,600 HP
Top Drive System (TDS)	TDS250 Ton	TDS350 & 500 Ton	TDS350 & 500 Ton	TDS350 & 500 Ton
Number of loads	60 - 80 loads	80 - 100 loads	80 - 120 loads	80 - 140 loads
Minimum footprint size	80 x 70 meter	100 x 80 meter	130 x 90 meter	130 x 90 meter
Daily fuel consumption (average)	4,000 - 6,000 liter	6,000 - 8,000 liter	7,500 - 9,000 liter	8,000 - 10,000 liter
Typical drill pipe stock	5,000 feet (1,524 m)	7,500 feet (2,286 m)	10,000 feet (3,048 m)	12,000 feet (3,658 m)
Mud system capacity	1,000 bbl	1,000 - 1,500 bbl	1,500 - 2,000 bbl	2,000 bbl
Typical standpipe pressure rating	4" at 5,000 psi	4" at 5,000 Psi	4" at 5,000 - 10,000 psi	4" at 5,000 10,000 psi

It is uncommon for geothermal companies in Indonesia to own and operate the rig. They usually rent the rig and crew from a rig company, which serves both geothermal and oil and gas industries. This is the reason why many geothermal projects are also affected by the continuously changing rig rental price following oil price fluctuations as mentioned by Gul and Aslanoglu (2018). When oil price is high, the oil and gas industry will be most likely executing drilling activities aggressively, which creates difficulty for geothermal companies to get drilling rigs. Thus, in such circumstances, the geothermal drilling engineer often will be forced to contract a rig with the capacity higher-than-required due to rig availability issue.

Typically rig size or capacity is one of the main factors than influence the rig rental rate, which influenced by:

1. Casing design: Well type (i.e., big hole, standard hole, or slimhole). The bigger the hole size the higher rig capacity required.

2. Casing setting depth: Depends on casing set ting depth for each hole sect ion / casing size. Mainly defined by the Top of Reservoir (TOR) and deepest feed zone targeted. Hole problems (i.e., reactive formation, unconsolidated formation, and shallow permeable zone) contributes to the casing set ting depth decision-making.

3. Deepest feed zone depth: Mainly defined by the Top of Reservoir (TOR) and deepest feed zone targeted. Hole problems such as reactive formation, unconsolidated formation lost circulation, and shallow permeable zone are some considerations used in defining the casing setting depth.

In brief, to effectively optimize rig costs, a drilling engineer should be capable of determining the minimum specifications of a rig that can efficiently drill and construct geothermal wells according to the design. The following section will specifically discuss several examples of criteria that must be fulfilled to calculate the minimum requirements of a rig in a hypothetical geothermal exploration project.

3. RIG SIZING: EVALUATING FACTORS AND DECISION-MAKING CRITERIA

The objective of this paper is to provide preliminary rig sizing based on proposed well design that already explained in previous section. The purpose of rig sizing is to determine the appropriate size and capability of the drilling rig required to drill the well safely, efficiently, and economically. The rig size is determined based on various factors such as the depth of the well, the diameter of the wellbore, the drilling method to be used, and the anticipated drilling flow rate.

The rig's size, power, and capacity must match the drilling program's requirements to ensure efficient drilling operations. For instance, if the well depth is deep, the rig must have sufficient power and drilling capacity to penetrate the formation and reach the target depth. Similarly, the rig's size must match the drilling program's requirements to ensure that it can fit on the drilling site and operate efficiently.

The importance of rig sizing lies in the fact that the rig size and capability have a significant impact on the overall cost and timeline of the drilling project. A rig that does not meet the minimum criteria for the drilling program may not be able to perform the necessary tasks, resulting in project delays, increased costs, and even safety hazards. On the other hand, a rig that is too large (overcapacity) for the job may be unnecessary and result in unnecessary extra expenses.

Proper rig size also affects the safety and efficiency of the drilling operation. A rig that is too small may not have the necessary equipment or capacity to handle unexpected situations or emergencies that may arise during the drilling process. The determination of minimum rig criteria also helps in evaluating and selecting the appropriate rig for the drilling program. By knowing the minimum rig criteria, drilling engineers can evaluate the different rigs available in the market and select the most cost-effective option that meets the drilling program's requirements.

3.1 Rig Sizing Calculation: Hoisting Capacity

Simply, the derrick/mast capacity can be defined as the capacity of the derrick/mast to withstand the load of the BHA/drillstring when it is running into the well which usually stated in pounds (lbs). The hoisting capacity of the derrick or mast is an important factor in the rig sizing assessment for geothermal exploration drilling projects because it determines the maximum weight of the drill string and associated equipment that can be lifted during drilling operations.

The objective of assessing the derrick or mast hoisting capacity is to ensure that the drilling rig selected for the project has sufficient capacity to handle the weight and size of the drilling equipment and materials required for the geothermal exploration drilling program. This is critical for the safe and efficient execution of the drilling operations and helps to minimize the risk of accidents, equipment damage, and operational downtime.

If the derrick or mast hoisting capacity is insufficient for the required drilling equipment and materials, it can lead to delays, cost overruns, and safety hazards. Therefore, it is essential to preliminary determine the hoisting capacity of the derrick or mast and select a drilling rig that has sufficient capacity to meet the needs of the project.

For example, in a drilling project, if it is found that the heaviest BHA load expected is the BHA when drilling 12-1/4” hole section with total 338,943.32 lbs, and it is found that the heaviest casing load is when running casing 13-3/8” with total load 292,543.95 Lbs then the hook load capacity is usually used for the heaviest identified load with consideration of margin of overpull which in this assessment is assumed with 100,000 lbs and apply safety factor which ranging from 110% - 125%.

Considering the heaviest load which is BHA 12-1/4” load with total load 338,943,32lbs, the minimum rig hoisting capacity required to execute proposed well design and drilling program is 548,679.15 lbs. It also must be noted that the heaviest BHA load above is the weight on air, which is very unlikely to happen as the wellbore is supposed to be filled with drilling fluid/water during the drilling operation. The summary of minimum rig hoisting capacity is summarized in Figure 4.

Load Summary			
BHA Load		**Casing Load**	
BHA 26"	115371.56 lbs	Casing 20"	284020.82 lbs
BHA 17-1/2"	251600.86 lbs	Casing 13-3/8"	292543.95 lbs
BHA 12-1/4"	338943.32 lbs	Tie-Back 13-3/4"	197410.76 lbs
BHA 9-7/8"	325512.92 lbs	Casing 9-5/8"	219896.79 lbs
BHA 7-7/8"	333117.43 lbs	Liner 10-3/4"	197410.76 lbs
BHA 6-1/8"	176760.09 lbs	Liner 8-5/8"	140330.85 lbs
		Liner 7"	136871.46 lbs
		Liner 5-1/2"	116115.13 lbs
MOP (Assumption)	100000 lbs		
SF	1.25		
Minimum Rig Hoisting Capacity	548,679.15 lbs		

Figure 4: Example of BHA Load and Casing Load Summary.

3.2 Rig Sizing Assessment: Drawwork Rating

Simply, the rig rating / drawwork rating can be defined as the power possessed by the rig when carrying out certain activities and certain depths which generally stated in horsepower (HP). The drawworks is a hoisting mechanism that is responsible for raising and lowering the drill string during drilling operations. The drawworks rating is an important factor in the rig sizing assessment for geothermal drilling projects because it determines the maximum depth and size of the hole that can be drilled.

This sub-section contains results of the calculation of drawwork capacity (HP) required to carry out drilling operations based on the BHA that have been explained in the previous section. The objective of assessing the drawworks rating is to ensure that the drilling rig selected for the project has sufficient power to lift and lower the drill string and associated equipment during drilling operations.

The drawworks rating is critical for the safe and efficient execution of the drilling operations and helps to minimize the risk of accidents, equipment damage, and operational downtime. If the drawworks rating is insufficient for the required drilling depth and hole size, it can lead to delays, cost overruns, and safety hazards. Therefore, it is essential to preliminary determine the drawworks rating and select a drilling rig that has sufficient power to meet the needs of the project.

In general, the hoisting equipment on the rig consists of drawwork, overhead tools (top drives, traveling blocks, hooks, elevators), and drilling lines (Herianto, 2008). The values for parameters such as drill pipe weight, block and hook weight, top drive weight, lifting speed, and margin of overpull (MOP) which will affect the amount of power/rating that will be required by the rig in carrying out an operation. The heavier the equipment used and the faster the lifting speed, the greater the amount of force needed in the drawworks.

To drawworks rating, it is necessary to calculate the static hook and dynamic hook at the first place. Static hook is a heavy accumulation of BHA, block and hook, and also top drive. While the dynamic hook is the sum of the static hook, fast line and deadline taking into account the overpull and safety factor (SF). Then, this value can be converted into the power needed by the drawwork by involving the value of lift speed, efficiency, and the number of lines owned by the rig (Herianto, 2008).

For example, continuing the previous example (Figure 4) of the drawwork rating calculation, to execute the proposed well design require at least 1,264 HP rig. For safety factor, it is recommended to upsize the calculated minimum requirement to 1500 HP drawwork rating. Moreover, the availability of 1300 HP rig is also not much in Indonesia's market. The summary of minimum drawwork rating calculation is summarized in Figure 5.

DRAWWORKS			
Heaviest Drill String (lbs)	338,943	lbs	12-1/4" drill string+ top drive+block
Heaviest Drill String (lbs) with bouyancy 0.87	295,838	lbs	assume hole full of water
Desired Minimum Hookload Speed (fpm)	110	feet/min	
Hook HP = Total Hoist Load x Hoist Speed / 33000	986	HP	
Drawworks HP = Hook HP / Eff^no. lines	1,258	HP	assume 8 lines
Minimum Rig HP 1500 HP			

Figure 5: Drawwork Rating Calculation Summary.

3.3 Rig Sizing Assessment: Rotary Table Opening

Simply, the rotary table opening can be defined as the size of the hole in the rotary table that will be passed by the bit or tubular that usually stated in inches (in). It is an important factor in rig sizing assessment for geothermal drilling projects because it determines the maximum size of the drill string, casing, and associated equipment that can pass through the rotary table during drilling operations.

The importance of rotary table opening for rig sizing assessment in geothermal drilling projects lies in the fact that it limits the size of the drill string and associated equipment that can be used during drilling operations. If the rotary table opening is too small, it can restrict the size of the drill string, which may not be sufficient for the required drilling depth and hole size. Thus, it is essential to accurately determine the rotary table opening and select a drilling rig that has sufficient clearance to meet the needs of the project.

For example, it is found that in this project, the largest OD size of the bit and BHA that will be used based on the current drilling program is 26" of drilling bit. This size is the minimum size of the rotary table opening that must be accommodated by the rig.

3.4 Rig Sizing Assessment: Make-Up Torque

Make up torque can be defined as the amount of force required to securely tighten the threaded connections between section of BHA, casing, and other downhole tools. In short this is the ability of the rotary function on the rig in connecting tools (make-up) that generally stated in foot pounds (lbs-ft).

The importance of makeup torque in rig sizing assessment is that it helps to determine the minimum torque capacity of the drilling rig's top drive or iron roughneck, which are the primary tools used to make up or break out drill string connections.

A sufficient makeup torque capability is critical for efficient drilling operations and minimizing non-productive time. Without adequate makeup torque capacity, the drilling crew may struggle to make up connections properly, which can result in safety hazards, stuck pipe, or damage to the downhole equipment. Therefore, it is important to consider the makeup torque requirements when selecting a drilling rig for geothermal exploration projects.

Generally, deciding the minimum make up torque is by identifying the make-up torque from various BHA and casing. For example, in this project, based on the assessment, the highest make up torque is on drill collar (DC) with size 8" that generally used in 26" hole section until 12-1/4" hole section which the estimated make up torque is 57,400 ft-lbs. The summary of minimum makes up torque assessment is summarized in Figure 6.

3.5 Rig Sizing Assessment: Pump Flowrate

Simply, the pump flowrate and pressure rating can be defined as ability of pump on the rig to perform drilling activities such as circulation during drilling operation for hole cleaning and killing if well control activity occurred which generally stated in gallons per minute (GPM) and pounds square inch (psi).

In this section, the minimum flowrate assessment is used to determine the minimum rig pump capacity to supply drilling fluid during drilling operation. The assessment for this section is determined based on hydraulic and hole cleaning simulation and excel calculation that incorporates various assumption and best practice that used for geothermal drilling operation. For example, the summary of minimum flowrate for each hole section are summarized in Figure 7 and Figure 8.

Casing	Pounders (lbs/ft)	Grade	M/U Torque (ft-lbs)					
			Long round thread (LC)			Short round thread (SC)		
			Minimum	Optimum	Maximum	Minimum	Optimum	Maximum
Surface 20"	133	K-55	10,890 ft-lbs	14,520 ft-lbs	18,150 ft-lbs	9,399 ft-lbs	12,532 ft-lbs	15,665 ft-lbs
Prod Casing 13-3/8"	68	L-80	N/A	N/A	N/A	7,413 ft-lbs	9,524 ft-lbs	11,905 ft-lbs
Tie Back 13-3/8"	68	L-80	N/A	N/A	N/A	7,413 ft-lbs	9,524 ft-lbs	11,905 ft-lbs
Prod Casing (Contingency) 9-5/8"	47	L-80	6,690 ft-lbs	8,920 ft-lbs	11,150 ft-lbs	5,827 ft-lbs	7,769 ft-lbs	9,711 ft-lbs
Liner 10-3/4"	40.5	K-55	N/A	N/A	N/A	3,377 ft-lbs	4,502 ft-lbs	5,628 ft-lbs
Liner 7"	23	K-55	2,558 ft-lbs	3,410 ft-lbs	4,263 ft-lbs	2,320 ft-lbs	3,094 ft-lbs	3,867 ft-lbs

OD BHA (in)	ID BHA (in)	Thread Type	Typical M/ U Torque
DC 8"	2 1/2	6 5/8" REG	57,400 ft-lbs
DC 8"	2 13/16	6 5/8" REG	53,300 ft-lbs
DC 8"	3	6 5/8" REG	50,700 ft-lbs
DC 6-1/2"	2 1/4	4 1/2" IF NC 50	29,700 - 32,700 ft-lbs
DC 6-1/2"	3	4 1/2" IF NC 50	29,700 - 32,700 ft-lbs
DC 4-3/4"	1 3/4 - 2 1/2	3 1/2" NC-38	10,000 - 11,000 ft-lbs

OD BHA (in)	ID BHA (in)	Thread Type	Typical M/ U Torque
DP 5"	4 2/7	G-105, 4 1/2" IF, NC 50	25,600 - 30,700 ft-lbs
DP 4-1/2"	3 17/50	G-105, 4 1/2" IF, NC 46	20,500 ft-lbs
DP 3-1/2"	2 3/5	G-105, 3 1/2" IF, NC 38	9,600 - 11,500 ft-lbs
DP 3-1/2"	2 3/5	S-135, 3 1/2" IF, NC 38	10,000 - 12,100 ft-lbs

Figure 6: Make up Torque Assessment for Proposed Casing and Drill Collar.

Hole Section & Mud Weight	Min. flow rate for good hole cleaning	Flow rate limitation due to mud motor / MWD / another tool	Max. surface pressure
26" hole using 9 ppg MW	1177 gpm	600 – 1200 gpm (9-5/8" mud motor)	3482 psi using 1200 gpm
17-1/2" hole using 9 ppg MW	1179 gpm	600 – 1200 gpm (9-5/8" mud motor)	3667 psi using 1200 gpm
12-¼" hole using 8.33 ppg	796 gpm	600 – 1200 gpm (9-5/8" mud motor)	3060 psi using 800 gpm
9-7/8" hole using 8.33 ppg	701 gpm	300 – 900 gpm (8" mud motor)	2795 psi using 800 gpm
8-1/2" hole using 8.33 ppg	601 gpm	300 – 600 gpm (6-¾" mud motor)	2974 psi using 700 gpm
7-7/8" hole using 8.33 ppg	654 gpm	300 – 600 gpm (6-¾" mud motor)	3020 psi using 750 gpm
6-1/8" hole using 8.33 ppg	689 gpm	No mud motor on BHA	3424 psi using 500 gpm

Figure 7: Minimum Flowrate Assessment based on hydraulic and hole cleaning simulation for Each Hole Section.

Pumps Requirement							
Hole Section	**26**	**17 1/2**	**12 1/4**	**9 7/8**	**8 1/2**	**7 7/8**	**6 1/8**
Drill pipe OD (in)	5	5	5	5	5	5	3.5
Mud weight (ppg)	9	9	8.4	8.4	8.4	8.4	8.4
PV	8	8	8	8	8	8	8
Diameter of Cutting Dp (in)	0.25	0.25	0.25	0.25	0.25	0.25	0.25
Slip Velocity (fpm)	45.05	45.05	47.93	47.93	47.93	47.93	47.93
Minimum Pump Rate (gpm)	1197.00	1034.27	489.35	283.74	184.88	144.84	98.86
Best practice pump rate to anticipate mud degradation (due to temperature)	1197.00	1034.27	978.69	851.22	554.64	434.51	296.58

Figure 8: Minimum Flowrate Assessment based on various best practices.

3.6 Summary: Minimum Rig Specification Requirements

After carrying several assessments that already explained in the previous subsection, the summary of rig sizing assessment result is presented in Figure 9.

Aspects	Minimum Rig Specification Requirement	Basis of Minimum Requirement
Mast / Hook Load Capacity	548,679.15 lbs	Heaviest BHA load which is 12-1/4" BHA configuration + MOP assumption (100,000 lbs) with safety factor 25%
Setback Capacity	416,396.79 lbs	Minimum capacity of racked Drill string during open hole section in reservoir zone (12-1/4") + safety factor 25%.
Rotary Table Opening	27-1/2"	Biggest OD of bit and BHA that will be run in hole during operation (26"). Considering clearance 1-1/2", the minimum rotary table opening should be 27-1/2".
Below Rotary Table Clearance	Typical 4.5 – 8 m, depends on Wellhead and BOP height	Typical wellhead in geothermal has height range from 1.7 – 2.5 m, and BOP 3.5 – 4.5 m when drilling 12-1/4" hole section.
Make Up Torque	57,400 lbs-ft	Make up torque of 8" Drill Collar with ID 2-1/2"
Minimum Flowrate	250 gpm	Estimated flowrate in 6-1/8" hole section (perforated liner contingency 5-1/2")
Maximum Flowrate	1200 gpm	Based on hydraulics and hole cleaning simulation in 26" hole section and based on flowrate calculation during blind drilling scenario

Figure 9: Basis of Rig Requirement for the Example Project Well.

The summary comparison of minimum requirement with typical rig specification in Indonesia is summarized in Figure 10 and Figure 11 as follows:

Aspects	Minimum Rig Specification Requirement	750 HP Spec. / Rating	1,000 HP Spec. / Rating	1,500 HP Spec. / Rating	Remarks on Prefered Rig Adequacy
Drawwork Rating	1,264 HP	750 HP	1000 HP	1500 HP	1,500 HP Rig
Mast / Hookload Capacity + MOP 100,000 lbs	550,768.88 lbs	250,000 lbs	400,000 lbs	680,400 lbs	1,500 HP Rig
Setback Capacity + MOP 100,000 lbs	425,768.68 lbs	250,000 lbs	412,000 lbs	500,000 lbs	1,500 HP Rig

Figure 10: Comparison of Minimum Requirement with Typical Rig Specification in Indonesia for Load Rating.

Aspects	Minimum Rig Specification Requirement	750 HP Spec. / Rating	1,000 HP Spec. / Rating	1,500 HP Spec. / Rating	Remarks on Prefered Rig Adequacy
Rotary Table Opening	27.5"	17.5"	27.5"	27.5"	1,000 HP & 1,500 HP Rig
Below Rotary Table Clearance	Typical 4.5 – 8 m, depends on Wellhead and BOP height	5.49m / 18 ft	5.49 m / 18 ft	9.45 m / 31 ft	1500 HP Rig
Make Up Torque	57,400 lbs-ft	32,000 ft-lbs (475 HP Top Drive)	45,000 ft-lbs (600 HP Top Drive)	60,000 ft-lbs (800 HP Top Drive)	1,500 HP Rig
Minimum Flowrate	300 gpm	162 gpm	189 gpm	180 gpm	All Rig Spec
Maximum Flowrate	1200 gpm	1739 gpm (750 HP x 3 pumps, 7" liner)	1754 gpm (1000 HP x 3 pumps, 7" liner)	2118 gpm (1600 HP x 3 pumps, 7" liner)	All Rig Spec

Figure 11: Comparison of Minimum Requirement with Typical Rig Specification in Indonesia for Load Rating.

4. DISCUSSION

The complicated nature of geothermal drilling projects, characterized by diverse stakeholders, complex organizational dynamics, and multifaceted equipment requirements, underscores the pivotal role of meticulous rig sizing. This paper delves into the critical components and decision-making criteria underpinning the selection of drilling rigs in geothermal exploration endeavors.

The paper commences by elucidating the significance of rig selection in ensuring efficient and cost-effective drilling operations. It highlights the need for alignment between rig specifications and project demands, emphasizing that the size, power, and capacity of the rig must harmonize with the drilling program's requisites. Geothermal projects are inherently distinct, with factors such as well depth, formation characteristics, and temperature conditions influencing the selection of the most suitable drilling rig.

The deliberations extend to the evaluation of rig sizing criteria, encompassing hoisting capacity, drawwork rating, rotary table opening, makeup torque, and pump flowrate. Rig sizing emerges as a critical determinant in the success of drilling operations, impacting cost, safety, efficiency, and adherence to project timelines. Proper rig sizing facilitates the seamless execution of drilling activities, preventing accidents, equipment damage, and operational downtime. Rig size and capability play a crucial role in defining drilling project outcomes, as evidenced by the interplay of unit price, quantity, and the ensuing total cost.

The findings underscore the priority of a strategic approach to rig selection, considering geological, technical, economic, safety, and environmental factors. Collaborative engagement among geoscientists, drilling engineers, and project managers emerges as essential to the rig selection process. The study advocates for a rig sizing framework rooted in well-defined criteria, ensuring that the selected rig aligns with project specifications, optimizes operational efficiency, and mitigates risks.

In conclusion, rig sizing stands as a linchpin in the intricate web of geothermal drilling projects. The judicious assessment of factors and decision-making criteria delineated in this paper empowers stakeholders to make informed choices in rig selection, ushering in successful exploration outcomes while fostering safety, efficiency, and cost-effectiveness. By grasping the nuances of rig sizing, geothermal projects can navigate complexities with precision, propelling the industry toward sustainable growth and innovation.

REFERENCES

Adityatama, D.W., Purba, D., Muhammad, F., Agustino, V., Wiharlan, H., and Pasmeputra, K. K. (2020). *Slimhole Drilling Overview for Geothermal Exploration in Indonesia: Potential and Challenges*, *Proceedings*, 45th Workshop on Geothermal Reservoir Engineering, Stanford University, Stanford, California, United States.

Asokawaty, R. F., Purba, D. P., Adityatama, D. W., Muhammad, F., & Umam, M. (2020). *Indonesia's Geothermal Development Comp are to World Top Geothermal Producers*. 45th Workshop on Geothermal Reservoir Engineering.

Chandra, V. R., Asokawati, R. F., Purba, D. P. (2021a). *Common Practice of Formation Evaluation Program in Geothermal Drilling*. *PROCEEDINGS*, 46th Workshop on Geothermal Reservoir Engineering. Stanford University, Stanford, California, February 15-17, 2021.

Chandra, V. R., Purba, D., Nayoan, G. P. A., Fadhillah, F. R., Ramadhan, R. F., Anggara, R. (2021b). *Identifying and Assessing Geohazard in Indonesia Geothermal Area: How Difficult Is It? PROCEEDINGS*, 46th Workshop on Geothermal Reservoir Engineering. Stanford University, Stanford, California, February 15-17, 2021.

Darma, S. (2016). Indonesia: Vast geothermal potential, modest but growing exploitation. In *Geothermal Power Generation: Developments and Innovation* (pp. 609–643). Elsevier Inc. https://doi.org/10.1016/B978-0-08-100337-4.00021-8

Direktorat Panas Bumi. (2022). *Buku Pintar Umum Panas Bumi*.

DPR RI. (2022a). Live Streaming – Komisi VII DPR RI RDP dengan Kementerian ESDM RI *Terkait Penjelasan Kejadian Kebocoran Sumur Gas PT Sorik Merapi Geothermal Power pada Bulan April 2022*, retrieved from: https://www.youtube.com/watch?v=CWmqBQWGnJw&t=7826s.

DPR RI. (2022b). Live Streaming – Komisi VII RDP dengan Dirjen EBTKE KESDM RI *Terkait Penjelasan kejadian kebocoran gas dan keracunan gas beracun (H2S, S02) yang dialami masyarakat sekitar lokasi PT Sorik Marapi Geothermal Power dan PT Geo Dipa Energi (Persero)*, retrieved from: https://www.youtube.com/watch?v=VDTK9xYbkwI&t=655s.

GeothermEx (2010). *An assessment of geothermal resource risks in Indonesia*.

Ibrahim, R. F., & Fauzi, A, Suryadarma. (2005). *The progress of geothermal energy resources activities in Indonesia*. Paper presented at the *Proceeding* World Geothermal Congress 2005, 1-7.

IGA. (2014). *Best practices guide for geothermal exploration*. Bochum, Germany: International Geothermal Association.

Lavis, J. (2018). *Drill Well on Paper (DWOP) – The Gift of Foresight*. Article published in Drillers.com, 21 August 2018. Retrieved from: https://drillers.com/drill-well-on-paper-dwop-the-gift-of-foresight/#:~:text=Drilling%20the%20well%20on%20paper,and%20potential%20contingency%20action%20points.

McAndrews, K., L. (2011). *Consequences of Macondo: A Summary of Recently Proposed and Enacted Changes to U.S. Offshore Drilling Safety and Environmental Regulation. Proceedings*. SPE Americas E&P Health, Safety, Security and Environmental Conference held in Houston, Texas, USA, 21–23 March 2011.

MCG. (2022). *Studi Kelayakan Proyek Pembangkit Listrik Panas Bumi (PLTP) WKP Blawan Ijen Unit 1 – 35 MW (gross) Kabupaten Bondowoso - Jawa Timur*, PT Medco Cahaya Geothermal, (unpublished report).

MCG. (2020). *IJN 6-1 / IJN 6-1 ST 1 End of Well Report*, PT Medco Cahaya Geothermal, (unpublished report).

Nugraha, R. P., O'Sullivan, J., and O'Sullivan, M. J. (2018). *A 3D Geological Model and Natural State Simulation of Jaboi Geothermal Field, Nangro Aceh Darussalam, Indonesia*, *Proceedings*, New Zealand Geothermal Workshop, Taupo, New Zealand.

Nwokoma, P. & Knobben, X. (2017). *Rethinking the Typical Line-Item DWOP Exercise: Does it Present a Complete Picture?. Proceedings.* 2017 SPE/IADC Drilling Conference and Exhibition in The Hague.

O'Sullivan, J., Archer, R., O'Sullivan, M., Krom, T., & Williams, B. (2017). *A NEW GEOTHERMAL MODELLING WORKFLOW USING LEAPFROG AND TOUGH2*. 6th ITB International Geothermal Workshop. Bandung. (2017)

O'Sullivan, M. J., & O'Sullivan, J. P. (2016). *Reservoir Modeling and Simulation for Geothermal Resource Characterization and Evaluation*. In R. D. (Ed), Geothermal power generation: developments and innovation. Woodhead Publishing.

Purba, D.P., Adityatama, D.W., Nugraha, R. P., Ayuningtyas, R. R., Chandra, V. R., Al-Hassan, M. A., Ramadhan, R. F., Rizqy, M. M. (2021). *Resource Assessment Methods Selection for Geothermal Exploration Project in Indonesia: What Are the Considerations? Proceedings*, 46th Workshop on Geothermal Reservoir Engineering, Stanford University, Stanford, California, United States.

Purba, D.P., Adityatama, D.W., Agustino, V., Fininda, F., Alamsyah, D., and Muhammad, F. (2020). *Geothermal Drilling Cost Optimization in Indonesia: A Discussion of Various Factors, Proceedings*, 45th Workshop on Geothermal Reservoir Engineering, Stanford University, Stanford, California, United States.

Purba, D.P., Adityatama, D.W., Umam, M.F., and Muhammad, F. (2019). *Key Considerations in Developing Strategy for Geothermal Exploration Drilling Project in Indonesia, Proceedings*, 44th Workshop on Geothermal Reservoir Engineering, Stanford University, Stanford, California, United States.

Purba, D.P (2018).: Energy 785 Research Project Report: *Investigation on Geothermal Resource Assessment Methods in Reducing Exploration Risk in Indonesia Geothermal System*. The University of Auckland, New Zealand. Unpublished manuscript.

Purwanto, E. H., Suwarno, E., Lukman, R. F., and Herdiyanto, B. (2018). *Geothermal Drilling in Indonesia: A Review of Drilling Operation, Evaluation of Well Cost and Well Capacity, Proceedings*, 6th Indonesia International Geothermal Convention & Exhibition, Jakarta, Indonesia.

Pusdatin ESDM. (2020): Ministry of Energy and Mineral Resources Media Center.

Poernomo, A. S. (2015). *An overview of Indonesia Geothermal Development – Current Status and Its Challenges*. Pp. 1 – 11. In: Proceedings of World Geothermal Congress, Melbourne, Australia.

Ramsey, M. S. (2019). *DWOPs, CWOPs, WOWOPs, and AWOPs for Fun and Profit!*, *Proceedings*, AADE National Technical Conference and Exhibition held at the Hilton Denver City Center, Denver, Colorado.

Ratouis, T. M., O'Sullivan, M., and O'Sullivan, J. (2015). *An Updated Numerical Model of Rotorua Geothermal Field, Proceedings*, World Geothermal Congress, Melbourne, Australia.

Sanyal, S. K., Morrow, J. W., Jayawardena, M. S., Berrah, N., Li, S. F., and Suryadarma. (2011). *Geothermal Resource Risk in Indonesia – A Statistical Inquiry*, *Proceedings*, 36th Workshop on Geothermal Reservoir Engineering, Stanford University, Stanford, California, United States.

Siahaan, M. F., Purba, D., Septiani, G. A., Paripurna, A. (2023). *Preparing Technical and Commercial Documents for Geothermal Exploration Project Financing in Indonesia, Proceedings*, 48th Workshop on Geothermal Reservoir Engineering, Stanford University, Stanford, California, United States.

SOL. (2019). *Siaran Pers Kebocoran Pipa di Namora I Langit / Press Release Pipeline leakage at Namora I Langit*, Retrieved from: https://sarullaoperations.com/images/press-release/5c9e0a4d8ba6b1553861197.pdf.

ThinkGeoEnergy. (2023). *Top 10 Geothermal Countries 2022 – Power Generation Capacity (MW).* https://Www.Thinkgeoenergy.Com/Thinkgeoenergys-Top-10-Geothermal-Countries-2022-Power-Generation-Capacity-Mw/Amp/. 11 January 2023.

Umam, M., Adityatama, D., & Purba, D. (2018). *Tantangan Pengembangan Energi Panas Bumi Dalam Perannya terhadap Ketahanan Energi di Indonesia*. Swara Patra, 8(3), 48-65.

Utami, P. (2010). *High-temperature Geothermal Area and its Challenges for Civil Engineering Works*. PERTEMUAN ILMIAH TAHUNAN XIV HATTI. Indonesia.

The Effort to Achieve The Best Performance Geothermal Drilling

Redha Bhawika Putra, Idam Rafif Maulana, Irfan Rasyid, Sentanu W. Reksalegora, Huda Nahrudi Ilham, and Charlotte T Mandagi

PT. Arka Data Pratama, ASA Tower, Kebayoran Baru, Jakarta Selatan, 12140, Indonesia

redha.putra@arkadata.net

Keywords: drilling operation, geothermal drilling, drilling performance, drilling improvement

ABSTRACT

Drilling is one of the most cost-taking activities in geothermal development. According to the annual report from Energy Sector Management Assistance Program (ESMAP) in 2011, drilling contributes 35-40% of the total cost of geothermal energy development. Drilling cost is mainly affected by the time needed to drill one well. The lower the drilling operation time, the lower the drilling cost.

The fastest drilling operation of a geothermal well in Indonesia happened while drilling one of the geothermal wells in West Java (Well X) in 2012 for only 9.82 days with 1736.5 mMD depth, about 176.8 m/days. Until now, there hasn't been a geothermal well drilled that could surpass Well X's performance in terms of drilling operation time. Currently, the fastest geothermal well drilled in North Sumatra (Well Y) spent 22.05 days with 2200 mMD depth, about 99.8 m/days, which was drilled in 2021.

To achieve or even beat the performance of Well X, a new comparable well as a baseline is needed in order to break down the performance of the drilling operation of Well X. Since Well Y is one of the fastest geothermal wells that has been drilled, yet its performance is not even close to the drilling performance of Well X. Also, Well Y has many things in common with Well X, so Well Y becomes comparable and suits as a baseline.

Potential areas of improvement will be identified after comparing the performance of Well X and Well Y and trying to improve it without compromising any factors. The final result of this research will be recommendations for improvement to beat the drilling performance of Well X.

1. INTRODUCTION

Geothermal energy is considered to be one of the most promising renewable energy sources due to its abundant and clean nature. However, the development of geothermal energy requires substantial investment, especially in the drilling process. Drilling contributes 35-40% of the total cost of geothermal energy development. Therefore, it is crucial to improve the drilling efficiency to reduce the cost of geothermal energy.

The drilling cost is mainly affected by the time needed to drill one well, and the lower the operation time, the lower the drilling cost. Commonly, it takes 32-60 days to drill one geothermal well with an average total depth of 2000-2500 m (Bjorn Mar S, 2012), and the average cost needed to drill a geothermal well is around 5 million dollars (Yudi Hartono, 2023). The biggest factor in reducing the cost is time. Hence, further, this paper will discuss drilling performance in terms of drilling operation time.

The fastest drilling operation of a geothermal well in Indonesia happened while drilling one of the geothermal wells in West Java in 2012 (Well X) for only 9.82 days with 1736.5 mMD depth, about 176.8 m/days. Currently, the fastest geothermal well drilled in North Sumatra (Well Y) spent 22.05 days with 2200 mMD depth, about 99.8 m/days, which was drilled in 2021. This paper will try to identify the areas of time improvement in order to beat the drilling performance of Well X and achieve the best geothermal drilling performance after comparing the best well with the baseline well.

2. METHODOLOGY

The methodology used in this research involves analyzing the drilling activity and determining the fastest and most effective ways to achieve the best geothermal drilling performance. To accomplish these goals, the following steps were taken:

Data collection: In this step, involved collecting data related to geothermal drilling operations. This data included the drilling time, drilling depth, drilling speed, and other factors that could affect the drilling performance.

Performance analysis: In this step, the drilling operation time of both wells would be breakdown into sub-activities. The time and rate of each sub-activity were evaluated and the fastest of each sub-activity was selected.

Improvement recommendations: The drilling operation of the sub-activities was analyzed and would be generated some practicable improvements that provides to be implemented for the next geothermal drilling operation.

Drilling operation simulation: After generating some practicable improvements, then simulation was created to drill a new well using Well Y profile with improved performance and compared the time results with the original performance.

3. WELL DATA

3.1 Well Background

Well X, drilled in West Java, achieved a depth of 1736.5 m with a remarkable performance of about 176.8 m/days, making it the fastest well drilled in the area, taking only 9.82 days. Meanwhile, in Sumatra, Well Y achieved a depth of 2200 m, becoming the fastest well drilled in the area, but it took 22.05 days to reach it, with a performance of about 99.8 m/days. These drilling days counted started from drilling the 26" hole section until the perforated liner is set and release the rig excluding the logging and well testing operations. Both wells successfully penetrated the feed zone and experienced lost circulation.

3.2 Well Profile

These two wells were drilled using the same hole and casing size for each section with different depths (as shown in Table 1). These two wells were drilled directionally with J type design. Well X has a final inclination of 55.51° and Well Y has a final inclination of 21.48°.

Table 1: Well Schematic.

Hole Section	Casing Size	Depth (mMD)	
		Well X	Well Y
26"	20"	362.7	406
17-1/2"	13-3/8"	670	1199.7
12-1/4"	10-3/4"	1736	2200

3.3 Drilling Operation

3.3.1 Equipment Problem

Even though these two wells are the best-performance wells in their locations, equipment problems still happened while drilling these wells. As shown in Table 2 below, both wells have limited hours of equipment problems. However, there are still areas for improvement if the equipment problem could be eliminated for future geothermal drilling.

Table 2: Equipment Problem.

Hole Section	Well X		Well Y	
	Problem	Duration (hours)	Problem	Duration (hours)
26”	Leaking wash pipe	1.25	-	-
17-1/2”	Bowl head seal damaged	1.5	Union connection washed out	5.5
12-1/4”	-	-	Flowline plugged	3.5

3.3.2 Hole Problem

While drilling these two wells there were several hole problems that occurred. As shown in Table 3 below, both wells have no major incident caused by hole problem. Therefore, by avoiding these hole problems it would be beneficial for future drilling operations.

Table 3: Hole Problem.

Hole Section	Well X		Well Y	
	Problem	Depth (mMD)	Problem	Depth (mMD)
26”	Tight hole	283-295	Pipe stalled	53
17-1/2”	-	-	Pipe stalled	1140
12-1/4”	Pipe stalled & Well kick	1232.3-1241.45	Tight spot	3.5
			Erratic torque	1960-1970

3.3.3 Drilling Operation Performance

These two wells (Well X and Well Y) are drilled with the same hole section which is 26”, 17-1/2”, and 12-1/4” hole section. For both wells, the 30” conductor casing was pre-installed using augering method. The final depth of both wells is different in each section, hence these two wells have different drilling operation times even though these two wells have the same hole section size (as shown in Table 4).

Table 4: Drilling Operation Time.

Hole Section	Well X			Well Y		
	From (mMD)	To (mMD)	Time (hr)	From (mMD)	To (mMD)	Time (hr)
26”	56.7	362.7	30.6	42	406	51
17-1/2”	362.7	670	30.1	406	1199.7	95
12-1/4”	670	1736	78.9	1199.7	2200	171

3.3.4 Bit Selection and Performance

All of those bits that were run for each section were new ones in Well X and Well Y. Well X used one drilling bit for each hole section. On the other hand, Well Y used one bit to drill 26” and 17-1/2” hole sections, but it was needed to run two drilling bits while drilling a 12-1/4” hole section due to the limit of bit Krev. The performance of the bit can be seen by looking at meterage and ROP on the bottom in these two wells (detailed information of the bit is shown in Table 5).

The roller cone bit used to drill a 12-1/4” hole section in Well X has severe damage on the bit (2-8 dullgrade), but it could finish the 12-1/4” hole sections with a meterage of 1066 m using only 1 drilling bit.

3.3.5 Wiper Trip

A wiper trip is needed to fulfill the borehole quality aspect, especially in terms of hole geometry. Even though a wiper trip is needed, it takes time to pull the drill string out of the hole to a certain depth and then run it back into the hole to continue the drilling activity. During the drilling operation, Well X only did a wiper trip if it is really needed. Even in drilling the 17-1/2” hole section, Well X didn’t do any wiper trip. On the other hand, during drilling Well Y wiper trip has been done 2x for every section drilled (as shown in Table 6).

Table 5: Drilling Bit General Data.

Well	Bit Type	Manufacture	Size	Depth In (mMD)	Depth Out (mMD)	Meterage (m)	ROP on bottom (m/hr)	Dull Grading
X	Roller Cone	Baker Hughes	26”	56.7	362.7	306	16.76	1-1-WT-A-E-I-NO-TD
	Roller Cone	Halliburton	17-1/2”	362.7	670	307.3	13.1	1-1-WT-A-E-I-NO-TD
	Roller Cone	SLB	12-1/4”	670	1736	1066	15.85	2-8-WT-A-E-I-CT-TD
Y	Roller Cone	Baker Hughes	26”	42	406	364	12.3	1-1-WT-A-E-I-BT-TD
	Kymera Hybrid	Baker Hughes	17-1/2”	406	1199.7	793.7	16.7	1-1-SD-A-F-I-WT-TD
								1-2-SD-S-X-I-WT-TD
	Roller Cone	Baker Hughes	12-1/4”	1199.7	1564	364.3	13.4	1-4-BT-A-E-I-WT-HR
	PDC	NOV	12-1/4”	1564	2200	636	13	1-2-WT-S-X-1/16”-CT-TD

Table 6: Wiper Trip.

Well	Hole Section	Wiper Trip	Reasons
X	26”	1x	Make up Dummy BHA
	17-1/2”	-	-
	12-1/4”	1x	Abnormal torque and drag
Y	26”	2x	-
	17-1/2”	2x	-
	12-1/4”	2x	-

4. DISCUSSION

4.1 Drilling Activity Comparison

Drilling Operation of Well X and Well Y needed to be breakdown into each activity to easier to compare and analyze the performance. This analysis uses “hr/m” unit for the depth-dependent activities and “hr” unit for the depth-independent activities. The use of “hr/m” and “hr” as the performance units are also intended to make this performance applicable in other drilling operations. Then, the performance of each activity will be compared to determine which one has the best performance according to the lower value of both “hr/m” and “hr” units (as shown in Table 7).

Table 7: Drilling Activity Comparison.

Hole Section	Activity	Well X	Well Y	Units	Diff.
26”	1. Drilling 26"	0.10	0.14	hr/m	**0,040**
26”	2. POOH and L/D 26” BHA	0.005	0.010	hr/m	0,005
26”	3. Running Casing 20"	0.025	0.025	hr/m	0,000
26”	4. Cementing 20"	11	40	hr	-
26”	5. N/U and test BOPE and flowlines.	5	7	hr	-
26”	6. M/U 17-1/2" BHA, shallow test MWD and RIH to TOC	0.014	0.035	hr/m	0,021
17-1/2”	7. Drilling 17-1/2"	0.098	0.134	hr/m	**0,036**
17-1/2”	8. POOH and L/D 17-1/2” BHA	0.002	0.010	hr/m	0,008
17-1/2”	9. Running Casing 13-3/8"	0.008	0.011	hr/m	0,003
17-1/2”	10. Cementing 13-3/8" Liner	10.5	19.5	hr	-
17-1/2”	11. M/U hole opener. RIH and redress tieback receptacle. POOH	0.024	0.064	hr/m	**0,040**
17-1/2”	12. N/D BOP. Final cut 20" casing	5.5	5.5	hr	-
17-1/2”	13. Running 13-3/8" Tieback	0.02	0.02	hr/m	0,000
17-1/2”	14. Cementing 13-3/8" Tieback	9.5	20.5	hr	-
12-1/4”	15. Drilling 12-1/4"	0.074	0.171	hr/m	**0,097**
12-1/4”	16. POOH and L/D 12-1/4" BHA	0.004	0.003	hr/m	0,001
12-1/4”	17. Running 10-3/4" Perforated Liner	0.007	0.01	hr/m	0,003

According to Table 7, the best performance is dominantly achieved during drilling Well X, and only 1 activity of Well Y is faster than what was done in Well X, that is L/D 12-1/4" BHA. Well Y as a baseline is still not even close to the performance of Well X in terms of operation time. Hence, as a baseline, Well Y is still able to improve its performance to achieve better results and reduce drilling operation times.

4.2 Areas of Improvement

Determining the areas of improvement or what things that could be done to achieve the best drilling performance to cut the drilling days is the most important part of this research. So, this research will provide recommendations of improvement for the activity that has the most impactful effect on drilling performance which are the top four activities that have a far difference (as shown in Table 7).

4.2.1 Single-Run BHA

It is really beneficial if a drilling operation only uses single BHA runs for each drilling section, regardless of well location, hole angle, and TVDs. Single BHA runs are really recommended since if another BHA is used to drill the same section, it will be a time-wasting to pull out of hole (POOH) the last BHA and run in hole (RIH) the next BHA. In most geothermal or oil companies, single-run BHA is commonly set as the key performance indicator of the drilling activity.

By looking at these two wells, Well X already fulfills the requirement to only use single BHA runs for every section drilled. In drilling 12-1/4" hole section of Well Y, two BHA were used due to the first BHA being limited on the Krev, therefore the second BHA is needed to continue drilling to reach TD. Based on what happened in drilling 12-1/4" Well Y, if it is not possible to reach TD using a single BHA due to bit hours, we could increase the ROP to achieve the TD before the bit's Krev reaches the limit. Increasing the ROP need to consider the BHA limitation (maximum applicable drilling parameter) so this paper doesn't compromise the bit durability.

Hence, a proper BHA that could accommodate the needs to achieve TD using only a single BHA and applying optimum drilling parameters are recommendations for future drilling operations. It is also possible to extend the depth of the previous section or to use a high-performance bit. In order to achieve lesser meterage for the last section and could be drilled to TD with only a single BHA run.

4.2.2 Effective Wiper Trip Application

The current application of wiper trips in the drilling industry is based on the rule of thumb or just a drilling practice instruction from each company, commonly 300 meters after drilling a new formation (might vary by company). The amount of wiper trips done could affect the drilling operation time which is related to the drilling cost. The lesser the wiper trips done the faster the well drilled.

The wiper trip application in these two wells is quite minimum (as shown in Table 8), which is one of the reasons these two wells become the fastest well drilled in their location. Well X uses the least amount of wiper trips in its drilling activities compared to Well Y. Well X only did 2 times wiper trips during its drilling activity, while Well Y did 6 times wiper trips (2 times each section).

Table 8: Wiper Trips.

Hole Section	Well X		Well Y	
	Wiper Trip (times)	Duration (hours)	Wiper Trip (times)	Duration (hours)
26"	1	1.75	2	2.5
17-1/2"	-	-	2	8
12-1/4"	1	1	2	1.5

By looking at the wiper trips practice in Well X drilling activity, wiper trips only be done if there are any specific reasons. The wiper trip in 26" Well X was done because of the need to replace 3 stands of HWDP with 3 stands of drill collar, and the 12-1/4" wiper trip was done due to experiencing abnormal torque and drag. Meanwhile, the wiper trips which were done in Well Y were to ensure the borehole quality, but it took 12 hours.

For most of those wiper trips done in Well Y, the hole was still in good condition. Therefore, based on this analysis, it will be beneficial if the drilling operation is able to decrease the number of wiper trip activities. In order to eliminate any unnecessary wiper trip activities to reduce drilling operation time, it is recommended to analyze the offset well data regarding the borehole quality. So that only necessary wiper trips would have been done without compromising the borehole quality.

4.2.3 Technical Limit Understanding & Optimal Drilling Parameter Application

To increase the drilling efficiency, especially in terms of reducing drilling operation times, it is recommended to apply an optimal drilling parameter. An optimal drilling parameter is obtained by doing an analysis of the technical limits of all equipment used. Having an understanding of equipment's technical limits, allows us to apply drilling parameters close to the limit.

From these two fastest wells, 3 parameters that have the most effect on drilling efficiency (WOB, ROP, & RPM) were analyzed (as shown in Figure 1). It is proven that in Well X drilling operations higher drilling parameters were applied compared to Well Y drilling operations, resulting in a higher drilling performance. The takeaway from this case is to do a technical limit analysis to get a better understanding, so it is possible to push the drilling performance with no other aspect that will be compromised.

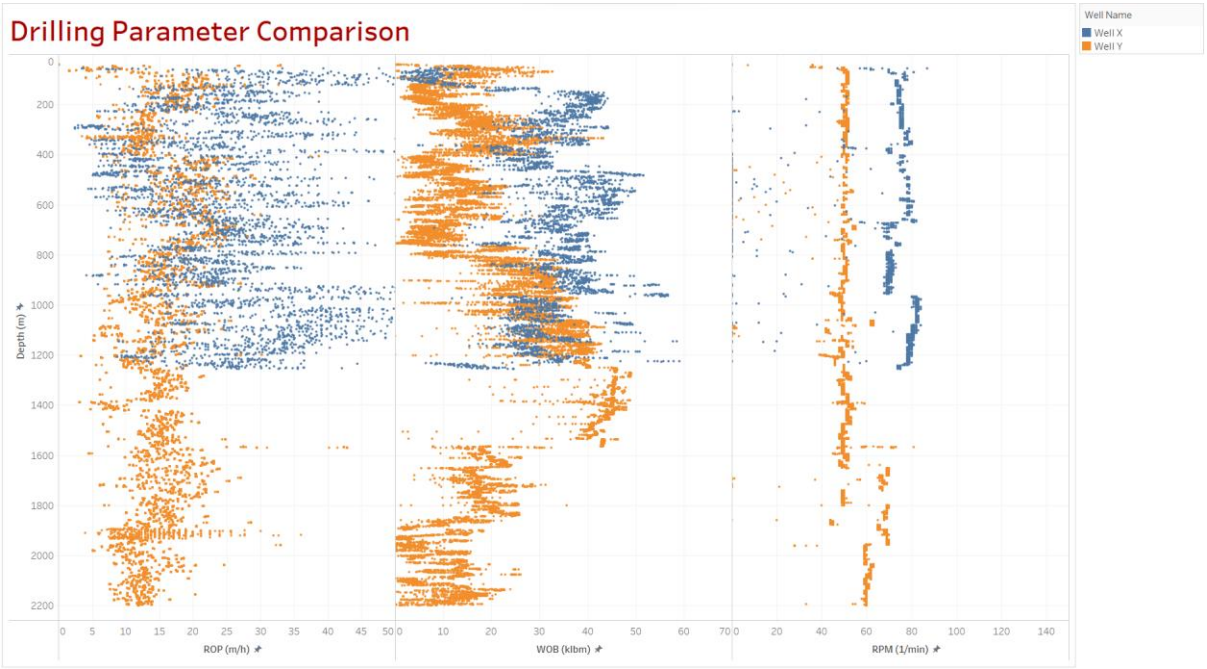


Figure 1: Drilling Parameter Comparison Between Well X vs Well Y *(Source : dashboard.arkadata.net)*.

4.2.4 Single Clean-Out BHA

After the liner cementing has been done, we need to clean the excess cement, especially inside the tieback receptacle, therefore it is important to use only a single clean-out BHA to clean the excess cement. Using a single clean-out BHA is directly related to the drilling operation time, because it has the same concept as the previous discussion about single-run BHA, if we use another clean-out BHA it will be a time-wasting to POOH and then RIH the next clean-out BHA.

Regarding the clean-out activity in these two wells (Well X and Well Y), Well X already applied a single clean-out BHA to clean the inside tieback receptacle using one drilling bit and two hole openers with different sizes, meanwhile, Well Y used two clean-out BHA with different bit size (as shown in Table 9).

Table 9: Clean Out BHA Assembly.

Well	Tieback Casing Size	Clean Out BHA	RIH Time (Hours)	POOH Time (Hours)
X	13-3/8”	12-1/4” TCB x 14-3/4” HO x 17-1/2” HO	1.5	1.5
Y	13-3/8”	17-1/2” TCB	4	3
	13-3/8”	14-3/4” TCB	2.5	2

As shown in Table 9, the tieback receptacle clean-out activity of Well X using single clean-out BHA Various sizes of bit and hole opener only spent 3 hours in the RIH and POOH activity. On the other hand, Well Y using two clean-out BHA with only a drilling bit, without utilizing any hole opener spent 11.5 hours for RIH and POOH those two clean-out BHA assemblies.

Designing a single clean-out BHA is recommended for future drilling operations since it could save time which is related to saving up drilling costs. The thing that needs to be considered to design this single clean-out BHA using a drilling bit and hole openers is the placement of the hole openers, if the hole opener placement is too close to the bit perhaps it could damage the tieback receptacle and compromise the casing integrity, but if the placement is too far from the bit the cleaning activity would not be optimum.

4.3 Well Y (Improved) Simulation

According to the areas of improvement, using the data of Well Y then Well Y (Improved) is generated as shown in Table 10.

Table 10: Well Y (Improved).

Hole Section	Activity	Well Y	Well Y (Improved)	Units	Diff.
26”	1. Drilling 26"	**0,14**	**0,1**	hr/m	**0,040**
26”	2. POOH and L/D 26” BHA	0,01	0,01	hr/m	0,000
26”	3. Running Casing 20"	0,025	0,025	hr/m	0,000
26”	4. Cementing 20"	40	40	hr	-
26”	5. N/U and test BOPE and flowlines.	7	7	hr	-
26”	6. M/U 17-1/2" BHA, shallow test MWD and RIH to TOC	0,035	0,035	hr/m	0,000
17-1/2”	7. Drilling 17-1/2"	**0,134**	**0,098**	hr/m	**0,036**
17-1/2”	8. POOH and L/D 17-1/2” BHA	0,01	0,01	hr/m	0,000
17-1/2”	9. Running Casing 13-3/8"	0,011	0,011	hr/m	0,000
17-1/2”	10. Cementing 13-3/8" Liner	19,5	19,5	hr	-
17-1/2”	11. M/U hole opener. RIH and redress tieback receptacle. POOH	**0,064**	**0,024**	hr/m	**0,040**
17-1/2”	12. N/D BOP. Final cut 20" casing	5,5	5,5	hr	-
17-1/2”	13. Running 13-3/8" Tieback	0,02	0,02	hr/m	0,000
17-1/2”	14. Cementing 13-3/8" Tieback	20,5	20,5	hr	-
12-1/4”	15. Drilling 12-1/4"	**0,171**	**0,074**	hr/m	**0,097**
12-1/4”	16. POOH and L/D 12-1/4" BHA	0,003	0,003	hr/m	0,000
12-1/4”	17. Running 10-3/4" Perforated Liner	0,01	0,01	hr/m	0,000

By improving the most impactful performance, it is possible to calculate the drilling days of a well drilled of which the well profile is identical with Well Y using these areas of improvement. The total calculated drilling days to drill Well Y using the recommendations of areas of improvement was 15.66 days (Well Y Improved). It is way shorter compared to the drilling days of Well Y (Actual) which is 22.05 days. As a result of improving the most impactful performance, drilling days are able to be reduced 29% days compared to the actual Well Y (as shown in Table 11).

Table 11: Drilling Days of Well Y (Actual) & Well Y (Improved).

Hole Section	Drilling Days		Diff.	
	Well Y (Actual)	Well Y (Improved)		
26”	4.66	4.05	0.61	13%
17-1/2”	9.07	7.33	1.74	19%
12-1/4”	8.32	4.28	4.05	49%
Depth (Meter)	2200	2200	-	-
Total Drilling Days	**22.05**	**15.66**	**6.39**	**29%**
Meter/Days	**99.79**	**140.50**	**40.71**	**41%**

5. CONCLUSION

Based on all of the discussion in the previous section, several things can be concluded from this research, such as:

- The current best drilling performance (Well X) is achievable and can be mimicked for future drilling operations.
- After comparing the fastest performance with a baseline and then improving the most impactful operation, Well Y (Improved) showed a significant performance and reduced almost 30% days than the original one. The recommendations of the areas of improvement are:
    - Single-run BHA to drill each hole section.
    - Single-run BHA Clean-out using the combination of drill bit and hole opener to clean the inside of tie-back receptacle.
    - Offset well analysis regarding borehole quality is needed to eliminate unnecessary wiper trips application.
- May the fastest well didn't apply the technical limit of each drilling parameter. However, understanding the equipment's technical aspect and applying optimal drilling parameters could result in increasing the drilling performance.

REFERENCES

Finger, John, and Doug Blankenship. Handbook of Best Practices for Geothermal Drilling. Sandia Report (SAND2010-6048), (2010).

Hartono, Yudi. The Economic Way in Drilling Geothermal Wells. EBTKE, Jakarta (2022)

Thorhallsson, Sverrir, Bjorn Mar Sveinbjornsson. Geothermal Drilling Cost and Drilling Effectiveness. Short Course on Geothermal Development and Geothermal Wells. United Nations University, Iceland (2012).

World Bank. 2011. Energy Sector Management Assistance Program: 2011 Annual Report. Washington DC; World Bank.

Reducing Stuck Pipe Risk in Geothermal Drilling Operations Through Anomaly Prediction with Artificial Neural Network Algorithm

Fandika Galih Pradana[1,3], Redha Bhawika Putra[1], Darnisa Azzahra Nasution[1], Charlotte T. Mandagi[1], Ridha Nugraha[2], and Edyson Purba[2]

[1]Arka Data Pratama, Infiniti Office, Bellezza BSA 1st Floor, Jakarta Selatan 12210, Indonesia
[2]Jakarta Drilling Society, Jakarta Energy Hub, Kebayoran Lama, Jakarta Selatan, 12210, Indonesia
[3]Petroleum Engineering Dept, Universitas Pertamina, Jakarta Selatan, 12210, Indonesia

Fandikagp5@gmail.com

Keywords: geothermal drilling, machine learning, anomaly detection, stuck pipe prevention

ABSTRACT

Stuck pipe is a common issue encountered and is one of the most significant contributors to Non-Productive Time (NPT) during geothermal drilling. The stuck pipe can be a costly and time-consuming problem because it can delay drilling operations and will require special equipment and techniques to free the pipe. In preventing stuck pipes there are various techniques that can be used, in this case, a machine learning approach will be used for stuck pipe prediction.

The dataset that will be used is geothermal drilling wells in Indonesia that have stuck pipe experience 12-1/4" and 9-7/8" hole sections and are in lost circulation conditions. The machine will try to identify any anomaly or pre-stuck condition which happen prior to being stuck pipe. To determine pre-stuck conditions several drilling parameters will observe, such as ROP, WOB, Hookload, RPM, etc.

For the data learning process, the Artificial Neural Network (ANN) algorithm is applied with the feed-forward back-propagation learning method. The dataset will be divided into 70% training data and 30% testing data. The results of testing the data show an accuracy of 0.68 and the results on blind data show an accuracy of 0.59. By using machine learning to predict "pre-stuck" conditions, geothermal drilling companies can take proactive measures to prevent stuck pipes and reduce downtime and costs associated with drilling delays.

1. INTRODUCTION

Stuck pipes are one of the problems encountered during geothermal drilling and are often one of the largest contributors to Non-Productive Time (NPT) (Purba et al., 2021). A stuck pipe is an event when the drill string cannot move up, down, or rotate. Usually, geothermal operators define a stuck pipe as a condition when the pipe cannot move for 15 minutes. Before the pipe could not move, there was an anomaly that made the parameters change so the driller had to be more vigilant. Changing parameters so that the pipe cannot move is called zone "pre-stuck" condition (Figure 1). In geothermal drilling operations, the chance of a stuck pipe is high, because the target is within lost circulation in the reservoir depth zone. Some other causes of stuck pipe events are improper hole cleaning, poor well trajectory, improper use of drilling mud, pressure differences, etc.

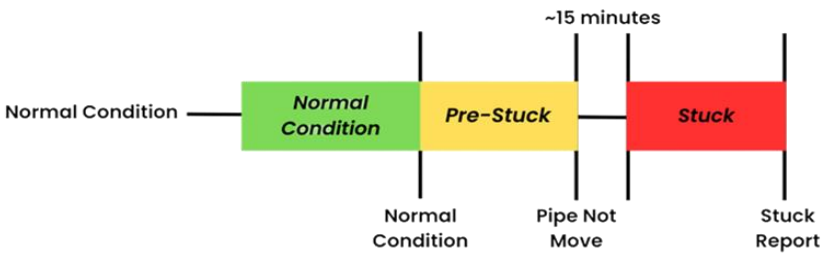


Figure 1: Zone "on the way" to the stuck pipe.

Of the most recent cases in Indonesia, stuck pipes accounted for about 10-30 percent of the total NPT and the losses amounted to hundreds of thousands of dollars, which included costs related to equipment and special techniques for freeing up pipes, replacement of lost downhole equipment, and delayed drilling operations (Sarwono et al. (2022). As for ways to overcome stuck pipes, among others, mechanical back-off, jet-cutter, plug and abandonment, and sidetrack.

Prevention of stuck pipe is preferable and very important to do because it will save more cost and time than carrying out even the most efficient stuck pipe-freeing procedures. Therefore, in this study, a machine learning algorithm, specifically Artificial Neural Network (ANN) will be applied to the set of historical data of geothermal fields in Indonesia. ANN will predict "pre-stuck" conditions, to enable engineers to prepare actions in advance to prevent stuck pipe incidents.

2. METHODOLOGY

The objective of this study is to predict "pre-stuck" conditions for minimize the risk of stuck pipes in geothermal drilling operations using machine learning, especially the Artificial Neural Network (ANN) algorithm. In this study, the following methodology was used:

2.1 Literature Study

In this study, the literature study was conducted to collect data, information related to stuck pipe problems, and to identify the parameters that have a strong correlation with the incidence of stuck pipes. Additionally, the study gathered information on machine learning techniques such as prediction, the tools used in the data processing phase and Artificial Neural Network (ANN).

2.2 Data Collecting

This study involved approximately 50 geothermal well data from the North Sumatra and West Java fields. The data set includes DDR (daily drilling report) and mud logging data which is measured in real-time every 5 seconds. The data criteria used in this research are wells that have stuck pipes at the depth of the reservoir zone (section 12-1/4” and 9-7/8”) and lost circulation conditions, so it is necessary to filter the 50 well data first. Based on the DDR analysis, there are 8 wells that are stuck pipe according to the criteria, where 4 wells come from geothermal fields in West Java and 4 wells come from geothermal fields in North Sumatra.

2.3 Data Visualization and Labelling

The data that has been collected needs to be visualized first using time-based mud logging data. Visualization was carried out on 8 wells, where this aims to find out what normal drilling conditions were like at first, when did the stuck pipe start, and look for anomalies before the stuck pipe happened. Visualization is made with the y-axis is the time (datetime) and the x-axis is the drilling parameters on time-based mud logs. The following is an example of visualization on the SD-168 well (Figure 2),

The next step is to validate the time-based mud log information that has been visualized with the daily drilling report data. After knowing what the conditions are like when it’s normal, anomaly or pre-stuck, and when the stuck pipe, you can label each condition. Normal conditions will be labeled '0', anomaly or pre-stuck conditions will be labeled '1', and conditions when stuck pipe will be labeled '2'. These three labels will be the target or output of machine learning.

2.4 Data Preprocessing

Data preprocessing is a crucial stage in research that involves processing, cleaning, and preparing data to optimize its quality for interpretation by machines. The following are some stages of data preprocessing carried out:

2.4.1 Feature Selection

There are 9 parameters that are used as input, where these parameters are chosen because they have a significant relationship when the drilling operation is in normal, pre-stuck, or stuck pipe conditions. The following parameters as used:

- Torque (klb.ft)
- Hookload (klb)
- Weight On Bit (klb)
- Rate Of Penetration (m/hr)
- Standpipe Pressure (psi)
- Flow Pump (gpm)
- Total RPM (rpm)
- Return (%)
- Activity (On Bottom Rotate Mode and Reaming/Tripping)

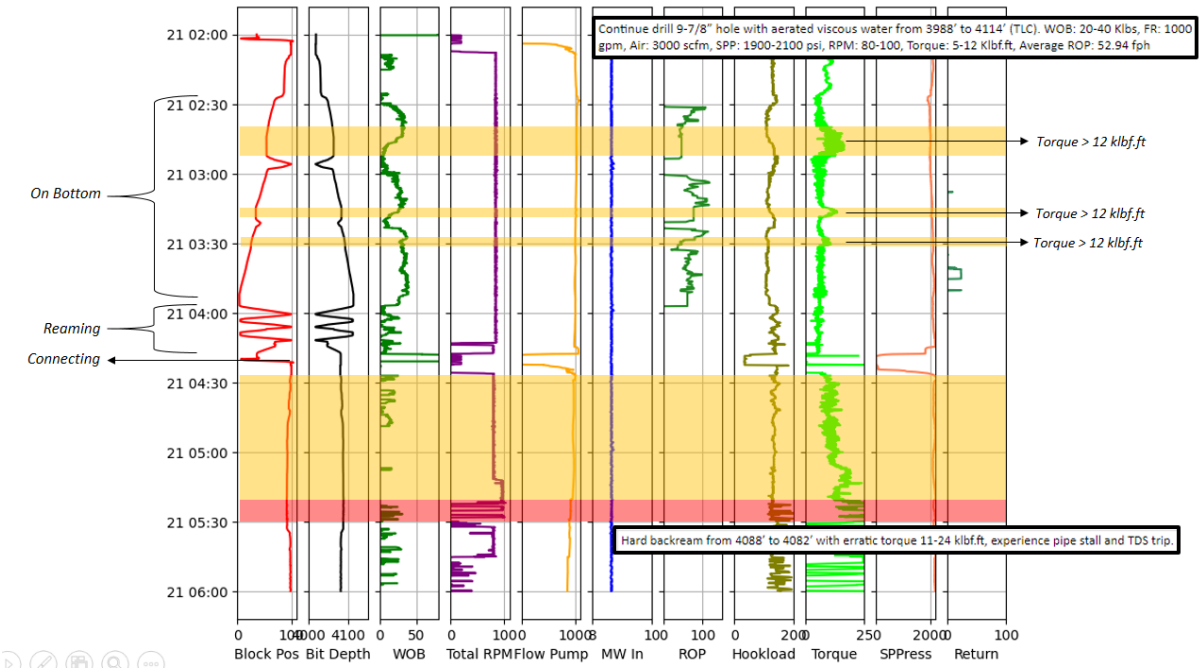


Figure 2: Visualization of time-based mud logging data on the SD-168 well.

2.4.2 Data Cleaning

This stage will identify and handle irrelevant data such as missing values and outliers (invalid data). The irrelevant data will be deleted or replaced with zero according to the conditions.

2.4.3 Categorical Encoding,

Convert "category" variables to "numeric" for use in models, such as one-hot encoding.

2.4.4 Data Balanced

There is an imbalance in the class or data label. To overcome the imbalance of data classes, using the SMOTE (Synthetic Minority Over-Sampling Technique) method. The SMOTE method will make the minority data class synthetic sample equivalent to the majority data class..

2.4.5 Data Split

The data will be split into training data and testing data. The training data set is used to train an algorithm model, while data testing is used to evaluate the accuracy of the built algorithms. At this stage, the data is split into 70% training data and 30% testing data.

2.4.6 Data Normalization

The last stage before modelling is change the format or scale of data to make it easier for system or machine to process. Data normalization was carried out using the min-max normalization method

(equation 1). Applying this method scales all columns in the data to a range between 0 and 1. It aims to subtract the minimum value of each column and divide it by the range of values from that column so that it has the same scale.

$$normalized\ (x) = \frac{minRange+(x-minValue)(maxRange-minRange)}{maxValue-minValue} \quad (1)$$

2.5 Modelling

This stage is the application of the Artificial Neural Network (ANN) algorithm with the Feed Forward learning method. The ANN algorithm learns patterns and trends in the data through a training process. The ANN structure is created by specifying the input layers, the number of hidden layers, the number of neurons, activations, and solver. Sensitivity analysis is performed by changing the number of hidden layers, neurons, activations, and solver to determine the best structure of the ANN model.

2.6 ANN Model Evaluation

Model evaluation is carried out to measure the performance of the model in predicting "pre-stuck" conditions in reducing the risk of stuck pipes. Evaluation is carried out to ensure that the model built has succeeded in learning patterns from the training data properly and can explain data that has never been seen before. Accuracy scores can help evaluate model performance and determine if adjustments or improvements are needed. Accuracy is the percentage of predictions that are correct against all predictions made. The greater the accuracy value, the better the model performance. The following is the Accuracy Score equation (equation 2).

$$Accuracy\ Score = \frac{(TP+TN)}{(TP+TN+FP+FN)} \quad (2)$$

Description:

TP (True Positive) = the number of positive data predicted correctly by the system

TN (True Negative) = the number of negative data correctly predicted by the system

FP (False Positive) = the number of positive data but predicted incorrectly by the system

FN (False Negative) = the number of negative data but predicted incorrectly by the system

3. RESULTS AND DISCUSSION

In this study, a combined dataset of eight wells with stuck pipes was used (Figure 2). The dataset is used for data training and testing. The dataset contains 195019 rows and 12 column parameters, which include dt (datetime), WOB (Weight On Bit), RPM (Rotation per Minute), Flow Pump, ROP (Rate of Penetration), Hookload, Torque, STPpress (Standpipe Pressure), Return (% mud flow out), Condition (Reaming/Tripping and On Bottom), Well (Name of Well), and class/target (0, 1, 2).

	dt	WOB	RPM	Flow Pump	ROP	Hookload	Torque	STPpress	Return	Condition	Well	Class
0	2021-09-08 10:00:00	0.0	136	796.71	0.0	189.06	0.00	1964.51	19.0	Reaming/Tripping	SD-06	0
1	2021-09-08 10:00:05	0.0	135	797.53	0.0	188.89	0.00	2025.50	20.0	Reaming/Tripping	SD-06	0
2	2021-09-08 10:00:10	0.0	135	795.07	0.0	188.89	0.00	2044.97	20.0	Reaming/Tripping	SD-06	0
3	2021-09-08 10:00:15	0.0	134	793.43	0.0	188.89	0.00	2051.34	21.0	Reaming/Tripping	SD-06	0
4	2021-09-08 10:00:20	0.0	135	793.43	0.0	188.89	0.00	2055.37	21.0	Reaming/Tripping	SD-06	0
...	...	...	...	...	...	...	...	...	...	...	...	...
195014	2020-01-20 10:10:00	0.0	38	348.81	0.0	226.75	0.00	852.52	0.0	Reaming/Tripping	SD-02	0
195015	2020-01-20 10:10:10	0.0	38	348.81	0.0	286.73	0.00	843.88	0.0	Reaming/Tripping	SD-02	0
195016	2020-01-20 10:10:20	0.0	107	343.90	0.0	245.51	24.17	861.15	0.0	Reaming/Tripping	SD-02	2
195017	2020-01-20 10:10:30	0.0	38	343.90	0.0	245.51	34.27	866.91	0.0	Reaming/Tripping	SD-02	2
195018	2020-01-20 10:10:40	0.0	44	343.90	0.0	245.91	29.32	861.15	0.0	Reaming/Tripping	SD-02	2

195019 rows × 12 columns

Figure 3: Dataset for train and test.

Before using this dataset to create a machine learning model, it is necessary to remove irrelevant data and handle missing values first. Several irrelevant values were found in the drilling parameters, such as -999.25 on WOB, -304.57 on ROP, etc. (Figure 4). The fix is to replace that value to zero (Figure 5).

	WOB	RPM	Flow Pump	ROP	Hookload	Torque	STPpress	Return	Class
count	195019.000000	195019.000000	195019.000000	195019.000000	195019.000000	195019.000000	195019.000000	195019.000000	195019.000000
mean	-36.844463	133.646583	892.810871	-48.604412	149.009568	10.654578	1786.336195	30.892890	0.069773
std	235.478905	56.722915	176.309017	121.388828	37.464153	4.640939	512.832273	37.255897	0.281025
min	-999.250000	0.000000	0.000000	-304.571400	28.560000	-0.220000	-0.040000	-5.000000	0.000000
25%	3.200000	99.000000	886.770000	0.000000	127.850000	7.670000	1549.000000	0.060000	0.000000
50%	18.700000	109.000000	911.000000	4.700000	145.770000	10.410000	1751.000000	0.290000	0.000000
75%	34.155000	194.000000	979.130000	10.789920	174.670000	13.640000	2093.090000	73.000000	0.000000
max	178.470000	1825.000000	4866.150000	1035.170000	312.890000	55.650000	2840.000000	235.000000	2.000000

Figure 4: Dataset before handling missing value.

	WOB	RPM	Flow Pump	ROP	Hookload	Torque	STPpress	Return	Class
count	195019.000000	195019.000000	195019.000000	195019.000000	195019.000000	195019.000000	195019.000000	195019.000000	195019.000000
mean	19.374526	133.646583	892.810871	7.050199	149.009568	10.655163	1786.336197	30.893301	0.069773
std	15.979642	56.722915	176.309017	9.851573	37.464153	4.639583	512.832267	37.255553	0.281025
min	0.000000	0.000000	0.000000	0.000000	28.560000	0.000000	0.000000	0.000000	0.000000
25%	3.200000	99.000000	886.770000	0.000000	127.850000	7.670000	1549.000000	0.060000	0.000000
50%	18.700000	109.000000	911.000000	4.700000	145.770000	10.410000	1751.000000	0.290000	0.000000
75%	34.155000	194.000000	979.130000	10.789920	174.670000	13.640000	2093.090000	73.000000	0.000000
max	178.470000	1825.000000	4866.150000	1035.170000	312.890000	55.650000	2840.000000	235.000000	2.000000

Figure 5: Dataset after handling missing value.

The next stage is changing the data type which was originally categorical to numeric, because the input parameters in the artificial neural network algorithm must be numeric. The technique of changing the data type is called One-Hot Encoding. In this study, there is a 'Condition' which contains 'On Bottom' and 'Reaming/Tripping' (Figure 6). Using the One-Hot Encoding technique, we will divide the 'Condition' column into two new columns containing 'Condition_On Bottom' and 'Condition_Reaming/Tripping' (Figure 7).

	WOB	RPM	Flow Pump	ROP	Hookload	Torque	STPpress	Return	Condition
0	0.0	136	796.71	0.0	189.06	0.00	1964.51	19.0	Reaming/Tripping
1	0.0	135	797.53	0.0	188.89	0.00	2025.50	20.0	Reaming/Tripping
2	0.0	135	795.07	0.0	188.89	0.00	2044.97	20.0	Reaming/Tripping
3	0.0	134	793.43	0.0	188.89	0.00	2051.34	21.0	Reaming/Tripping
4	0.0	135	793.43	0.0	188.89	0.00	2055.37	21.0	Reaming/Tripping
...	...	...	...	...	...	...	...	...	...
195014	0.0	38	348.81	0.0	226.75	0.00	852.52	0.0	Reaming/Tripping
195015	0.0	38	348.81	0.0	286.73	0.00	843.88	0.0	Reaming/Tripping
195016	0.0	107	343.90	0.0	245.51	24.17	861.15	0.0	Reaming/Tripping
195017	0.0	38	343.90	0.0	245.51	34.27	866.91	0.0	Reaming/Tripping
195018	0.0	44	343.90	0.0	245.91	29.32	861.15	0.0	Reaming/Tripping

195019 rows × 9 columns

Figure 6: Column 'Condition' before categorical encoding.

	WOB	RPM	Flow Pump	ROP	Hookload	Torque	STPpress	Return	Condition_On Bottom	Condition_Reaming/Tripping
0	0.0	136	796.71	0.0	189.06	0.00	1964.51	19.0	0	1
1	0.0	135	797.53	0.0	188.89	0.00	2025.50	20.0	0	1
2	0.0	135	795.07	0.0	188.89	0.00	2044.97	20.0	0	1
3	0.0	134	793.43	0.0	188.89	0.00	2051.34	21.0	0	1
4	0.0	135	793.43	0.0	188.89	0.00	2055.37	21.0	0	1
...	...	...	...	...	...	...	...	...	...	...
195014	0.0	38	348.81	0.0	226.75	0.00	852.52	0.0	0	1
195015	0.0	38	348.81	0.0	286.73	0.00	843.88	0.0	0	1
195016	0.0	107	343.90	0.0	245.51	24.17	861.15	0.0	0	1
195017	0.0	38	343.90	0.0	245.51	34.27	866.91	0.0	0	1
195018	0.0	44	343.90	0.0	245.91	29.32	861.15	0.0	0	1

195019 rows × 10 columns

Figure 7: Column 'Condition' after categorical encoding.

The following action are for handling data class imbalances. There is a data class imbalance at label 0 (Figure 8). In overcoming the imbalance of data classes, SMOTE (Synthetic Minority Over-sampling Technique) is applied to duplicate labels 1 and 2 so that they are equivalent to label 0 (Figure 9).

```
0    182784
1     10863
2      1372
Name: Class, dtype: int64
```

Figure 8: Class data before data balancing.

```
0    182784
1    182784
2    182784
Name: Class, dtype: int64
```

Figure 9: Class data after data balancing.

The next phase is to split the dataset into data train and test. As much as 70% of the dataset is used for data train and 30% is used for data test, so there are 383846 rows for data train (Figure 10) and 164506 rows for data test (Figure 11).

	WOB	RPM	Flow Pump	ROP	Hookload	Torque	STPpress	Return	Condition_On Bottom	Condition_Reaming/Tripping
491328	13.735586	0	915.900717	0.000000	129.554757	25.700892	2187.446434	0.00	0	1
512004	0.000000	187	715.218466	0.000000	201.218792	29.218523	2263.398689	0.00	0	1
85747	8.940000	100	915.000000	0.000000	157.020000	9.910000	1544.000000	0.00	0	1
44916	9.460000	214	962.920000	17.930000	141.010000	6.760000	1958.180000	79.00	1	0
299672	31.962865	110	1008.778792	6.861938	154.686390	18.350316	1608.294944	0.06	1	0
...	...	...	...	...	...	...	...	...	...	...
359783	0.000000	202	733.836542	0.000000	204.240000	22.747941	2071.953078	0.00	0	1
152315	13.300000	113	1006.000000	18.592800	154.320000	8.160000	1555.000000	0.06	1	0
117952	24.930000	93	904.000000	2.895600	124.120000	5.950000	2111.000000	83.85	1	0
435829	0.000000	156	636.552859	0.000000	173.395782	21.600371	1373.013865	0.00	0	1
305711	0.000000	78	961.634052	0.000000	135.131536	11.477213	2194.222359	0.00	0	1

383846 rows × 10 columns

Figure 10 Data Train.

	WOB	RPM	Flow Pump	ROP	Hookload	Torque	STPpress	Return	Condition_On Bottom	Condition_Reaming/Tripping
312496	32.394937	97	892.000000	9.484129	121.853675	14.721876	1500.603965	0.355841	1	0
388497	0.000000	189	720.289193	0.000000	199.241312	26.341294	2218.450459	0.000000	0	1
374300	0.000000	200	736.120000	0.000000	199.634239	26.920519	2076.332720	0.000000	0	1
500177	35.032048	0	979.754175	0.000000	118.517957	24.258771	1776.877088	0.260000	0	1
359556	0.000000	82	824.405088	0.000000	124.558328	15.394387	1337.525818	72.531847	0	1
...	...	...	...	...	...	...	...	...	...	...
183037	14.860000	177	1007.130000	1.620000	216.190000	12.500000	1912.870000	0.000000	1	0
168050	0.000000	20	491.000000	0.000000	183.660000	15.130000	778.000000	0.060000	0	1
528155	0.578881	0	917.139867	0.000000	144.571623	25.710584	2135.336738	0.000000	0	1
270662	37.677310	109	991.310914	19.050000	149.670926	16.863605	1699.689086	0.060000	1	0
299341	19.096207	140	865.000000	1.096207	133.903793	10.000000	1518.807587	14.384827	1	0

164506 rows × 10 columns

Figure 11 Data Test.

The final stage, change the scale feature on the input variable using the Min-Max Scaler method. By using this method, the data range is only in the range of 0 – 1, so that the data distribution becomes more uniform. The following shows the data train and test after normalizing the data using the Min-Max Scaler.

	WOB	RPM	Flow Pump	ROP	Hookload	Torque	STPpress	Return	Condition_On Bottom	Condition_Reaming/Tripping
0	0.077015	0.000000	0.188219	0.000000	0.355203	0.461831	0.770228	0.000000	0.0	1.0
1	0.000000	0.162750	0.146978	0.000000	0.607248	0.525041	0.796971	0.000000	0.0	1.0
2	0.050126	0.087032	0.188034	0.000000	0.451799	0.178077	0.543662	0.000000	0.0	1.0
3	0.053042	0.186249	0.197881	0.017321	0.395491	0.121473	0.689500	0.336170	1.0	0.0
4	0.179214	0.095735	0.207305	0.006629	0.443592	0.329745	0.566301	0.000255	1.0	0.0
...	...	...	...	...	...	...	...	...	...	...
383841	0.000000	0.175805	0.150804	0.000000	0.617874	0.408768	0.729561	0.000000	0.0	1.0
383842	0.074572	0.098346	0.206734	0.017961	0.442303	0.146631	0.547535	0.000255	1.0	0.0
383843	0.139781	0.080940	0.185773	0.002797	0.336088	0.106918	0.743310	0.356809	1.0	0.0
383844	0.000000	0.135770	0.130812	0.000000	0.509393	0.388147	0.483456	0.000000	0.0	1.0
383845	0.000000	0.067885	0.197617	0.000000	0.374816	0.206239	0.772614	0.000000	0.0	1.0

Figure 12: Data Train after normalization.

	WOB	RPM	Flow Pump	ROP	Hookload	Torque	STPpress	Return	Condition_On Bottom	Condition_Reaming/Tripping
0	0.181515	0.053151	0.211024	0.020788	0.328517	0.404114	0.530442	0.002311	1.0	0.0
1	0.000000	0.103562	0.170402	0.000000	0.601991	0.723066	0.784190	0.000000	0.0	1.0
2	0.000000	0.109589	0.174147	0.000000	0.603379	0.738966	0.733953	0.000000	0.0	1.0
3	0.196291	0.000000	0.231785	0.000000	0.316729	0.665901	0.628100	0.001688	0.0	1.0
4	0.000000	0.044932	0.195033	0.000000	0.338075	0.422574	0.472796	0.470986	0.0	1.0
...	...	...	...	...	...	...	...	...	...	...
164501	0.083263	0.096986	0.238261	0.003551	0.661884	0.343124	0.676172	0.000000	1.0	0.0
164502	0.000000	0.010959	0.116158	0.000000	0.546929	0.415317	0.275012	0.000390	0.0	1.0
164503	0.003244	0.000000	0.216972	0.000000	0.408798	0.705753	0.754810	0.000000	0.0	1.0
164504	0.211113	0.059726	0.234519	0.041754	0.426818	0.462904	0.600815	0.000390	1.0	0.0
164505	0.107000	0.076712	0.204637	0.002403	0.371100	0.274499	0.536876	0.093408	1.0	0.0

164506 rows × 10 columns

Figure 13: Data Test after normalization.

After data pre-processing, the ANN model was built using the Multi-Layer Percepton Classifier from the scikit-learn library. The ANN structure consists of 2 hidden layers with 200 and 100 neuron units, the activation function used is "tanh", and the solver used is "adam". The training data obtained an accuracy score of 0.994. Then on data testing obtained an accuracy score of 0.68.

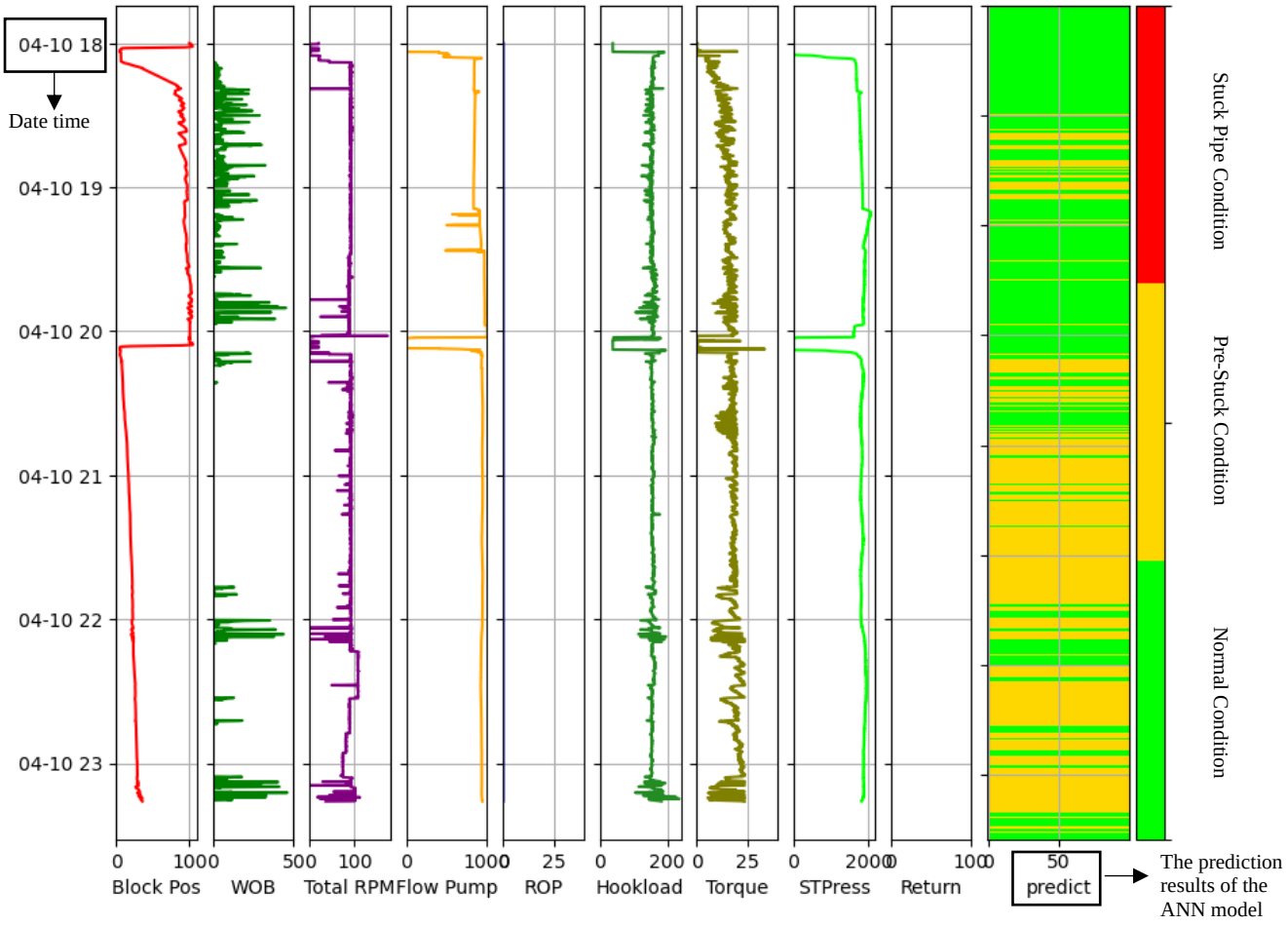


Figure 14: Visualization of the model's prediction results at the SDA well (April 10th, 2021, 18:00 - 23:30 WIB).

The ANN model that has been used in the data train and test, will be implemented in the blind data, namely SDA wells. However, the data must first be transformed and normalized data as is done on the training data and data testing. After that, the data was entered into the ANN model and obtained an accuracy score of 0.59. Even though the score is not high, when it is validated with information on DDR, there are still many similarities. Following are some visualizations of drilling parameters with model prediction results on SDA wells (Figure 14).

Following are the details on the daily drilling report for SDA wells on April 10, 2021, 17.00 – 23.59 WIB (Figure 15).

4/10/21 17:00	4/10/21 20:00	REAM	Continue back ream from 4600' to 4318' (TLC). Parameter FR: 850-900 gpm, SPP: 1800 – 2000 psi, RPM: 90-100, Torque: 7 – 20 Klbf,ft. Air 2200 scfm Note: - Experienced erratic torque at 4598 -4695 - Experience pipe stalled at 4412', 4330', 4325', 4318'. Work pipe between 4336' – 4318' several time to normalize parameter. - Increase Flowrate to 900 gpm.
4/10/21 20:00	4/11/21 0:00	REAM	Continue back ream from 4318' to 4267' (TLC). Parameter FR: 950 gpm + Air 2200 scfm, SPP: 1750 – 2000 psi, RPM: 75-110, Torque: 6 – 25 Klbf,ft. Note: - Erratic torque 13 -20 Klbf.ft at depth 4318' -4310', - Experience pipe stall, no rotate, torque increase to 25 Klbf.ft at depth 4318', 4315', 4313', 4310', 4308', 4306', 4304', 4303', 4302', 4300', 4297', 4295', 4284', 4280'.

Figure 15: Detailed information on the daily drilling report on SDA wells (April 10th, 2021, 18:00 - 23:30 WIB).

In Figure 14, during that time, there are many indications of anomaly/pre-stuck condition. then when it is validated with the information contained in the daily drilling report (Figure 15), in that time span it is indeed indicated that there are many erratic torques and pipe stalls. If the anomaly is not resolved immediately, it can cause a stuck pipe.

After validating some of the prediction results with the information contained in the daily drilling report, the results are still relevant, even though the prediction accuracy score produced by the model is only 0.59. If you want to increase the accuracy score, you need to collect more data, because a larger and more diverse dataset will make an ANN model that can learn more complex patterns.

4. CONCLUSION

1. A machine learning program to identify "pre-stuck" condition is developed by utilizing 196019 rows of data from 8 stuck pipe events at 8 geothermal wells in 12-1/4" and 9-7/8" hole section during lost circulation

2. Based on the evaluation of the model using data testing, an accuracy score of 0.68 was obtained and when blind data was implemented, an accuracy score of 0.59 was obtained.

3. Even though the model still gets a low accuracy score when predicting data that has never been seen, when the prediction results are validated with the daily drilling report, it is still relevant.

REFERENCES

Bayan, M., & Zulkarnain. (2020). Stuck Pipe Prediction in Geothermal Well Drilling at Darajat Using Statistical and Machine Learning Application. In Proceedings of ACM APCORISE '20, June 2020, Depok, West Java, Indonesia. ACM, New York, NY, USA. https://doi.org/10.1145/3400934

Elmousamalmi, H. H., & Mahmoud E. (2020). Drilling Stuck Pipe Classification and Mitigation in The Guld of Suez Oil Fields using Artificial Intelligence. Journal of Petroleum Exploration and Production Technology, March 2020. https://doi.org/10.1007/s13202-020-00857-w

K. Salminen et al. (2017). Stuck-Pipe Prediction by Use of Automated Real-Time Modelling and Data Analysis. SPE Drilling and Completion, 32(3). Sep 2017. https://doi.org/10.2118/178888-pa

Purba et al. (2019). Key Considerations in Developing Strategy for Geothermal Exploration Drilling Project in Indonesia. Proceedings 44th Workshop on Geothermal Reservoir Engineering, Standford University, California, February 2019.

Sarwono et al. (2022). Stuck Pipe Detection for North Sumatra Geothermal Drilling Operation Using Artificial Neural Network. Jurnal Migasian, 6(1). Juni 2022.

Exploring Geothermal Energy Development Strategies: Insights from Indonesian Practice, Regulation, and Case Studies

Daniel Adityatama[1], M. Rizqi Al Asy'ari[1],
Ferdino R. Fadhillah[2], Dorman Purba[3], and Nadya Erichatama[1]

[1]Geoenergi Solusi Indonesia (GEOENERGIS), Jakarta, Indonesia
[2]ITB School of Business and Management, Graha Irama 12th floor, Jakarta, Indonesia
[3]ENERKA Bhumi Pratama, Cibis Nine 11th floor, Jakarta Selatan, Indonesia

Fandikagp5@gmail.com

Keywords: geothermal, Indonesia, development scenario, regulation, drilling

ABSTRACT

This paper provides an in-depth analysis of geothermal energy development strategies across three distinct sites in Indonesia. It delves into the intricate processes of project inception, exploration, and expansion that lead to the generation of electricity from geothermal resources. By examining these anonymized case studies, the paper explores the regulatory frameworks governing each site, the methods used for exploration, the drilling techniques employed, and the collaborative efforts involved in these projects.

Furthermore, the paper emphasizes the pivotal role played by different drilling phases—namely exploration, resource mapping, feasibility assessment, project expansion, and ongoing maintenance—in shaping the trajectory of geothermal initiatives at various developmental stages. Understanding these phases offers valuable insights for stakeholders and policymakers seeking to navigate the complexities of sustainable energy endeavors within the Indonesian context. By capturing these practical insights, the paper contributes to a nuanced understanding of geothermal energy development strategies, offering actionable guidance for informed decision-making in the realm of renewable energy development.

1. INTRODUCTION

Geothermal energy has emerged as a promising avenue for sustainable electricity generation, with Indonesia standing as a notable proponent of this renewable resource. With its rich geothermal potential, the country has embarked on diverse geothermal energy development projects across various locations. This paper endeavors to unravel the intricacies of these projects, shedding light on the distinct strategies employed in project initiation, exploration, and expansion phases. By delving into the geothermal landscapes of three anonymized Indonesian fields, we aim to uncover the diverse pathways that contribute to the realization of operational geothermal power plants.

The development of geothermal energy projects involves a series of strategic decisions influenced by regulatory frameworks, geological considerations, and collaborative endeavors. These factors collectively shape the trajectory of projects, leading to their successful integration into the nation's energy portfolio. Through the examination of these real-world cases, this paper aims to offer valuable insights into the interplay of regulations, exploration methodologies, drilling techniques, and partnership dynamics that drive geothermal energy initiatives in Indonesia.

Moreover, the paper underscores the significance of purpose-driven drilling phases, each catering to distinct project goals—ranging from confirming resource existence to achieving planned operational capacities. The evolving nature of these projects calls for a nuanced understanding of the geothermal development process, encompassing technical, regulatory, and collaborative dimensions. By analyzing these dimensions across multiple sites, we aim to equip stakeholders and policymakers with practical insights that can inform decision-making, foster sustainable energy practices, and contribute to the broader discourse on geothermal energy development strategies.

The objectives of this paper are as follows:

1. **Examine Geothermal Development Strategies:** The paper aims to explore the strategies employed in the development of geothermal energy projects. It seeks to shows the diverse approaches taken in project initiation, exploration, and expansion phases.
2. **Analyze Regulatory and Collaborative Dynamics:** By examining the real-world cases, the paper intends to analyze the role of regulatory frameworks and collaborative efforts in shaping geothermal projects. It aims to shed light on how regulations, exploration methods, drilling practices, and partnership dynamics interact within the context of geothermal energy initiatives.
3. **Highlight Drilling Phases and Their Significance:** The paper aims to emphasize the importance of different drilling phases—exploration, delineation, appraisal, development, and make-up drilling—in driving the progress of geothermal projects. It seeks to explain how each drilling phase serves specific objectives and contributes to the overall success of the project.

2. GEOTHERMAL DEVELOPMENT PROJECT STAGES ACCORDING TO REGULATIONS AND PRACTICES.

Based on international best practices, geothermal projects have several key phases before the actual electricity production or Operation and Maintenance (O&M) commences. ESMAP Geothermal Handbook (Gehringer & Loksha, 2012) divides the project phases into 8 phases:

1) Preliminary survey & concession acquisition.
2) 3G Exploration.
3) Test / Exploration drilling.
4) Project review and planning.
5) Field development.
6) Power plant construction.
7) Commissioning.
8) Operation and maintenance.

Other researchers, developers, and regulatory bodies may classify the process into different number of phases, but the basic process and activities are effectively the same (IGA, 2014). For example, Jacobs classifies the geothermal development phase into six phases as shown in Figure 1.

The developer needs to evaluate whether to proceed to the next phase or stop after each stage or milestone. The decision gate for each phase of geothermal development is shown in Figure 1. This is crucial because the following phase will require much more financial resources. For instance, after finishing the preliminary survey and 3G exploration, the developer has to compile all the technical and non-technical studies and surveys into a pre-feasibility report. The pre-feasibility report should be able to explain the rationale and risk assessment to justify exploration drilling.

The word “Exploration” usually covers the first three phases (including exploration drilling), while the “Project Review” or “Feasibility Study” will examine the outcomes of the exploration phase and any additional appraisal/confirmation drilling needed. Unlike other power generation technologies, such as gas, coal, or hydro, it is impossible to conduct power production feasibility study until the geothermal reservoir potential has been confirmed by drilling. This is because the source of the energy (heat carried out by geothermal fluid) is directly connected to the development of power plants.

The feasibility report will provide the developer and potential financier with confidence in the economic viability of the project (IGA, 2014). The feasibility report often can serve as a basis for Final Investment Decision (FID), although some financiers may have other requirements before committing to financing the project. Therefore, the FID usually marks the beginning of the exploitation or development stage of geothermal projects.

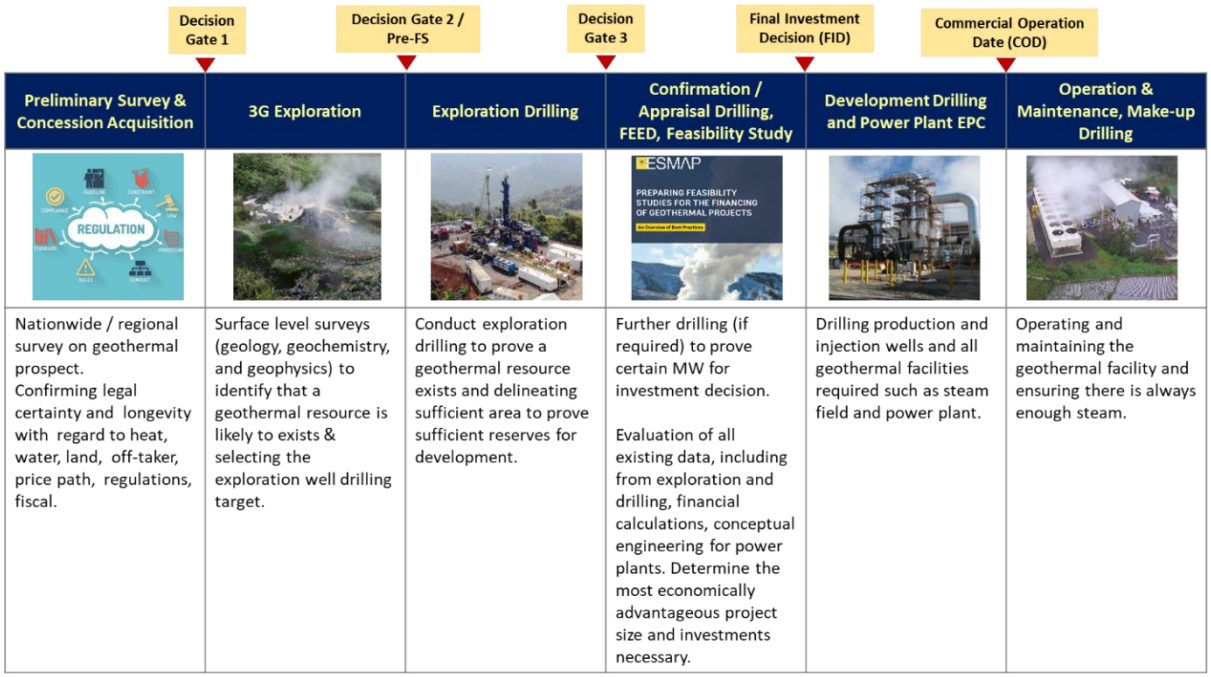


Figure 1: Example of geothermal project phases along with associated decision gate. Modified from Jacobs (2022) and IGA (2014).

Based on regulations in Indonesia, Geothermal business in Indonesia is regulated in Law (UU) No. 21 / 2014 and Government Regulation (Peraturan Pemerintah / PP) No. 7 / 2017. The simplified geothermal business flow based on government regulation is illustrated in Figure 2.

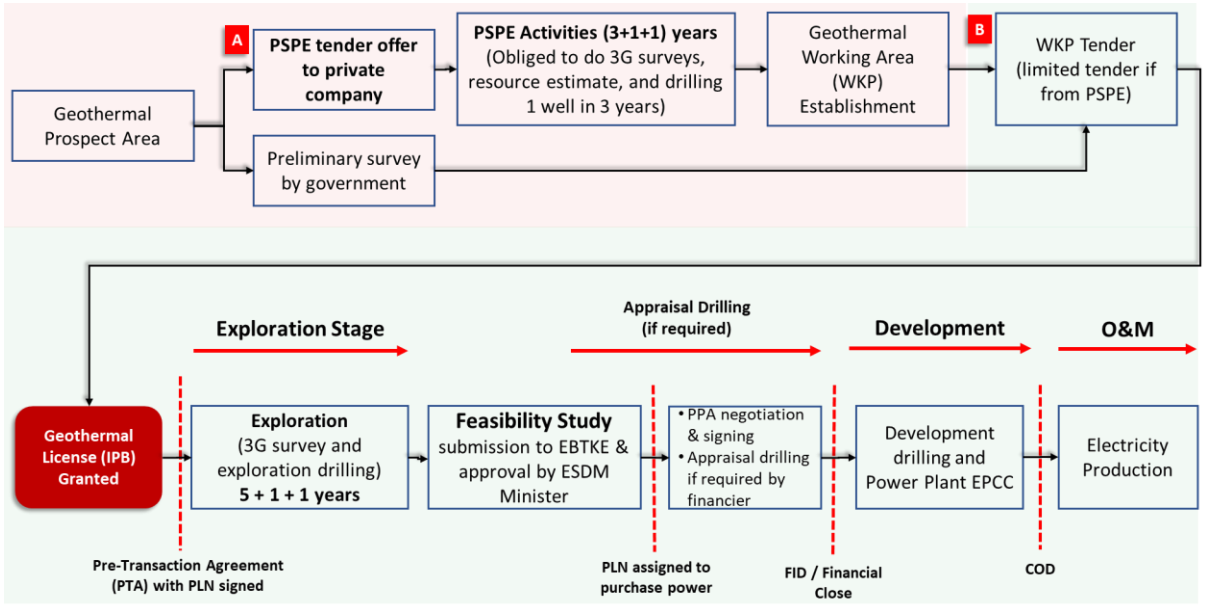


Figure 2: Simplified geothermal business process in Indonesia. Modified from EBTKE (2022) and Jacobs (2022).

In general, there are two ways for a private company to operate geothermal power production business in Indonesia as shown in Figure 2:

1. Through Preliminary Survey and Exploration Assignment (Penugasan Survei Pendahuluan dan Eksplorasi (PSPE) tender. If the company is awarded the PSPE license, it has to do 3G survey and at least 1 exploration drilling in the first 3 years. After finishing the 3G survey, 1 exploration drilling, resource assessment, and submitting PSPE report to the Government, the company can

participate in the Geothermal Working Area (Wilayah Kerja Panas Bumi / WKP) limited tender. The rest of the process is similar to scheme B below.

2. If the WKP has been surveyed by the government, the company can directly participate in the open tender to obtain Geothermal License (Izin Panas Bumi / IPB). The IPB holder then should do further detailed 3G survey, exploration drilling, resource assessment, and submit Feasibility Study (FS) report to the government. Only after the FS report is approved by the Minister of Energy and Mineral Resources (Menteri Energi dan Sumber Daya Mineral / ESDM), then the company can proceed to the development stage.

The Indonesian Law No. 21 of 2014 and its related regulations, such as Government Regulation No. 7 of 2017, do not explicitly address the appraisal drilling process that is often required by lenders such as banks. This implies that the government does not directly intervene in the financing aspects of the projects, but rather leaves them to the financiers' judgment.

In reality, lenders may demand appraisal drilling to be done before they commit to fund a geothermal project. The drilling is usually necessary to achieve a certain level of confirmed capacity (MW), which is normally around 50% or more of the intended development size. This is crucial to ensure that the project is economically feasible and can generate enough returns to pay back the funding.

To sum up, the Indonesian government has set up a legal framework to oversee geothermal energy development, but the financing aspect of the projects is usually left to the financiers' judgment. This may involve requirements for appraisal drilling to be done to ensure the economic feasibility of the project. Therefore, it is essential for geothermal developers to collaborate closely with lenders to reach financial close and ensure the successful execution of geothermal projects in Indonesia.

Table 1 shows the typical activities breakdown for each geothermal development phase, combining industry best practices with the development stages regulated by the Indonesian government. Generally, the exploration stage ends when the government approves the Feasibility Study Report, and the development stage activity generally starts after reaching Financial Close or Final Investment Decision (FID).

3. GEOTHERMAL DEVELOPMENT APPROACH

Constructing a power plant within a geothermal field is a process that can consume a significant amount of time. In accordance with Indonesian government regulations, the entire journey from the exploration phase to the Commercial Operation Date (COD) of the power plant is expected to be completed within a span of 5 years. There's also a provision for a potential extension of an additional 2 years. However, it's worth noting that the actual timeline for development, starting from the drilling of the initial exploration well, often exceeds this baseline. This extended period is depicted in Figure 3. In some instances, the development timeline has even stretched beyond a decade. Although, it's important to acknowledge that in recent years, there have been instances of achieving faster development timelines, as indicated by the red boxes in Figure 3.

However, it's essential to recognize that the graph presented only captures a portion of the overall scenario. In the period from 2010 to 2021, numerous exploration drillings were conducted within Geothermal Working Areas (known as Wilayah Kerja Panas Bumi or WKP). Nevertheless, among these, only a total of 4 fields have successfully advanced to the production phase. This reality underscores the considerable challenges and complexities associated with the development of geothermal projects.

Table 1: Activity breakdown for each geothermal development phase.
Modified from EBTKE (2022), Purwanto (2019), and Gehringer & Loksha (2012).

Financial Close / FID
v

	Exploration				Exploitation / Development		
	Preliminary survey	**Exploration survey**	**Exploration / test drilling**	**Project review and feasibility**	**Field development**	**Power plant construction and commissioning**	**Operation and maintenance**
Activities	• Power market analysis. • Review on other possibilities of geothermal utilization. • Infrastructure condition preliminary review. • Review on regulation, political, environmental, and social issue. • Assess and obtain all required permitting. • Review and solve any issues relating to political and financial stability. • Review on the available / existing remote sensing or aerial survey data. • Review the information from any available geoscientific data. • Review the information from previous exploration wells or offset well (if any).	• Detailed surface geoscientific survey. - Geological survey (volcano stratigraphy, structural mapping, thermal features identifications, etc.) - Geochemistry survey (thermal features sampling and measurements, fluid geothermometry, soil sampling and gas flux, etc.,). - Geophysical survey (heat flow, gravity, resistivity, magneto telluric, passive seismic, temperature gradient and conductive flow, etc.,). • Geotechnical study. • Environmental study. • Temperature gradient well. • Develop conceptual model. • Resource estimation • Pre-Feasibility Study.	• UKL/UPL. • Exploration drilling infrastructure (access road, well pad, drilling water supply system, etc.,) construction. • Drilling exploration wells. • Well logging. • Well testing. • Conceptual model update and refining. • Assessing well productivity. • Design for production well.	• **Submitting Feasibility Study report to EBTKE.** - Determine the location and design of well pads and other required civil work. - Development drilling target and well design. - Reservoir performance forecast with reservoir numerical modelling. - Update resource estimation. - Steam field, power plant, and transmission design (FEED). - Project budget and revenue projections. • **Appraisal / confirmation drilling as required by financier.** • **PPA finalizations and signing.** • Environmental and social assessment. • Financial close.	• Additional infrastructure construction for development drilling and power plant construction. • Development drilling for production and injection well. • Well logging. • Well testing. • Conceptual model update • Numerical reservoir model update.	• Steam field, power plant, and transmission EPC - Engineering - Procurement - Construction - Commissioning	• Operation and maintenance. • Well intervention. • Make-up well drilling • Annual inspection. • Major overhaul.

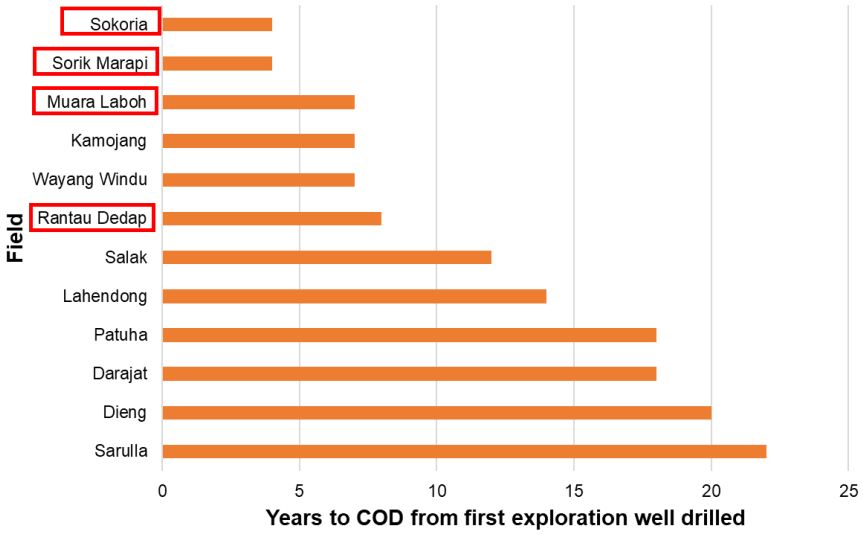


Figure 3: Duration to the power plant COD from the first exploration well drilling (Modified from Jacobs, 2022).

The prolonged duration leading up to the Commercial Operation Date (COD) directly translates into an extended period before developers can start earning revenue. This, in turn, significantly impacts the overall project economics. Conversely, when pursuing a staged development approach, there's a trade-off involving relatively smaller revenue streams and higher initial capital expenditures (CAPEX), which can be attributed to the economy of scale principle. This interplay between revenue and CAPEX constitutes a critical challenge in the context of geothermal development. Striking the right balance amidst these factors is indeed a noteworthy challenge in the field of geothermal energy projects.

The extended timeframe also implies that the developer must continually invest capital (typically sourced from its equity) over a prolonged duration before they can generate revenue. This particular problem is illustrated in Figure 4. Considering this issue, developers face the task of not only maximizing power plant capacity (through direct large scale development), but also considering strategies to expedite the exploration phase. However, pursuing such acceleration carries the risk of substantial capital expenditure (for instance, drilling multiple full-size or significant diameter wells) while resource uncertainty remains notably high.

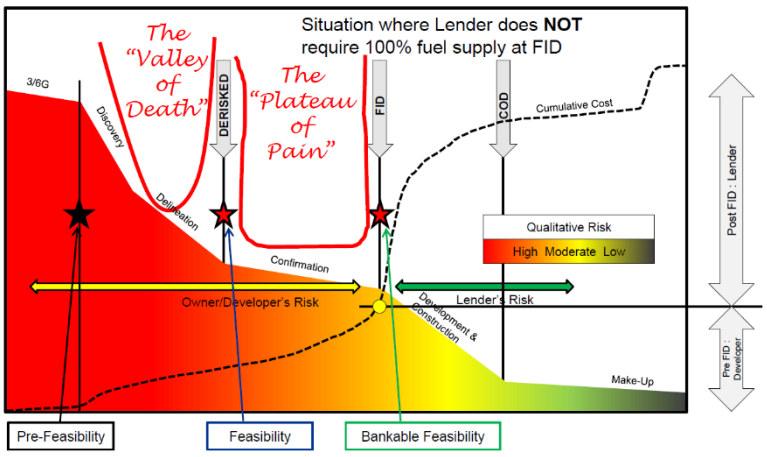


Figure 4: Geothermal project phase risk profile (modified from Jacobs, 2022).

Accelerated Exploration or Staged Exploration?

As shown in Figure 4 previously, the geothermal exploration drilling typically has three objectives:

1. Discover the resource
2. Delineate the resource
3. Confirm the resource

Going through those objectives in stages (Figure 5) can minimize risk and reduce the potential cost of abandonment if the desired resource size and characteristics are not met. However, that may mean longer exploration time, thus longer "plateau of pain" as shown in Figure 4. Consequently, some developers may opt for an accelerated process, despite the associated higher risk of increased abandonment costs, as illustrated in Figure 6.

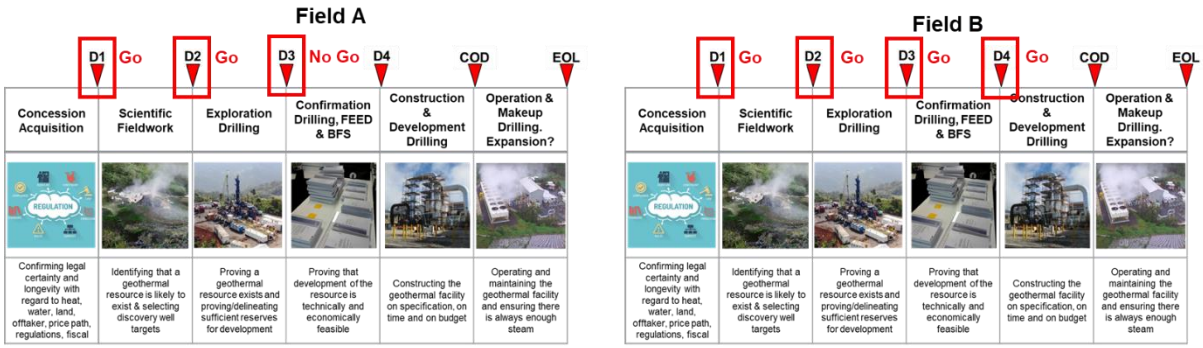


Figure 5: Illustration of geothermal project stages and decision gate prior deciding to proceed to next phase.

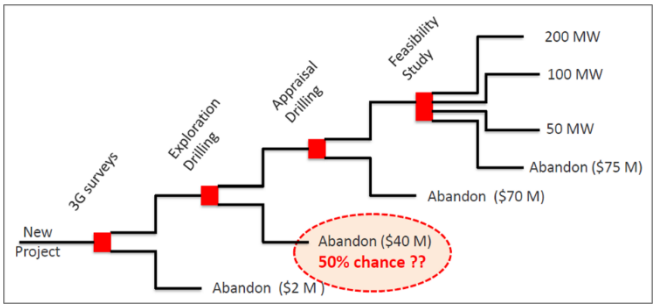


Figure 6: Illustration of cost of abandonment in geothermal project (modified from Jacobs, 2022).

The expedited exploration involves a drilling campaign that typically focuses on discovering, outlining, and at times confirming the availability of steam (a critical factor for bankable feasibility, often requiring around 50% verification of the anticipated power plant capacity) within a single campaign, as illustrated in Figure 6.

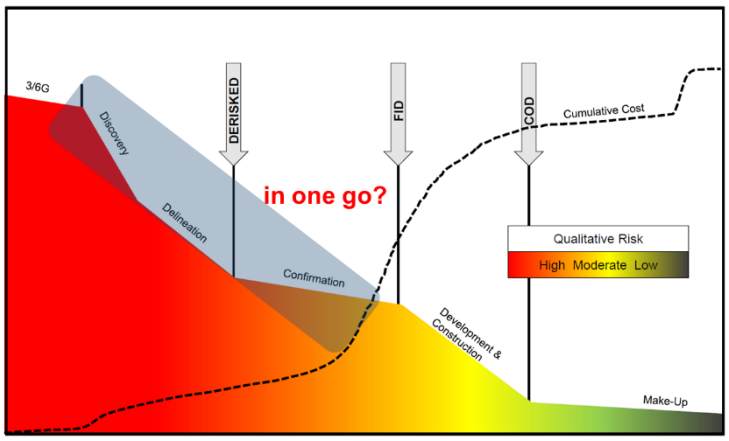


Figure 7: Illustration of accelerated exploration, aims to discover, delineate, and confirm the steam availability in one go.

This approach stands in contrast to the staged exploration strategy, where each step is conducted sequentially, and the outcome of each phase is assessed before making a decision to move forward. The primary objectives of this strategy usually revolve around minimizing the expenses associated with project abandonment, particularly in cases where resource uncertainty remains high or confidence levels are relatively low. This approach is illustrated in Figure 8.

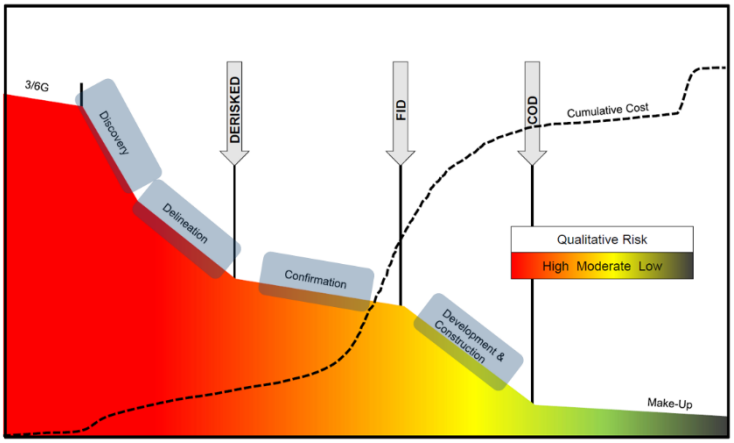


Figure 8: Illustration of staged exploration, typically aims to minimize cost of abandonment.

4. CASE IN VARIOUS GEOTHERMAL FIELDS IN INDONESIA

The objective of this section is to show the diverse range of geothermal development strategies that can be implemented to successfully develop a geothermal field. By examining the specific approaches taken in these projects, developers can learn from the experiences and outcomes from other geothermal field and identify the geothermal development strategies that are most relevant to their own project. In this section, there are three (3) examples of geothermal fields that have different project entry, also exploration and development strategies.

4.1 Muara Laboh Case

Liki Pinawangan Muara Laboh is geothermal working area located in Solok Selatan Regency, West Sumatra Province. Muara Laboh is one of the examples of geothermal working areas that developed starting from the assignment for the preliminary survey (*Penugasan Survei Pendahuluan* / PSP) to commercial operation until nowadays. Figure 9: shows the Muara Laboh geothermal project timeline starting from PSP assignment until the commercial operation date (COD) in 2019.

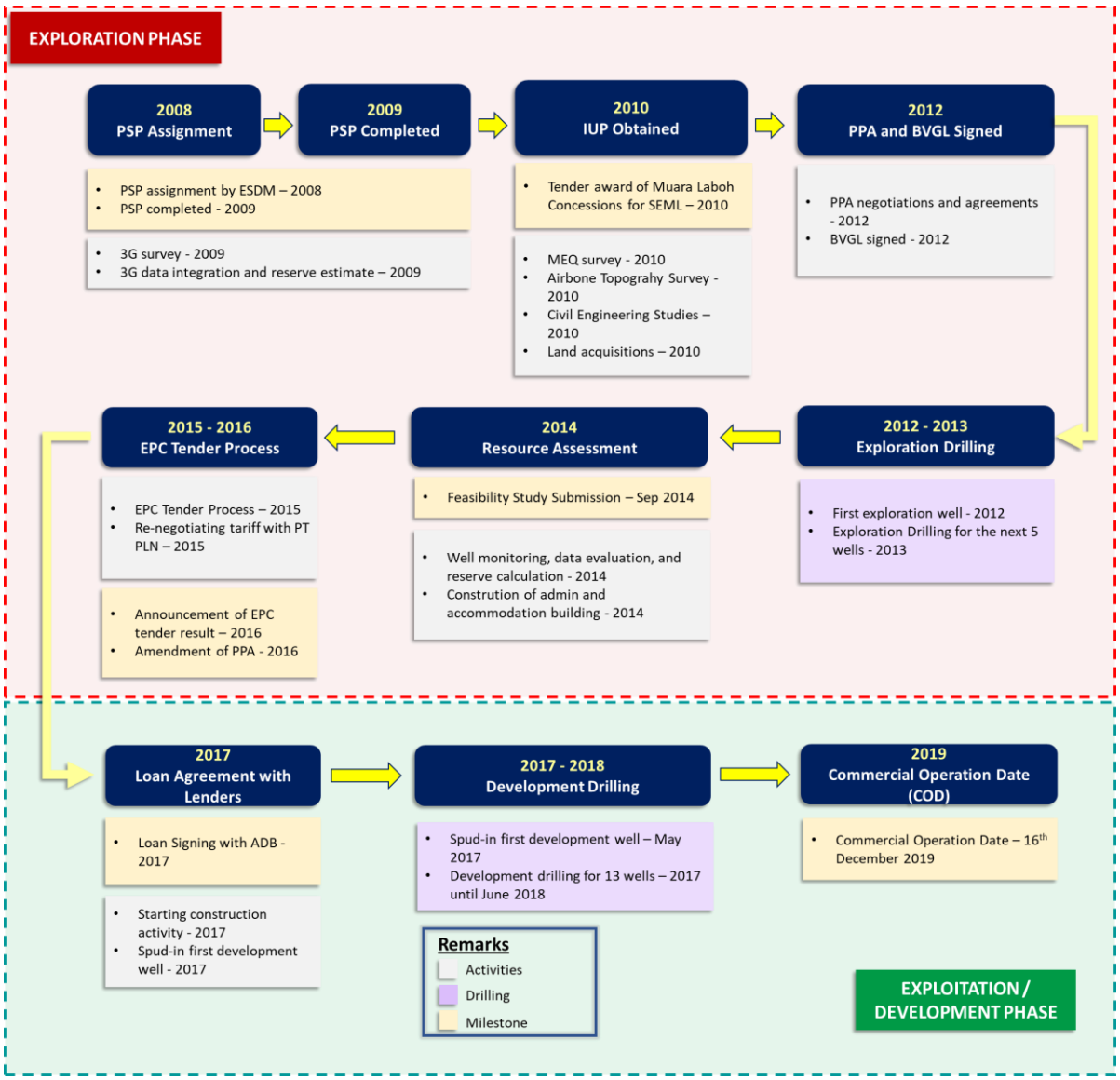


Figure 9: Muara Laboh Geothermal Field Project Timeline. Modified from (Supreme Energy, 2023; Ganefianto, 2021).

In 2008, PT Supreme Energy was assigned by ESDM to conduct pre-feasibility studies in Liki Pinangawan Muara Laboh geothermal prospect that was completed in 2009 within the time specified as per ESDM decrees. In the beginning, the prospect of geothermal resources is characterized by the presence of fumaroles, mud pools, and hot springs (Ganefianto, 2021). Then, after comprehensive studies, the pre-feasibility studies conclude there are several possible geothermal reserves based on the conceptual models that constructed by 3G data integration (Supreme Energy, 2023).

After completing their pre-feasibility studies assignment by the ESDM (PSP), PT Supreme Energy consortium following the auction award of the Muara Laboh concessions in 2010 and obtained geothermal license to their project company which is PT Supreme Energy Muara Laboh (SEML). Then, after obtaining the geothermal license, SEML continues their study by conducting Micro Earthquake (MEQ) and Airborne topographic surveys, civil engineering studies, and land acquisitions which were required for the exploration drilling (Supreme Energy, 2023).

In the end of 2013, SEML has already completed their exploration drilling campaign using full-size wells for 6 wells. These exploration wells are the basis of the feasibility study that confirming of 80 MW project development (Supreme Energy, 2023; Ganefianto, 2021). Then, in 2015 SEML focused in

EPC tender and also re-negotiating tariff adjustment with PT. PLN. Amendment of PPA with PT. PLN was issued in 2016 followed by the EPC tender result announcement (Supreme Energy, 2023).

In 2017, SEML secured loan agreements with lenders and start development drilling campaign in 2017-2018. The development drilling campaign resulting big production capacity ranging from 18 – 31 MWe/well (Ganefianto, 2021). Lastly, after the long journey from 2008 until 2019, the Muara Laboh Unit 1 is commercial operation date (COD) was announced in December 2019.

4.2 Blawan-Ijen Case

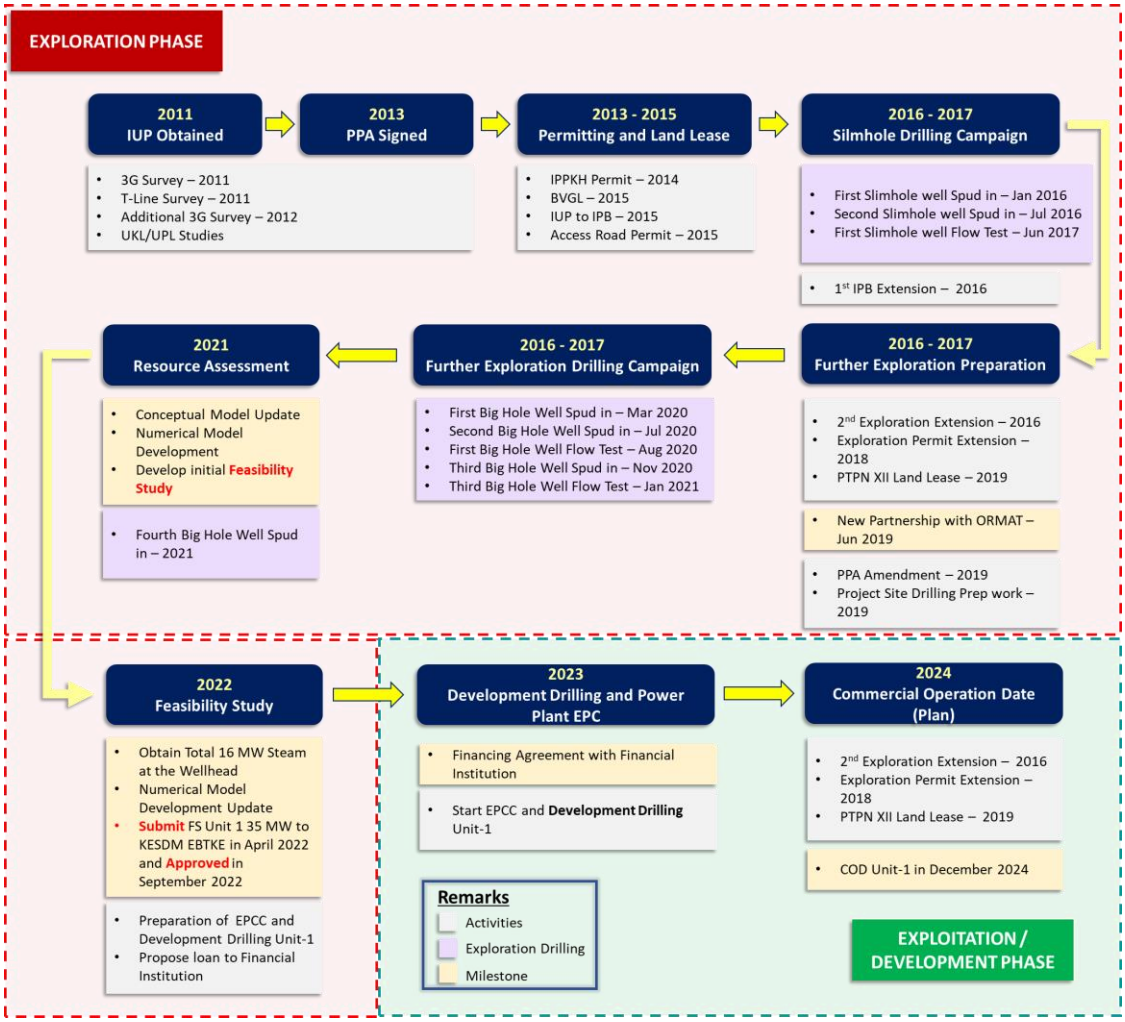


Figure 10: Blawan-Ijen Geothermal Working Area Project Timeline. Modified and updated from EBTKE (2022).

Blawan-Ijen geothermal working area is located in East Java Province. This geothermal working area has coverage area across three (3) regencies namely: Bondowoso Regency, Banyuwangi Regency, and Situbondo Regency. Blawan-Ijen is one of example of geothermal working area that uses staging project development strategy to mitigate risk uncertainty.

In June 2011, PT Medco Power Indonesia (MPI) secured a contract from the Provincial Government of East Java for the development of a 110 MW geothermal power plant at Ijen. Then, in 2012 PT Medco Cahaya Geothermal (MCG) a project company of MPI conducted 3G survey for early resource assessment and well targeting and conclude the Blawan-Ijen geothermal working area has blind geothermal system due to the lack of surface manifestations that are directly related to the reservoir system (EBTKE, 2022).

Based on 3G survey and well-targeting study that conduct previously, in order to reduce the uncertainty in blind geothermal system MCG conduct early exploration drilling campaign with 2 (two) slim-hole wells in 2016 to confirm potential exploitable geothermal resources underneath Blawan Ijen geothermal working area. These slimhole wells results was interpreted as good presence of geothermal resources since it has high temperature (292 °C) and has steam production of 2.8 kg/s at a wellhead pressure during flow test for 6 days (EBTKE, 2022).

As the result of slimhole drilling campaign that obtained good presence of geothermal resources, MCG continues to conduct exploration drilling campaigns with big hole well in 2020 – 2021 and resulting ± 16 MW steam under wellhead which equals 50% of the planned installed capacity for Unit 1. Figure 10 shows the simplified WKP Blawan-Ijen activities timeline from the exploration to the development phase.

The key milestone that marks the transition from the Exploration phase to the Exploitation phase is the Feasibility Study Report approval by EBTKE and the Financial Investment Decision (FID). As shown in Figure 10, the activities in Blawan-Ijen geothermal working area from 2021 – 2022 are classified into the "Exploration" phase, while the ongoing and planned activities in 2023 – 2024 are classified into the "Exploitation or Development" phase.

4.3 Sorik Marapi Case

Sorik Marapi is a geothermal working area that is located in Mandailing Natal Regency, North Sumatra Province. This field is one of example of geothermal working areas that start project development after acquiring geothermal license (IPB). Figure 11 shows the Sorik Marapi geothermal project timeline starting from exploration until the latest commercial operation date (COD) unit 2 in 2021.

Initially, Sorik – Marapi – Roburan – Sampuraga was be appointed as geothermal working area through ESDM Decree No. 2963 K/30/MEM/2008 with total concession area 62,900 ha (EBTKE, 2016). Then, the consortium of PT Supraco Indonesia – The Tata Power Company Ltd – Origin Energy is awarded as the auction winner for geothermal license on 26th August 2010 and appointed PT SMGP as the license holder of the concession area (EBTKE, 2016).

PT SMGP is owned by OTP Geothermal Pte. Limited with 95 percent share ownership and PT Supraco Indonesia with 5 percent share ownership. In 2010 – 2015, 3G survey and well-targeting study is conducted and followed by drilling infrastructure construction for access roads and well pad A. Initially, PT SMGP plan to construct 2 additional well pads at that time which area SM-B and SM-C pads, but it was constrained by land acquisition and licensing issues (EBTKE, 2016).

In 2014, The Power Purchase Agreement (PPA) between PT PLN (Persero) and PT SMGP was signed on with a development capacity of 3x80 MW and COD unit I in 2020. Then, in August 2016, KS Orka acquired 95% shares of PT Sorik Marapi Geothermal Power (EBTKE, 2016).

Within three years since the acquisition of majority shares of PT SMGP by KS Orka, the project has completed drilling using full-size wells for 18 wells and confirmed at least 55 MW of proven resources. As per early August 2019, SMGP has provided 15 MW via 150 kV transmission line to PLN Grid and is gearing up to the last phase for the commissioning of Unit 1 total 45 MW (gross) by end of September 2019 (KS ORKA, 2019). Then, after two years from the first unit COD, SMGP announce their second unit COD on 27th July 2021 with installed capacity 56,95 MW (EBTKE, 2022).

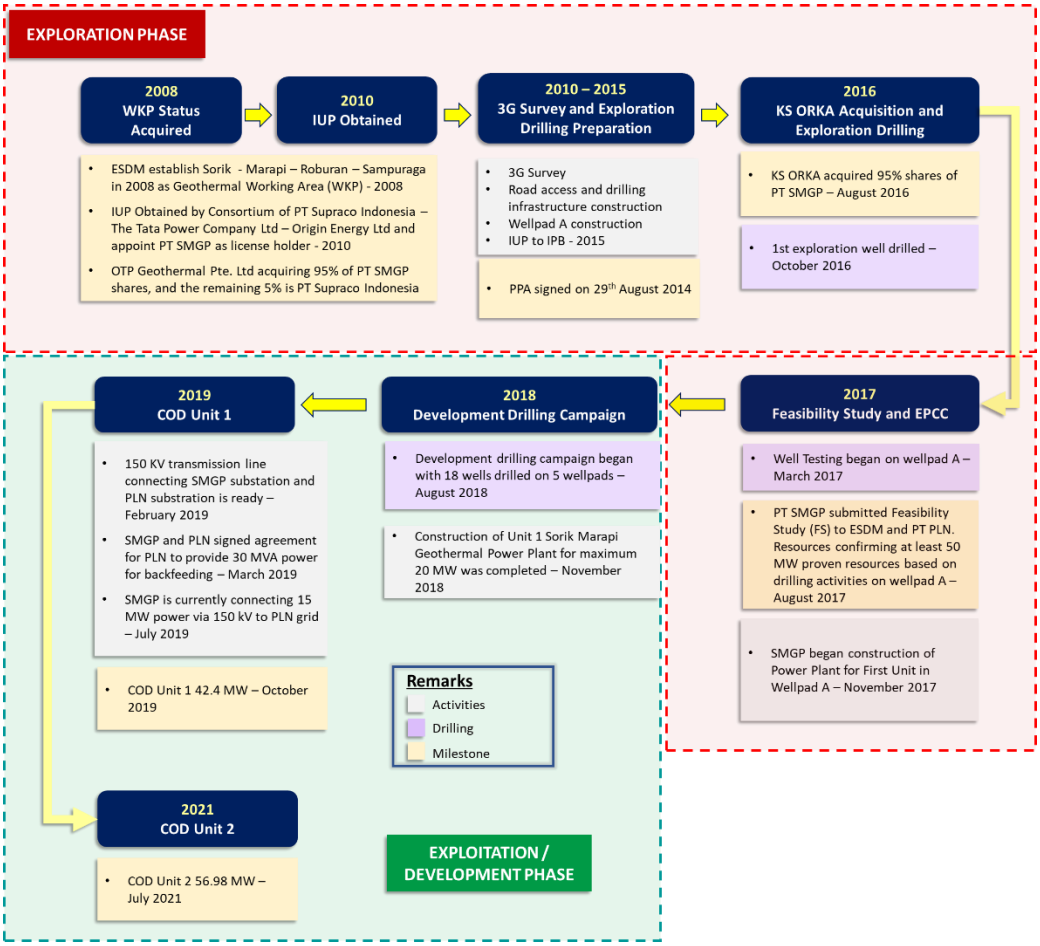


Figure 11: Sorik Marapi Geothermal Field Project Timeline. Modified from (KS ORKA, 2023; EBTKE, 2022; KS ORKA, 2019; EBTKE, 2016)

5. DESCRIPTION OF THE DIFFERENT PURPOSES OF GEOTHERMAL DRILLING

Geothermal drilling is one of the major activities (both in scale and cost) in geothermal projects that can span through almost every stage of geothermal development. Even though the activities seem similar, but the objectives of the drilling depend on the phase of the project. The drilling process in general involves various types of wells, each serving different purposes, and each type is designed and drilled with a specific goal in mind. The different purpose of drilling in every phase is summarized in Table 2.

5.1 Exploration Drilling

The purpose of exploration drilling is to prove the existence of a geothermal resource by obtaining as much as possible information related to the reservoir (e.g., temperature, permeability, geology, chemistry, etc.). Commonly, the success criteria of exploration wells are by obtaining good presence of geothermal resources that are interpreted by positive results on desired properties (temperature, permeability, benign chemistry, etc.) (Jacobs, 2022; IGA, 2014).

Slimhole wells or standard wells are two well types that can be considered at this phase. Standard hole wells are the most common, however slim hole wells are also commonly accepted as an alternate well design for confirming geothermal systems. Developers should have a thorough understanding of the risks associated with resource temperature and size, depth, permeability, productivity, and sustainability, and these risks should have been lowered to a level that allows deep drilling to be justified (Jacobs, 2022; IGA, 2014). In context with Hu'u Daha geothermal prospect area, the mineral well from deep mineral well also can be categorized as exploration well since those wells also provide valuable data for future STM's exploration drilling campaign.

Table 2: The Purpose of Geothermal Drilling in Each Phase. Modified from Jacobs (2022).

	Exploration			Development	O&M
	Exploration Drilling	**Delineation Drilling**	**Appraisal Drilling**	**Development Drilling**	**Make-up Drilling**
Objective	**Prove the existence** of a geothermal resource. **Obtain** as much information on the reservoir (e.g., temperature, permeability, geology, chemistry, etc.).	Find the boundaries of a geothermal field to define the resource / reservoir size / MW capacity.	Get MW target for deciding to proceed with the project (FID / Final Investment Decision) (if required, and if not already achieved in the Exploration/Delineation)	Seek to reach MW target of the project (COD)	Drill wells to add/replace declining existing production / injection well.
Well Success	Obtain positive results on desired properties (temperature, permeability, benign chemistry, etc.)	Able to define the boundary or extent of the resource. Therefore, even a 'cold' well can be considered a 'success' if it identifies the edge of a resource.	Get sufficient MW capacity or injection capacity as required by FID.	Get sufficient MW capacity or injection capacity as required by development plan.	Get sufficient production / injection capacity to sustain the power plant operation.
Well Type	Deep slimhole Standard-sized well	Deep slimhole / core hole Standard-sized well	Full size wells – standard / big holes	Full size wells – standard / big holes	Full size wells – standard / big holes

5.2 Delineation Drilling

The delineation phase is a sub-stage of the exploration phase. A drilling program is begun at the start of this phase to validate the existence, exact location, and potential of the reservoir. Typically, a set of three to five geothermal wells are drilled (ESMAP, 2012).

The objective of delineation drilling is to seek the boundaries of a geothermal field in order to gain understanding and define the resource /reservoir size / MW capacity to support the intended project size. The success criteria of the delineation drilling is able to define the boundary or extent of the resource. Therefore, even a 'cold' well can be considered a 'success' if it identifies the edge of a resource. The type of well used for delineation drilling commonly uses deep slimhole / core hole and standard-sized well depending on the confidence level regarding the resource's existence. (Jacobs, 2022; IGA, 2014)

5.3 Appraisal Drilling

The purpose of appraisal drilling is to get the proven capacity target (MW) for deciding to proceed with the project for the final investment decision (FID). The success criteria of appraisal drilling are defined by getting sufficient MW capacity or injection capacity as required by FID (Jacobs, 2022; IGA, 2014).

It should be noted that the appraisal drilling is optional and needs to be conducted if MW target is not achieved during the exploration and delineation drilling campaign. Commonly, the financiers will be proceeding with the FID if the proposed project already has at least 50% steam under wellhead. The type of well that is used for exploration drilling commonly uses full-size wells – standard/big holes (Jacobs, 2022; IGA, 2014).

5.4 Development Drilling

The objective of development drilling is to seek to reach MW target of the project (COD). Basically, the success criteria of the development drilling campaign are defined by getting sufficient MW capacity or injection capacity as required by the development plan. The type of well that is used for exploration drilling commonly uses full-size wells – standard/big holes (Jacobs, 2022; IGA, 2014).

5.5 Make-Up Drilling

The purpose of make-up drilling is to drill wells to add/replace declining existing production/injection well. The success criteria of the make-up drilling campaign are by getting sufficient production/injection capacity to sustain the power plant operation. The type of well that used for exploration drilling commonly uses full-size wells – standard/big holes (Jacobs, 2022; IGA, 2014).

6. SUMMARY AND CONCLUSION

In conclusion, the geothermal energy landscape in Indonesia is marked by its intricate dynamics and diverse approaches. The paper highlights various strategies that can be adopted in geothermal projects, showcasing the intersections of regulations, exploration methodologies, drilling techniques, and partnership dynamics. It underscores the significance of drilling phases tailored to distinct project objectives, emphasizing the need for an in-depth understanding of the geothermal development process.

The examined Indonesian cases highlight the challenges and complexities associated with geothermal projects, which can span over considerable periods. Accelerated exploration strategies and staged development approaches present contrasting trade-offs between revenue streams and initial capital expenditures. Striking the right balance emerges as a pivotal challenge in geothermal energy projects.

By delving into these aspects, this paper expects to contribute to the broader knowledge base surrounding geothermal energy development, providing valuable insights for stakeholders, policymakers, and industry practitioners. This is an attempt to support an informed decision-making, promotes sustainable energy practices, and advances the discourse on effective geothermal development strategies.

REFERENCES

Direktorat Panas Bumi EBTKE. (2022). Pengembangan Panas Bumi di Indonesia. EBTKE.

EBTKE. (2016). EBTKE ESDM. Retrieved from EBTKE ESDM: https://ebtke.esdm.go.id/post/2016/06/16/1263/direktur.panas.bumi.kawal.pengembangan.sorik.merapi

EBTKE. (2022). Pengembangan Panas Bumi di Indonesia. Jakarta: Ministry of Energy and Mineral Resources.

ESMAP. (2012). Geothermal handbook: Planning and Financing Power Generation. Energy Sector Management Assistance Program: World Bank.

Ganefianto, N. (2021). Lessons Learned from Geothermal Exploration in Muara Laboh. Jakarta: NQ Academy Webinar #8.

Gehringer, M., & Loksha, V. (2012). Geothermal Handbook: Planning and Financing Power Generation. Washington, DC: World Bank. Retrieved from https://openknowledge.worldbank.org/handle/10986/23712

IGA. (2014). Best Practices Guide for Geothermal Exploration. Second Edition. Bochum: IGA Service GmbH.

Jacobs. (2022). Geothermal 101: Resources, exploration, drilling, power development, energy evaluation, feasibility, development stages. Capacity Building Training for PT Sarana Multi Infrastruktur (Persero).

KS ORKA. (2019). Company Profile 2019.

KS ORKA. (2023). KS ORKA SORIK MARAPI. (KS ORKA RENEWABLES) Retrieved from KS ORKA SORIK MARAPI: https://www.ksorka-sorikmarapi.com/

Purwanto, E. (2019). Assessment of Exploration Strategies, Results and Costs of Geothermal Fields in Indonesia. Reykjavik: United Nation University (UNU) - Geothermal Training Programme. Retrieved from https://orkustofnun.is/gogn/unu-gtp-report/UNU-GTP-2019-24.pdf

Supreme Energy. (2023). https://www.supreme-energy.com/pt-supreme-energy-muara-laboh. (Supreme Energy) Retrieved 2023, from https://www.supreme-energy.com/: https://www.supreme-energy.com/pt-supreme-energy-muara-laboh

Geothermal Captive Use to Support Industrial Activities: Applicable Industry Sectors, Worldwide Experience, and Its Potential and Challenges in Indonesia

Vincentius A. Brilian[1,3], Daniel W. Adityatama[2,3], Agung W. Mukti[3], M. Rizqi Al Asy'ari[1,3], Dorman Purba[1,3], Ferdino R. Fadhillah[1,3], and Nadya Erichatama[1,3]

[1]PT Geoenergi Solusi Indonesia (GEOENERGIS), Cibis Nine 11th Floor, Jakarta, Indonesia
[2]PT Geo Dipa Energi (Persero), Soreang, Bandung Regency, Indonesia
[3]PT Enerka Bhumi Pratama (ENERKA), Cibis Nine 11th Floor, Jakarta, Indonesia

adven.brilian@geoenergis.com

Keywords: captive use, geothermal, industrial activities, mining

ABSTRACT

In the conventional geothermal power generation, the electricity is sold by the geothermal power plant operators to the offtakers that distribute the electricity to the buyers, such as the industries. However, some industries are located too far away for an economically viable connection to the existing grid so that they have to generate power independently to support their industrial activities. Geothermal captive use offers a new approach on how geothermal energy can provide clean and cheap electricity for the local industries yet no electricity grid is accessible and the costs of diesel and natural gas are high. Examples of geothermal captive use can be seen in Lihir (Papua New Guinea) and Florida Canyon (United States). Although geothermal captive use is yet to be implemented in Indonesia, several mining sites have the potential to implement geothermal captive use. This paper aims to identify the potential of geothermal captive use to support industrial activities, with an emphasis on the mining industry. A literature review is conducted to review the captive use mechanisms from the worldwide experience and extract the lessons learned that may be applicable in Indonesia. Additionally, the mining sites near to or intersecting geothermal prospect areas are identified. This study also reviews the challenges and pathforward to accelerate the industrial geothermal captive use in Indonesia.

1. INTRODUCTION

By the end of 2022, there are 46 geothermal power plant (GPP) units in Indonesia across 17 geothermal working areas with the total installed capacity of 2.3 GW (Pambudi, et al., 2023). The electricity generated from these GPPs are sold by the operator to the sole offtaker in Indonesia, which is PT Perusahaan Listrik Negara (Persero) (abbreviated as PLN). The electricity is then transmitted and distributed by PLN to the consumers from various sectors, including industries, offices, and households. The energy-intensive industries, such as steel factories, cement factories, and mining, require a significant amount yet stable electricity supply to support their primary equipment for continuous production, including electric-arc steel furnace, concrete grinding machine, and mining smelters (Su, et al., 2021). Meanwhile, the characteristics of geothermal energy are renewable, available around the clock, low CO_2 emissions, and negligible fuel requirements (Yao, et al., 2021). Therefore, these industries could benefit from geothermal captive use to fulfill their power needs independently without relying on the existing electrical grids, especially if the grid is not economically reachable from their locations. Moreover, in such cases, geothermal electricity is cost-competitive compared to other alternative options, such as diesel generators or liquefied natural gas (LNG) engines or turbines (IESR, 2023).

In the geothermal captive use business model, the industries develop GPP to power their primary industrial activities located near to the geothermal area instead of selling the electricity to the grid, such as PLN for the case of Indonesia. Therefore, such industries usually hold multiple permits that covers both the geothermal development and the main industrial activities. Figure 1 illustrates the differences between the conventional geothermal power generation and the geothermal captive use business models for the industrial sector. Two prominent examples of existing industrial geothermal captive use are the ones in Lihir (Papua New Guinea) and Cerro Prieto (Mexico). However, geothermal captive use has not been implemented in Indonesia despite the potential being present.

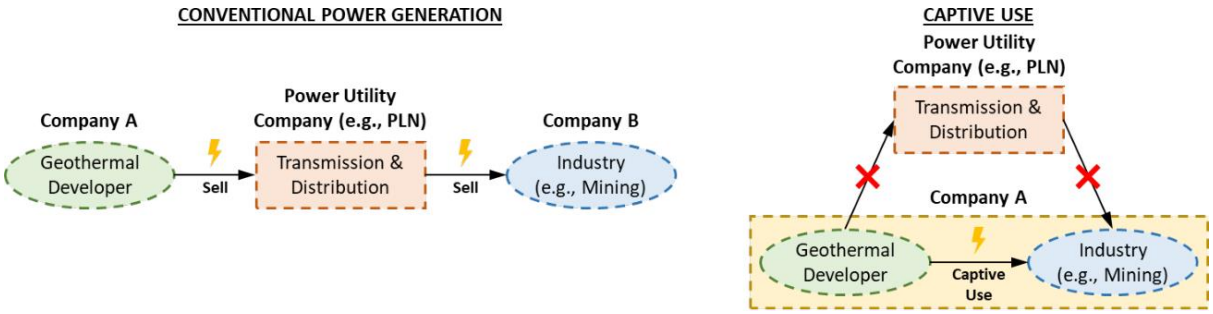


Figure 1: The differences between conventional geothermal power generation and geothermal captive use business models for the industrial sector.

The research questions to be answered in this study are as follows:

1. What are the examples of worldwide experience of geothermal captive use?
2. How is the potential of geothermal captive use in Indonesia?
3. What are the challenges of implementing geothermal captive use in Indonesia?

2. WORLDWIDE EXPERIENCE

2.1 Lihir (Papua New Guinea)

Lihir Island is located 800 km northeast of the Papua New Guinea's capital, Port Moresby. On the island, gold bearing ore has been mined by Newcrest Mining Ltd. since 1997 in an open-pit mining. The mining site's northern and western parts are located within an active geothermal system. The Lihir geothermal development was driven by the need of pit dewatering as well as cooling and depressurizing the rock formation to enable safe and efficient deep open-pit mining. Initially, the mining site was reliant on heavy fuel oil (HFO)-fired power plants to provide electricity for the mining activities. As the geothermal drillings were performed and the geothermal resource was better understood, the role of geothermal development in Lihir evolved from merely mine dewatering and depressurization to providing cheaper and cleaner electricity than HFO for the mining activities (Melaku, 2005).

The Lihir geothermal development started when eight deep (1260-1790 mMD) standard-hole directional geothermal wells were drilled in 1999 (Melaku, 2005). Three wells that were drilled northwards encountered high permeability and production capacity. Meanwhile, three wells that were drilled southwards produce smaller capacity. The produced fluid has high pH (around 9), high chloride content (30,000 ppm), and high sulphate content (40,000 ppm) with a low non-condensable gas content (0.6 %wt). Due to its high mineral content, calcite deposition in the wellbore and silica scaling in the pipelines caused some of the wells being clogged after sustaining the discharge for only several months. Afterwards, around 20 shallow (400-800 mMD) geothermal wells were drilled to accelerate the pit dewatering and depressurization. Most of the deep and shallow wells encounter steam or high temperature fluids that can be used for power generation. The output of the deep wells are tabulated in Table 1.

Table 1: The output of Lihir deep geothermal wells drilled in 1999 (Melaku, 2005).

Well	Mass Flow Rate (t/h)	Enthalpy (kJ/kg)	Gas Content (%wt)
GW1	320	1100	n/a
GW2	65	2000	n/a
GW4	95	2750	n/a
GW5	150	2700	2
GW6	180	2700	0.6
GW7	100	2400	0.6
GW8	400	1200	0.7

A 6 MW backpressure GPP was commissioned in 2003 just north of the pit boundary to utilize the steam from four of the 28 geothermal wells. The performance of the GPP was excellent in the first two years of operation, in which its availability factor was higher than 95% (Melaku, 2005). Subsequently,

a 30 MW flash GPP was commissioned in 2005, which was expanded to 50 MW in 2007 (Huttrer, 2021). As a result, Lihir GPP once had an installed capacity of 56 MW, which could supply 50% of the gold mine's electricity demand. However, due to the failure to reinject the utilized geothermal fluid and the decommissioning of the backpressure GPP in 2009, today's Lihir GPP only generates 15-18 MW. The site layout consisting of the Lihir gold mine pit, the geothermal wells, and the geothermal power plants is shown in Figure 2.

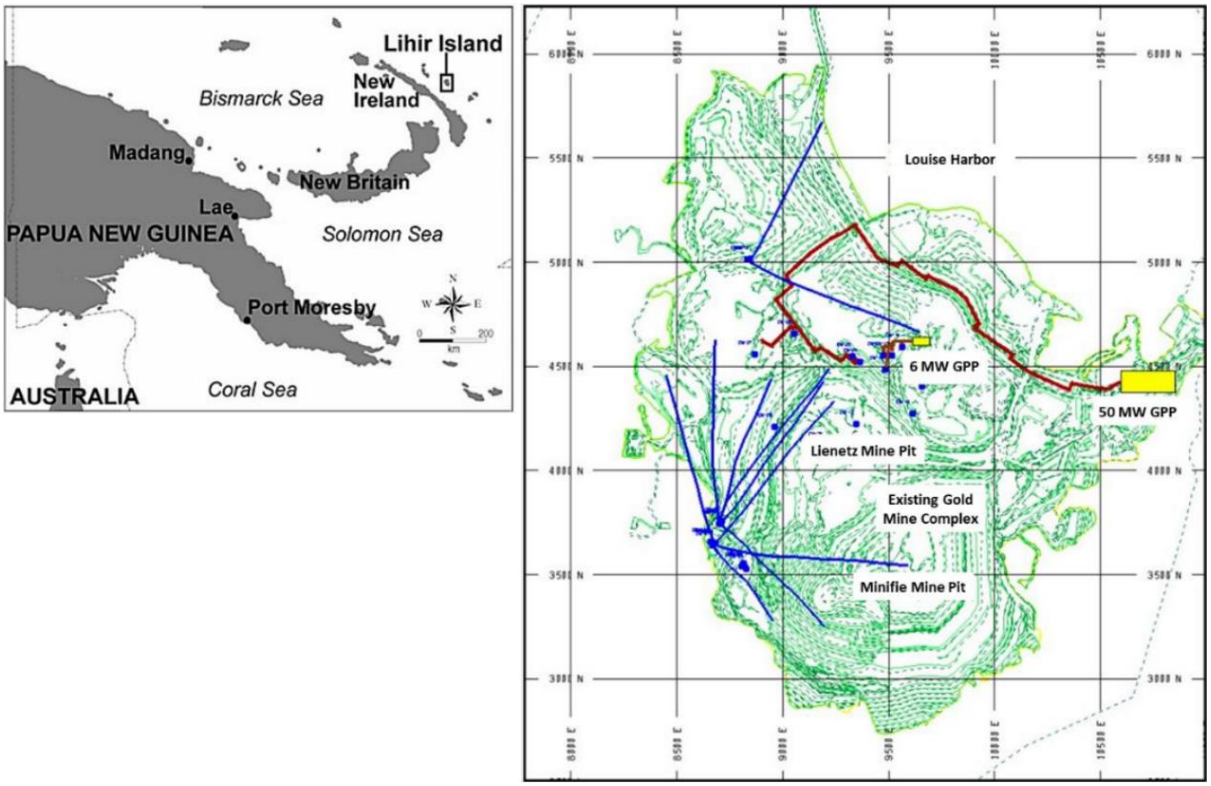


Figure 2: Site layout of Lihir gold mine and GPP (Modified from: Melaku, 2005; Flynn, et al., 2004).

The lessons learned from the geothermal captive use in Lihir are as follows:

- Geothermal utilization in mining areas could improve mining safety as well as reducing reliance on fossil fuel.
- The availability factor of the GPP is high (> 95%) and it could provide up to 50% of the mine's electricity needs.
- Proper geothermal reservoir management strategy is vital to maintain production level.
- Proper mineral scaling mitigation strategy is needed in geothermal fields located within mineral mining areas.

2.2 Florida Canyon (United States)

Florida Canyon is a gold mining site located in Nevada, United States, which was initially owned by Alio Gold Inc. The site has been producing gold through an open-pit mining for more than 30 years. Apparently, the mining site is adjacent to an active geothermal system, which leads to the belief that Florida Canyon is a hot spring-type epithermal gold deposit (MDO Data Online Inc., 2023). The mine wells at the Florida Canyon discharge 36 t/h of fluids at 100oC from the depth of 175 m. Initially, in 1980, the fluids were utilized as the heat source for heap leaching (NBMG, 2014). Afterwards, 2x50 kW binary GPP units were commissioned in 2010 and 2013, respectively, to convert the discharge fluid heat into electricity, which could provide 5% of the mining's electricity needs. Unfortunately, the GPPs have been decommissioned due to the mineral scaling in the piping and the acquisition of Alio Gold Inc. by Argonaut Mine Inc. in 2020 (NREL, 2022). Figure 3 shows the location of the pilot GPP within the Florida Canyon mining site.

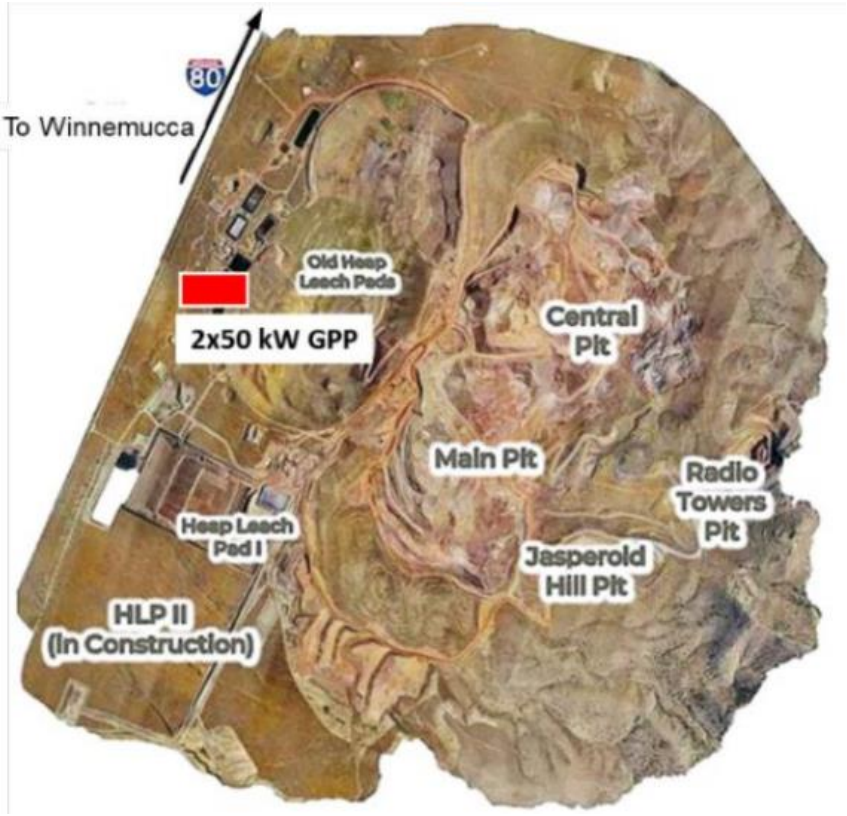


Figure 3: Site layout of Florida Canyon gold mine and GPP (Modified from: Harding, 2020).

The lessons learned from the geothermal captive use in Florida Canyon are as follows:

- Proper mineral scaling mitigation strategy is needed in geothermal fields located within mineral mining areas.
- Commitment from the mine owner is required to sustain the geothermal captive use.

3. POTENTIAL OF GEOTHERMAL CAPTIVE USE IN INDONESIA

3.1 Comparison of Electricity Generation Costs Between Various Energy Sources

In the absence of nearby electrical grids, the typical preferred energy source for industrial captive use is either gas turbines or diesel generators due to their low upfront cost, compact equipment, quick installation, and short ramp-up period (IRENA, 2019). However, these energy sources bring the operational challenges, such as expensive fuel requirements and insecure fuel supply chain, especially if the industrial location is in the rural areas or remote islands. Additionally, the use of fossil fuels creates high greenhouse gas (GHG) emissions. The presence of geothermal potential near to the industry could be a promising option of relatively cheap and clean captive use energy source, as shown in Table 2 and Figure 4. The levelized cost of electricity (LCOE) of geothermal is way lower than diesel generators and is equivalent to gas turbines. Additionally, the GHG emissions from geothermal is negligible compared to diesel and natural gas. Moreover, the LCOE shown in Table 2 and Figure 4 also has not considered the externalities, such as carbon tax for fossil fuel power generation. If it is considered, the GPP LCOE might be more favorable.

Table 2: Comparison between diesel generator, natural gas turbine, and geothermal power plant.

Parameter	Units	Diesel Generator	Gas Turbine	Geothermal	References
Capital expenditure	MUSD/MW	0.5-0.8	0.8-0.9	4-6 million	(Statista, 2023)
Land area	m^2/MW	900	800	5,000-20,000	(Strata Policy, 2017)
Installation duration	year	< 1	2-4	5-7	(ESMAP, 2012)
Ramp-up	minute	< 1	10-20	10-20	(Abudu, et al., 2020)
Capacity factor	-	10-30%	50-60%	80-95%	(U.S. DOE, 2020)
LCOE	USD¢/kWh	12.5-37.1	9.1-13.5	3.6-13.4	(IESR, 2023)
Fuel requirement	-	Yes	Yes	No	(IMF, 2019)
GHG emission	kg CO_2e/kWh	0.51-1.18	0.32-0.99	0.02-0.24	(NREL, 2021)
Subject to carbon tax	-	Yes	Yes	No	(IMF, 2019)

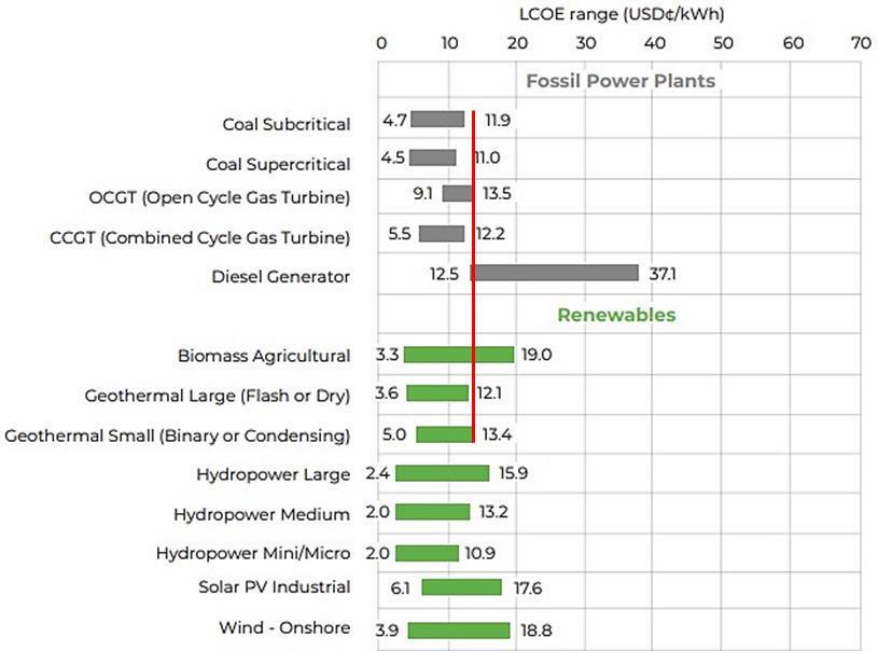


Figure 4: LCOE comparison between geothermal energy and other energy sources (Modified from: IESR, 2023).

3.2 Geothermal Prospect Areas Near to Mining Areas Without PLN's Grid Nearby

Currently, there are no commercially operational geothermal captive use by any industry in Indonesia, including mining. However, Hu'u Daha in West Nusa Tenggara is the only mining site that has made a notable progress on geothermal captive use development. Hu'u Daha is a copper-gold deposit, which is currently being explored by PT Sumbawa Timur Mining (abbreviated as "STM"). Apparently, the deposit is located within an active geothermal system. STM is interested in developing the geothermal potential in Hu'u Daha to provide electricity for their own mining activities, especially the smelter operation, since the mining site is located up to 30 km away from the nearest existing substation (Dompu 150 kV). In 2018, the Indonesian Ministry of Energy and Mineral Resources (MEMR) announced that STM was awarded the Hu'u Daha geothermal Preliminary Survey and Exploration Assignment or *Penugasan Survei Pendahuluan dan Eksplorasi* (PSPE), which was completed by STM in mid-2023. As a result of the PSPE award, STM currently holds two permits consisting of both the mining and geothermal permits. During the PSPE activities, STM discovered a temperature of more than 150°C (SuaraNTB.com, 2023) despite the presence of geothermal fluid is yet to be proven.

In this study, the mining sites in Indonesia that have the potential of implementing geothermal captive use are mapped and tabulated in Table 3 based on the following criteria:

- The geothermal prospect area has not been auctioned by MEMR (except for Hu'u Daha) so that there is still a potential for the mining permit holders to obtain the geothermal permit for their captive use.
- The distance between the mining site and the nearest existing or planned substation according to PLN's Electricity Supply Business Plan or *Rencana Usaha Penyediaan Tenaga Listrik* (RUPTL) Year 2021 – 2023 is larger than 30 km so that the connection to the substation is unlikely to be economical.
- The distance between the mining site and the nearest geothermal potential is less than 10 km so that the geothermal captive use is likely to be more economically attractive than the connection to the existing or planned substation with the distance of more than 30 km.

The information about the mining site and the nearby geothermal potential are gathered from MEMR's Renewable Energy Map, Electric Utility Map, and Minerba One Map Indonesia (MOMI), which are available online. Meanwhile, the distances from the mining site to the nearest substation and to the geothermal potential are measured approximately using the online Google Earth. As shown in Table 3, there are up to 425 MW potential of geothermal captive use by the mining industry across 10 mining sites in Indonesia. Most of the prospective mining sites are located on remote islands in eastern Indonesia without existing or planned electricity grid according to RUPTL 2021 – 2023. Therefore, this condition should prompt the mining industries in this region to seriously consider implementing geothermal captive use to achieve clean and cheap independent power generation.

Table 3: Prospective mining sites for geothermal captive use in Indonesia.

Mining Site Location	Mining Permit Holder	Distance to Nearest Substation	Commodity	Mining Status	Mining License Validity	Nearby Geothermal Potential	Geothermal Potential Size
Sarolangun and Merangin Regencies, Jambi	PT Aneka Tambang Tbk.	57 km (Tess 150 kV)	Gold	Exploration	2020 – 2024	Sungai Tenang (2 km)	74 MW (hypothetical resource)
Bima and Dompu Regencies, West Nusa Tenggara	PT Sumbawa Timur Mining	37 km (Dompu 150 kV)	Gold	Exploration	2022 – 2023	Hu'u Daha (inside the mining site boundary)	69 MW (probable reserve)
East Manggarai Regency, East Nusa Tenggara	PT Istindo Mitra Perdana	34 km (Ruteng 70 kV)	Manganese	Production	2016 – 2026	Wai Pesi (9 km)	54 MW (probable reserve)
East Flores Regency, East Nusa Tenggara	PT Adisti Indah	Remote island	Natural gravel sand	Backup (*Pencadangan*)	n/a	Oyang Barang (1 km)	37 MW (probable reserve)
Lembata Regency, East Nusa Tenggara	PT Trans Lembata	Remote island	Excavated gravel	Backup (*Pencadangan*)	n/a	Adum (9 km)	36 MW (probable reserve)
South West Maluku Regency, Maluku	PT Batutua Kharisma Permai	Remote island	Copper	Production	2018 – 2031	Lurang (2 km)	20 MW (speculative resource)
Sula Island Regency, North Maluku	PT Bintani Karya Bumi Persada	Remote island	Iron ore	Production	2018 – 2034	Kramat (1 km)	10 MW (speculative resource)
Sula Island Regency, North Maluku	PT Patria Sekarjaya	Remote island	Iron ore	Production	2018 – 2034	Losseng (inside the mining site boundary)	30 MW (speculative resource)
Sula Island Regency, North Maluku	PT Indotama Mineral Indonesia	Remote island	Iron ore	Production	2018 – 2034	Auponia (inside the mining site boundary)	20 MW (speculative resource)
Sula Island Regency, North Maluku	PT Wirabahana Perkasa	Remote island	Iron ore	Production	2018 – 2034	Bruokol (inside the mining boundary)	5 MW (speculative resource)
						Total	**425 MW**

Out of the 10 prospective mining sites that have been identified, 2 sites are still under exploration, while 6 sites are already in the production phase, as shown in Figure 5(a). The example of parallel mining and

geothermal captive use explorations could be seen in Hu'u Daha. Meanwhile, the example of performing geothermal captive use exploration after the mine has been operational could be seen in Lihir. Furthermore, four prospective mining sites have the geothermal potential inside their mining boundaries, the other four have the geothermal potential 1-5 km away, and the remaining two have the geothermal potential 6-10 km away, as shown in Figure 5(b). In order to make geothermal captive use more economically attractive than diesel and natural gas, the geothermal's higher upfront cost should be counterbalanced by the short distance between the mining site and the geothermal potential. Should the geothermal potential be more than 10 km away from the mining site, geothermal captive use is deemed to be less economically attractive than diesel and natural gas since it would require extensive electrical grid connecting the GPP to the mining site.

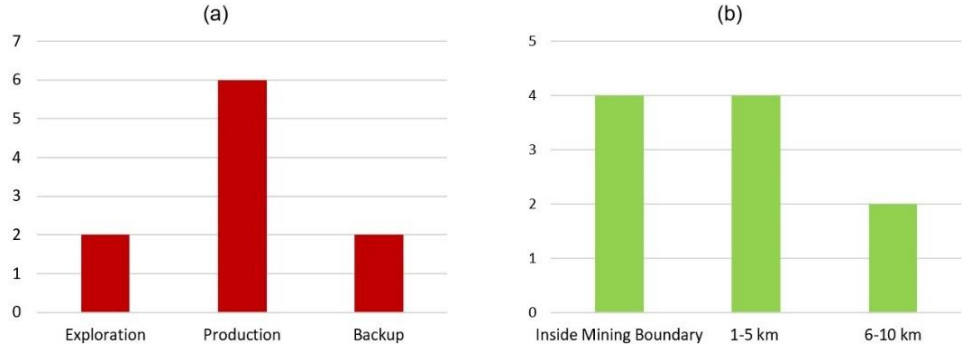


Figure 5: (a) prospective mine status; (b) distance between the mining site and geothermal potential.

The strategy of developing geothermal captive use either in the mining exploration phase or in the mining production phase has its own advantages and disadvantages, as shown in Table 4. Consequently, the mining permit holders should implement distinctive action plans to develop geothermal captive use using either strategy.

Table 4: Comparison between conducting geothermal captive use development during mining exploration and production.

During Mining Exploration		During Mining Production	
Advantages	Disadvantages	Advantages	Disadvantages
✓ Mining and geothermal site plans could be integrated	× High upfront cost × Uncertainty of mining discovery × No existing infrastructure × Limited subsurface data from mining wells	✓ Existing infrastructure ✓ Mining revenue could be allocated for geothermal captive use development ✓ More available subsurface data from mining wells	× Geothermal site plan should adjust to the existing mining site × Challenging geothermal equipment mobilization due to existing mining activities
Action Plan		Action Plan	
➢ Gather subsurface data as much as possible through both the mining and geothermal exploration wells ➢ Create an integrated mining and geothermal site plans to ease infrastructure preparation and later operation ➢ Allocate more financial resources to enable parallel mining and geothermal exploration activities		➢ Gather and evaluate the existing subsurface data from past mining exploration wells ➢ Conduct geothermal exploration drilling to gather subsurface data regarding the geothermal system ➢ Evaluate the existing infrastructure's readiness to support geothermal development activitiy ➢ Adjust the geothermal site plan to the existing mine site plan	

3.3 Challenges of Geothermal Captive Use in Indonesia

The limited geothermal captive use by the industries in Indonesia and globally is likely related to the technical, economic, and regulatory challenges facing its development. The challenges of developing geothermal captive use with an emphasis on the mining industry are listed as follows:

- Geothermal system within mineral deposits is likely to cause mineral scaling in the geothermal facilities within or near to mining sites (NBMG, 2014).
- Challenging geothermal equipment mobilization and installation within an operational mining site.

- Knowledge gap between geothermal and the company's preexisting core business, such as mining.
- Permits are required for both the mining and geothermal activities.
- Financially strong enterprises are required to develop both geothermal and their preexisting core business activities.
- Since natural gas turbines could provide similar LCOE and faster installation compared to geothermal power plants, strong commitments from the enterprise to provide clean source of electricity from geothermal captive use is mandatory.

As the consequences of these challenges, the industry should implement the necessary action plans as follows:

- Create mineral scaling mitigation strategy in the geothermal facilities within or near to mining sites.
- Assess whether the existing infrastructure is capable of supporting geothermal equipment mobilization and installation.
- Hire geothermal experts and conduct capacity building to fill the knowledge gap between geothermal and the company's preexisting core business, such as mining.
- Coordinate with MEMR for the possibility of acquiring geothermal permit to explore nearby geothermal prospect areas.
- Gather internal and external financial aid to support the geothermal captive use development.
- Build strong commitment to provide clean source of electricity from geothermal captive use despite natural gas turbines could provide similar LCOE and faster installation.

4. CONCLUSION

In the conventional geothermal power generation business model, the electricity is sold by the GPP operators to the offtakers that distribute the electricity to the buyers, including the industries. However, some industries are located too far away for an economically viable connection to the existing grid so that they have to generate power independently for their industrial activities. Geothermal captive use offers a new approach on how geothermal energy can provide clean and cheap electricity for the local industries yet no electricity grid is accessible and the costs of diesel and natural gas are high. Examples of geothermal captive use can be seen in Lihir (Papua New Guinea) and Florida Canyon (United States). Although geothermal captive use is yet to be implemented in Indonesia, up to 10 mining sites are identified as having the potential of geothermal captive use up to 425 MW in total. While the geothermal captive use development during either the mining exploration or production phase present its unique advantages and disadvantages, the mining permit holders should conduct necessary action plans to initiate the geothermal captive use development. Additionally, the technical, economic, and regulatory challenges should be addressed by the industry with the support from the government to accelerate geothermal captive use development in Indonesia.

REFERENCES

Abudu, K., Igie, U., Minervino, O. & Hamilton, R., 2020. Gas turbine Efficiency and Ramp Rate Improvement Through Compressed Air Injection. *Proceedings of the Institution of Mechanical Engineers: Journal of Power and Energy*, 235(4), pp. 866-884.

Directorate General of Electricity, 2021. *Statistik Ketenagalistrikan Tahun 2020*, Jakarta: Directorate General of Electricity.

ESMAP, 2012. *Geothermal Handbook: Planning and Financing Power Generation*, Washington, D.C.: Energy Sector Management Assistance Program.

Harding, A., 2020. *Argonaut Gold to Run Florida Canyon*. [Online] Available at: https://elkodaily.com/mining/argonaut-gold-to-run-florida-canyon/article_e17f6642-1acb-5834-b8bc-f8c31f302bf0.html [Accessed 16 July 2023].

Huttrer, G. W., 2021. *Geothermal Power Generation in the World 2015-2020 Update Report*. Reykjavik, International Geothermal Association, pp. 1-17.

IESR, 2023. *Making Energy Transition Succeed: A 2023's Update on The Levelized Cost of Electricity and Levelized Cost of Storage in Indonesia*, Jakarta: Institute for Essential Services Reform (IESR).

IMF, 2019. *What is Carbon Taxation?*, Washington, D.C.: International Monetary Fund.

Indonesian Ministry of Energy and Mineral Resources, 2023. *Geoportal Energi Baru Terbarukan*. [Online] Available at: https://geoportal.esdm.go.id/ebtke/ [Accessed 16 July 2023].

Indonesian Ministry of Energy and Mineral Resources, 2023. *Geoportal Ketenagalistrikan*. [Online] Available at: https://geoportal.esdm.go.id/ketenagalistrikan/ [Accessed 17 July 2023].

IRENA, 2019. *Flexibility of Conventional Power Plants: Innovation Landscape Brief*, Abu Dhabi: International Renewable Energy Agency.

MDO Data Online Inc., 2023. *Florida Canyon Mine*. [Online] Available at: https://miningdataonline.com/property/332/Florida-Canyon-Mine.aspx [Accessed 16 July 2023].

Melaku, M., 2005. *Geothermal Development at Lihir – An Overview*. Antalya, Proceedings, World Geothermal Congress 2005.

NBMG, 2014. *Site Description: Rye Patch Reservoir*, Reno: Nevada Bureau of Mines and Geology.

NREL, 2021. *Life Cycle Greenhouse Gas Emissions from Electricity Generation: Update*, Golden: National Renewable Energy Laboratory.

NREL, 2022. *Mining G.O.L.D. (Geothermal Opportunities Leveraged Through Data): Exploring Synergies Between the Geothermal and Mining Industries*, Golden: National Renewable Energy Laboratory.

Pambudi, N. A. et al., 2023. Renewable Energy in Indonesia: Current Status, Potential, and Future Development. *Sustainability*, 15(3), p. 2342.

PT PLN (Persero), 2021. *Rencana Usaha Penyediaan Tenaga Listrik (RUPTL) 2021-2030*, Jakarta: PT PLN (Persero).

Statista, 2023. *Forecast Capital Expenditure of a Conventional Natural Gas Combustion Turbine Power Plant in the United States from 2022 to 2050*. [Online] Available at: https://www.statista.com/statistics/243704/capital-costs-of-a-typical-us-gas-turbine-power-plant/ [Accessed 17 July 2023].

Strata Policy, 2017. *The Footprint of Energy: Land Use of U.S. Electricity Production*, Logan: Strata Policy.

SuaraNTB.com, 2023. *Ditemukan Potensi Panas Bumi 150 Derajat Celcius di Hu'u Dompu*. [Online] Available at: https://www.suarantb.com/2023/03/14/ditemukan-potensi-panas-bumi-150-derajat-celcius-di-huu-dompu/ [Accessed 16 July 2023].

Su, Z. et al., 2021. Opportunities and strategies for multigrade waste heat utilization in various industries: A recent review. *Energy Conversion and Management*, Volume 229, p. 113769.

U.S. DOE, 2020. *Capacity Factor by Energy Source in 2020*, Washington, D.C.: The United States Department of Energy.

Yao, Y., Xu, J.-H. & Sun, D.-Q., 2021. Untangling Global Levelised Cost of Electricity Based on Multi-Factor Learning Curve for Renewable Energy: Wind, Solar, Geothermal, Hydropower and Bioenergy. *Journal of Cleaner Production*, p. 123827.

Enhancing Geothermal Well Workover Planning Through Data-Driven Performance Evaluation

Nadya Erichatama[1], Daniel Adityatama[1], M. Rizqi Al Asy'ari[1], Agung W. Mukti[2], and Dorman Purba[3]

[1]Geoenergi Solusi Indonesia (GEOENERGIS), Jakarta, Indonesia
[2]ENERKA Bhumi Pratama, Cibis Nine 11th floor, Jakarta Selatan, Indonesia
[3]PT Geo Dipa Energi (Persero), Jakarta, Indonesia

nadyaerichatama@geoenergis.com

Keywords: geothermal, workover, workover planning, data-driven performance

ABSTRACT

Workover duration planning holds significant importance in minimizing non-productive time and preventing cost overruns. To achieve the optimal operational duration, it is imperative to acquire data pertaining to previous workover performances. This data encompasses various aspects, including the type and size of scaling, the length of the damaged casing, and the speed of the workover tool. By considering the similarity of well characteristics and challenges encountered, the distribution of this data can substantially enhance the success of workover planning. Regrettably, most often, the distribution of this data has not been adequately documented, resulting in heightened uncertainty and suboptimal workover planning. This, in turn, can adversely affect the accuracy of workover duration projections and overall operating costs.

A preliminary dataset of workover parameter durations is established based on the analysis of workover data encompassing the liquid-dominated field in Central Java. This paper strives to refine workover planning practices by collating a comprehensive workover database encompassing the liquid-dominated field in Central Java and fields exhibiting analogous characteristics. Through this endeavor, a substantial enhancement in the precision of workover planning is anticipated, contributing to heightened operational efficiency and improved cost-effectiveness.

1. INTRODUCTION

The exploitation stage of geothermal wells is frequently marred by declines in production or injection rates. Addressing these challenges becomes imperative to restore and optimize the well's production capacity. One prominent technique utilized to achieve this is through workover interventions. These interventions encompass a spectrum of methods such as wellbore cleanout, milling, acidizing, and casing relining. The specific methodology chosen is determined during the workover planning stage, wherein the well's relevant issues are meticulously evaluated. Beyond mere issue identification, the workover planning phase involves the formulation of comprehensive workover programs and the strategic allocation of operation durations.

Among the crucial components of workover planning, the meticulous determination of workover duration assumes paramount significance. Effective planning in this domain serves the dual purpose of curtailing non-productive intervals and circumventing cost overruns. To ascertain the optimal operational timeframe, the utilization of historical data derived from prior workover interventions becomes a necessity. This dataset encompasses a myriad of variables, including the nature and magnitude of scaling, the extent of casing damage, and the velocity at which workover tools are employed. Leveraging the congruity between well attributes and encountered challenges, the systematic distribution of this data emerges as a pivotal determinant in augmenting the efficacy of workover planning processes.

2. LEVERAGING HISTORICAL WORKOVER DATA

The optimal determination of workover duration relies on accurate historical data. The performance of previous workovers serves as a foundation for estimating the duration of new interventions. Factors

such as the type and size of scaling, damaged casing length, and workover tool speed significantly influence the time required for successful wellbore interventions. A robust database containing such information is essential for informed decision-making during the planning stage.

Despite the importance of historical data, challenges persist in maintaining well-documented records. In many cases, the distribution of critical data, vital for accurate workover planning, remains incomplete or inconsistent. This lack of comprehensive documentation results in uncertainties that hinder effective planning. An endeavor to systematically document and organize data related to workover operations is thus crucial to ensuring reliable planning outcomes.

3. DATASET ANALYSIS

To establish a reliable estimation of workover duration, it is essential to utilize a comprehensive dataset of recent workover operations. Workover data from offset wells with similar geological, reservoir, and operational characteristics are collected. This dataset includes the Daily Workover Report (DWR) from the previous year for six production wells and two injection wells. The use of offset wells helps ensure that the collected data is pertinent to the reservoir conditions under consideration.

The dataset is subject to rigorous criteria for analysis:

- Daily Workover Reports (DWR) from the most recent year are included.
- The dataset comprises workover records from six production wells and two injection wells.
- The workovers across all wells were conducted utilizing rigs with uniform capacity.

The gathered workover data is statistically analyzed, focusing on the following parameters:

- Rate of Penetration (ROP) during drilling operations.
- Running in Hole (RIH) and Pulling Out of Hole (POOH) speeds.
- Parameters pertinent to killing, quenching, and injectivity tests.
- Wireline logging tool velocities.
- Mud pump flow rates.

3.1. Rate of Penetration (ROP)

The Rate of Penetration (ROP) serves as a fundamental indicator in drilling and milling operations, denoting the speed of the drill bit or milling tool while reaming or milling. This document aims to establish a precise definition of ROP and its classification for workover operations. ROP is expressed in meters per hour (m/hr). In this paper, ROP is categorized into two distinct classes:

- Hard Reaming. Hard reaming pertains to reaming activities characterized by an ROP value of $\leqslant$ 15 m/hr. Data encompassed by the hard reaming classification are assumed to originate from workover operations that encounter wellbore zones with pronounced obstructions or thick scale deposits.

- Soft Reaming. Soft reaming refers to reaming activities with an ROP value exceeding 15 m/hr. Data corresponding to the soft reaming classification are presumed to originate from workover operations targeting wellbore zones with lesser obstruction intensity or thin scale deposits.

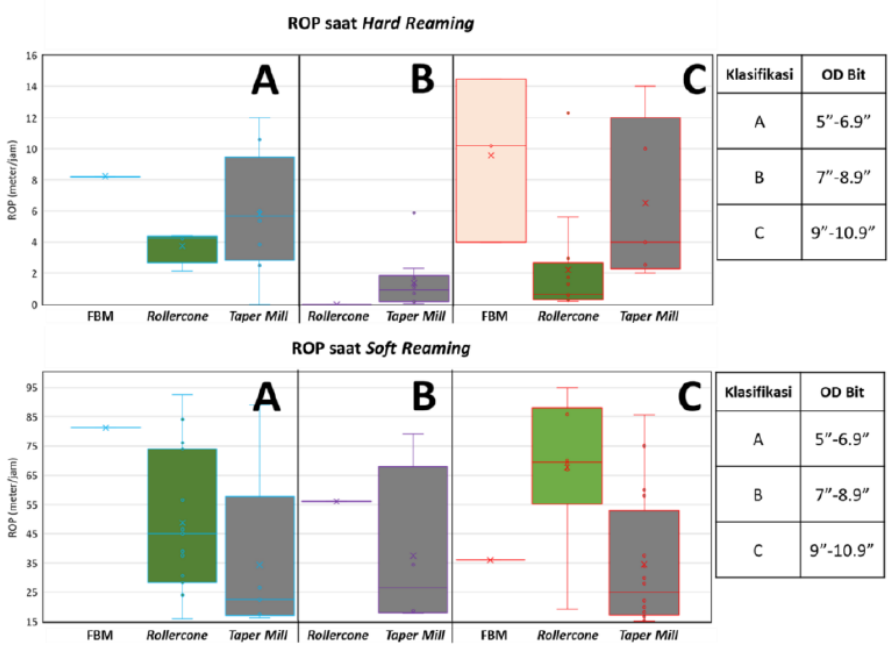


Figure 1: Distribution of ROP for Three Types and Three Categories of Bit Sizes during Soft Reaming and Hard Reaming.

3.2. Analysis of RIH-M/U and POOH-B/O Speeds

The speed of RIH-M/U and POOH-B/O is generally influenced by several factors:

- Hoisting System Capability: The hoisting system of the rig used determines the force and speed that the drawworks can provide to lower or raise the drillstring. Additionally, the ratio between the fast line and the deadline can impact the speed and maximum load that can be handled during RIH and POOH (Al-azzawi & Al-Duleimi, 2010).
- Wellbore Profile and Inclination: The inclination and profile of the wellbore affect hole cleaning after reaming due to the friction experienced by the drillstring during RIH and POOH. The greater the wellbore inclination, the longer the time required for RIH and POOH operations (Elgibaly, Farhat, Trant, & Kelany, 2016).
- Rig Crew Efficiency in Making-Up and Breaking-Up Connections: The speed and experience of the rig crew in performing making-up and breaking-up connections influence the time required for M/U and B/O operations (Valdez & Sager, 2005; Mahmud & Elmabrouk, 2016).

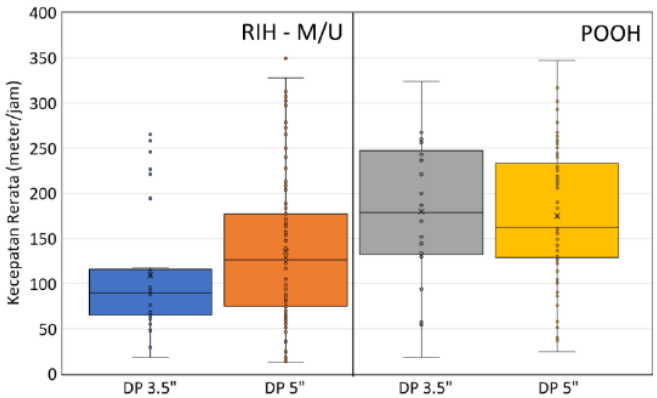


Figure 2: Distribution of RIH-M/U and POOH-B/O Speeds for 3.5" and 5" Drill Pipe Sizes.

3.3. Analysis of Killing & Quenching and Injectivity Test Durations

The analysis of killing & quenching activities and injectivity tests in this study serves the following objectives:

- Determination of Killing & Quenching and Injectivity Test Durations: The primary aim is to ascertain the durations required for killing & quenching activities and injectivity tests. These assessments provide insights into the timeframes necessary for these interventions to effectively restore well performance.
- Evaluation of Required Mud Pump Flow Rates: Additionally, the analysis seeks to determine the optimal mud pump flow rates required during killing & quenching activities and injectivity tests. By understanding the flow rates essential for successful execution, operational efficiency can be enhanced. This involves an exploration of the statistical distribution of killing & quenching and injectivity test values. The dataset comprises a predominance of killing & quenching activities (52 data points) and injectivity test activities (12 data points).

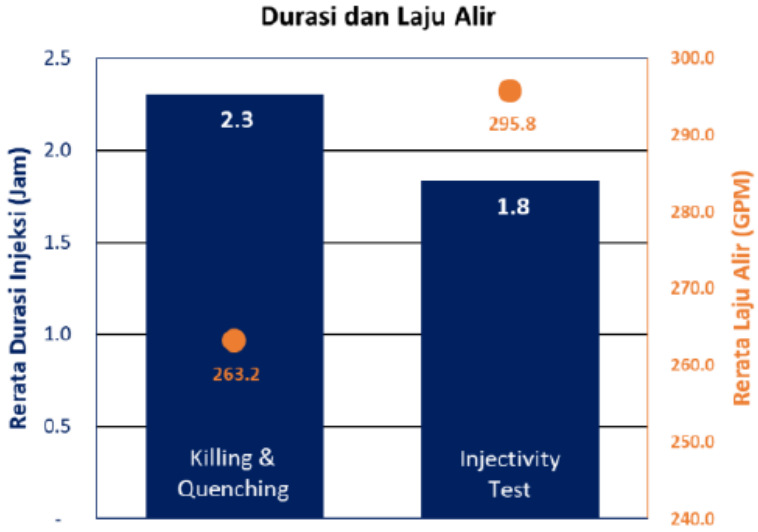


Figure 3: Average Duration and Flow Rate during Killing & Quenching and Injectivity Test.

3.4. Analysis of Wireline Logging Speeds

The wireline logging speeds analyzed in this study encompass two key operations:

- Running In Hole (RIH) Logging Tool Speed: This refers to the speed at which the logging tool is lowered into the wellbore.
- Pulling Out of Hole (POOH) Logging Tool Speed: This pertains to the speed at which the logging tool is raised to the surface.

Several factors influence the RIH and POOH wireline logging speeds:

- Tool Type: Each logging tool serves distinct purposes and is associated with varying job durations. Downhole Video (DHV) tools are commonly employed for real-time wellbore assessments, while Pressure and Temperature Survey (PTS) tools are utilized to identify feed zones within the well.
- Type of Operation: PTS and DHV logging activities differ significantly in terms of their operational sequences. PTS logging involves three primary sequences (log down, log up, and stationary), wherein log down (RIH) and log up (POOH) speeds can be executed quickly after data collection during stationary periods. In DHV logging, both RIH and POOH activities

exhibit relatively slower speeds compared to PTS logging due to concurrent video observation from the camera.

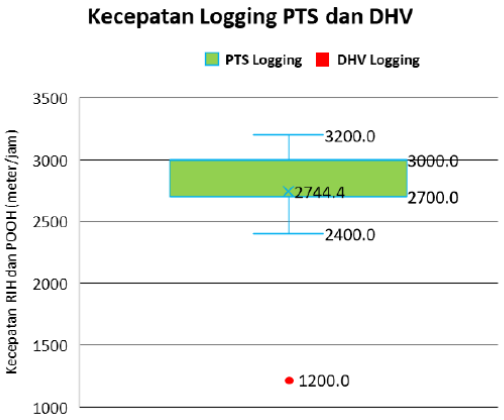


Figure 4: Distribution of Logging Speed Data.

3.5. Pump Flow Rate Analysis

In this study, pump flow rate is defined as the volume of fluid supplied by the pump per unit of time (in GPM) for Killing & Quenching, Circulating, Acidizing, and Reaming activities. The analysis of pump flow rates in this study aims to:

- Determine the Distribution of Pump Flow Rate Values: The primary objective is to ascertain the distribution of pump flow rate values across Killing & Quenching, Circulating, Acidizing, and Reaming activities. This analysis provides insights into the variability of fluid supply rates during these interventions.
- Determine the Distribution of Pump Pressure Values: Additionally, the study aims to establish the distribution of pump pressure values for Killing & Quenching, Circulating, Acidizing, and Reaming activities. This analysis enables an understanding of pressure variations experienced during these operations.

The pump flow rates analyzed in this study encompass the following activities:

- Killing & Quenching
- Circulating
- Acidizing
- Reaming and Milling

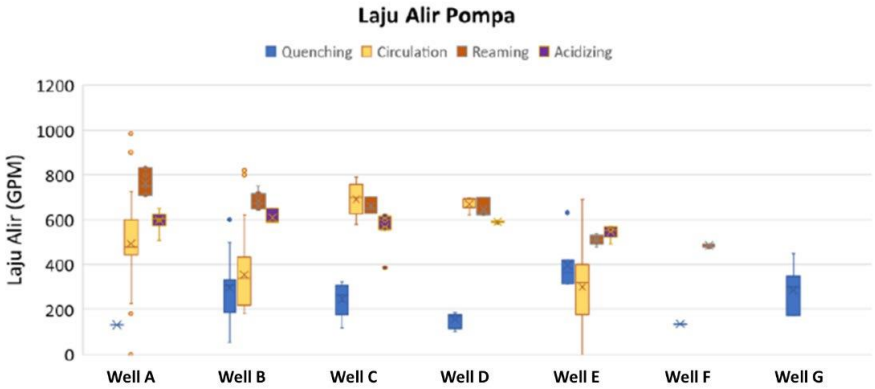


Figure 5: Pump Flow Rate Distribution.

4. PRELIMINARY DATASET OF WORKOVER PARAMETER DURATIONS BASED ON ANALYZED DATASET

In the previous section, the processed and analyzed dataset has culminated in a summarized presentation within Table 1, delineating the estimated durations associated with each workover parameter. This comprehensive tabulation stands as a crucial tool for assessing and optimizing workover strategies in geothermal operations. The discussion delves into the significance of this summarized data and its categorization into three distinct classes: optimistic, normal, and conservative. Each scenario represents a different projection of the time required for workover activities. The optimistic scenario suggests a best-case scenario with the shortest estimated duration, while the normal scenario reflects a moderate timeframe that considers typical operational conditions. Conversely, the conservative scenario provides an estimation under less favorable circumstances, accounting for potential challenges that may arise during workover operations.

Table 1: Categorized Workover Parameter Duration.

Activity	Scenario			Unit
	Optimistic	Normal	Conservative	
RIH	278.5	157.2	65.5	m/hr
POOH	244	179	133	m/hr
RIH/POOH Wireline	2,770	2,330	2,100	m/hr
ROP of Reaming Operation	11	10.5	7.5	m/hr
Circulation Duration	1.8	4.2	5.8	hour
Acidizing Rate	1.5	1.5	1.5	hr/10m
Run on Stand	0.5	0.5	0.5	hr/stand
Quenching and Killing	0.6	1	6.2	hour
Injection Test	1	1.5	3	hour

Decision-makers can utilize the optimistic estimation as a best-case scenario for rapid interventions, while the conservative estimation aids in identifying potential bottlenecks and challenges that might extend the duration. This classification framework assists in devising contingency plans, optimizing resource allocation, and managing stakeholder expectations, ultimately contributing to improved project management and cost-effectiveness.

5. APPLICATION OF THE PRELIMINARY DATASET OF WORKOVER PARAMETER DURATIONS

The dataset of workover parameter durations, as introduced in the preceding section, constitutes a valuable resource for estimating the duration of workover operations. This dataset not only provides essential insights into the timeframes associated with various workover activities but also offers a foundation upon which accurate duration projections can be built. The adaptability of this dataset to harmonize with predetermined workover programs is a pivotal factor that enhances the precision and efficiency of operational planning.

Case Study

Well X is a liquid-dominated well that is afflicted by scaling issues. The well is slated for a workover procedure encompassing three stages as outlined below:

1. Stage 1 – Preparation and Rig Up
   This initial phase involves preparatory activities and rig mobilization to facilitate the subsequent workover operations.

2. Stage 2 – Reaming
   In this phase, reaming operations will be conducted with the aim of reaching the depth of the scale. The reaming process is crucial for addressing the scaling issues and restoring the well's productivity.

3. Stage 3 – Acidizing Operations
   The third stage involves the execution of acidizing procedures. Acidizing is employed to

dissolve and remove scale deposits within the wellbore, thereby improving fluid flow and enhancing the well's overall performance.

The workover plan devised for these stages is outlined within the workover program. This program entails a meticulous breakdown of the stages. By aligning the workover data with the specific tasks outlined in the program, predicting the workover duration becomes straightforward. This prediction process employs the data from the plan to generate reliable time estimates for each task.

Table 2: Detail of Workover Duration Estimation of Well X.

No	Fase *Workover*	Scenario (days)		
		Optimistic	Normal	Conservative
Tahap 1 – *Rig Up* dan Persiapan				
I	*Quenching & Killing Well*	0.3	0.4	0.7
Tahap 2 – *Mechanical Reaming*				
II	*Reaming* 7" hingga 2,090 m MD	8.4	9.7	15.6
III	*Running* MTD	0.1	0.1	0.1
Tahap 3 – *Acidizing Job*				
IV	Survei PTS #1	0.1	0.1	0.1
V	*Acidizing Job*	1.5	2.0	3.6
VI	Survei PTS #2	0.1	0.1	0.1
VII	*Rig Release*	0.2	0.2	0.2
Total Waktu Operasi		**11**	**12.5**	**20**

Figure 6 illustrates the estimated duration of well X workover activities in a visual representation of time (days) versus depth (m MD) across three workover activity scenarios.

In conclusion, the estimation of workover operation duration for Well X exemplifies the integration of data-driven insights and strategic planning. By utilizing the workover parameter dataset and tailoring it to the program's specifics, geothermal professionals can enhance their ability to predict and manage workover durations effectively.

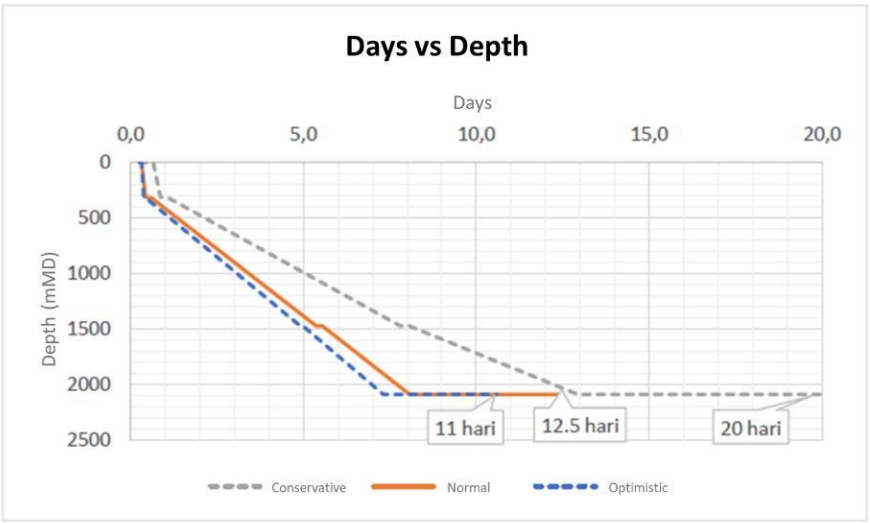


Figure 6: Time Curve of Well Workover Well X for Each Scenario.

6. PATH FORWARD

To further advance workover practices in the geothermal industry, fostering a culture of data-driven decision-making and continuous improvement is essential. This entails an ongoing commitment to data collection, strategic planning, and the integration of technological advancements. These efforts will result in even more accurate and versatile estimations, benefiting not only individual projects but also contributing to industry-wide best practices.

REFERENCES

Dumrongthai, P., and W.M. Putra. 2015. "SW-CPDEP, Project Management Process for the Right Decision in Geothermal Field Drilling and Completion." *Proceedings World Geothermal Congress 2015*. Melbourne: IGA.

ELC. 2019. *Dieng and Patuha Feasibility Study Update Part B: Dieng*. Technical Report, Milan: Electroconsult.

Harijoko, A., K. Hapsari, Y.T. Wibowo, R.W. Atmaja, and M.I. Nurpratama. 2015. "The Sulfide Minerals Deposit in the Geothermal Pipes of Dieng Geothermal Field, Indonesia." *Proceedings World Geothermal Congress 2015*. Melbourne: IGA.

Harijoko, Agung, Ryusuke Uruma, Haryo Edi Wibowo, Lucas Doni Setiadji, Akira Imai, Kotaro Yonezu, and Koichiro Watanabe. 2016. "Geochronology and magmatic evolution of the Dieng Volcanic Complex, Central Java, Indonesia and their relationship to geothermal resources." *Journal of Volcanology and Geothermal Research* 209-224.

Isa, B., Y. Hartono, C. Jayanto, and M.W. Putra. 2017. "A non IPM Contract for Exploration Drilling in PT Sorik Marapi Geothermal Power." *PROCEEDINGS, The 5th Indonesia International Geothermal Convention and Exhibition (IIGCE) 2017*. Jakarta.

Marza, S., C. Setiawan, and M.N. Chabib. 2013. "Brine Management System for the Northern Injection Wells in Dieng Geothermal Area." *PROCEEDINGS, Indonesia International Geothermal Convention & Exhibition 2013*. Jakarta.

MEMR. 2017. *Indonesia Geothermal Potential*. Jakarta: MEMR: Geothermal Directory.

Muhammad, F., V. Agustino, D. Purba, D.W. Adityatama, R. Husnie, M.F. Umam, and R. Asokawaty. 2019. "Utilization of Multi-Criteria Decision Analysis (MCDA) in Selecting Contract Types for Geothermal Exploration Drilling Project in Indonesia." *PROCEEDINGS, The 7th Indonesia International Geothermal Convention & Exhibition (IIGCE) 2019*. Jakarta.

Ngothai, Y, N. Yanagisawa, A. Pring, P. Rose, B. O'Neill, and J. Brugger. 2010. "Mineral Scaling in Geothermal Fields: A Review." *Australian Geothermal Conference*. Australian Geothermal Conference. 405-209.

Nugraha, R.B., R.B. Putra, and Mulyadi. 2019. "Successful Operation of Clean Out Well With HWU at Wayang Windu." *PROCEEDINGS, 8th ITB International Geothermal Workshop 2019*. Bandung: Institut Teknologi Bandung.

Ohia, N., C. Anayadiegwu, and K. Igwilo. 2014. "A Review of Hydraulic Work Over Unit (HWU) Application for Well Repairs in Nigeria." *Petroleum & Coal* 56 (4): 331. doi:ISSN 1337-7027.

Pambudi, N.A., R. Itoi, R. Yamashiro, B.Y. Alam, L. Tusara, S. Jalilinasrabady, and J. Khasani. 2015. "The behaviour of silica in geothermal brine from Dieng geothermal power plant, Indonesia." *Geothermics* 54: 109-114.

Rose, K.H. 2013. *A Guide to the Project Management Body of Knowledge (PMBOK® Guide)—Fifth Edition*. Wiley Online Library.

Sirait, P., T.T. Wibowo, and Elfina. 2013. "Work Over Sumur Produksi Lapangan Panas Bumi Dieng (in Indonesian)." *PROCEEDINGS, Indonesia International Geothermal Convention & Exhibition 2013*. Jakarta.

Suryanta, M.R., C. Cease, C.H. Simatupang, D.K. Hadi, and G. Golla. 2015. "Production Improvement Through Scale Removal by Condensate Injection in Darajat Geothermal Field Indonesia." *Proceedings World Geothermal Congress 2015*. Melbourne: IGA.

Utami, W.S., N.R. Herdianita, and R.W. Atmaja. 2014. "The Effect of Temperature and pH on the Formation of Silica Scaling of Dieng Geothermal Field, Central Java, Indonesia." *PROCEEDINGS, Thirty-Ninth Workshop on Geothermal Reservoir Engineering*. Stanford, California.

Wilson, D.R., J. Gilliland, and A. Austin. 2015. "Broaching, an Effective Method of Wireline Intervention for Calcite Scale Removal." *Proceedings World Geothermal Congress 2015*. Melbourne: IGA.

Yoan, M.R., A. Wijaya, and M. Thasril. 2013. "Lesson Learn of Workover Mechanical Program in an Injection Well at Dieng's Geothermal Field." *PROCEEDINGS, Indonesia International Geothermal Convention & Exhibition 2013*. Jakarta.

High Consumption of pH Adjuster in Geothermal Powerplant

A.H. Fauzi, A.T. Putra, A.K. Prabowo, B. Ilmi, and D. Cahyadi

PT Pertamina Geothermal Energy, Jl. Muara Dua, Kec. Ulubelu, Kab. Tanggamus, Lampung 35379

abdul.hfauzi@pertamina.com, ade.tputra@pertamina.com

Keywords: pH, NCG, Geothermal Powerplant

ABSTRACT

The exhausted steam driving the turbine will be cooled in the condenser. In the cooling process, a number of Non-Condensable Gases (NCG) contained in steam such as hydrogen sulfide (H_2S) and carbon dioxide (CO_2) will dissolve in the cooling water and be oxidized to form acid and lower the pH of the condensate. It is necessary to maintain the pH of the condensate in the normal range of 6.5-7 to prevent an increase in the corrosion rate which causes damage to the equipment/line it passes through. Caustic soda or sodium hydroxide (NaOH) is used as a pH adjuster. The Ulubelu power plant consumes high amount of NaOH. The amount of NaOH consumption might increase but needs to be evaluated to ensure the right amount of injection (efficiencies). After analysis, there are several factors that cause NaOH consumption to change, including changes in the composition of the steam composition, changes in pressure and temperature in the condenser, the presence of acid-forming bacteria in the cooling tower basin, the quality of the injected NaOH, the accuracy of the amount, the method of injection and the tools used in controlling pH.

1. INTRODUCTION

PT Pertamina Geothermal's Ulubelu Unit 3 and 4 geothermal energy area have an installed capacity of 2 x 55 MW and a total actual generation of 100 MW. The generation is obtained by utilizing energy from steam sourced from production wells, which are two-phase wells that have undergone processing in a separator to separate the vapor phase and liquid phase. The steam flowing towards the turbine for energy conversion contains a non-condensable gas content of 1.21% wt, with carbon dioxide dominating.

Table 1: NCG Content.

Component	% moles of Gas
Carbon dioxide (CO_2)	95.75
Hydrogen Sulfide (H_2S)	2.61
Ammonia (NH_3)	0.09
Argon (Ar)	0.006
Nitrogen (N_2)	1.23
Methane (CH_4)	0.12

The steam, after its energy has been utilized, enters the condenser to be cooled and condensed. Meanwhile, the non-condensable gases are removed using a gas removal system. During the condensation process, a certain amount of carbon dioxide and hydrogen sulfide gases dissolved in water form acids

Reaction carbon dioxide with water

$$CO_2 + H_2O \rightarrow H_2CO_3 \quad (1)$$

Reaction hydrogen sulfide with water

$$H_2S + H_2O \rightarrow H_2SO_4 + H_2 \quad (2)$$

This case causes the condensate to have a low pH value, requiring pH adjustment to maintain the equipment it passes through. Failure in pH control can lead to an increased corrosion rate and the formation of pitting corrosion, ultimately resulting in leaks in the pipeline. The pH is maintained within the range of 6.5 to 7 by adding a liquid pH adjuster, which is NaOH with concentration 48%. The pH control system needs to be evaluated to ensure its effectiveness and efficiency in operation.

The monthly consumption of NaOH is approximately 7,000-7,500 liters per unit, or equivalent to IDR 105,000,000 - 112,500,000 per month. Compared to the design operation, the amount of NaOH injected has reached around 2.8-3 times the design amount. Therefore, an analysis is needed to determine the cause of the increase in NaOH consumption and whether it is still within acceptable limits.

2. ANALYSIS METHOD AND RESULT

There are several variables that can contribute to the increase in NaOH consumption. In the first step, a recalculation of the theoretical NaOH consumption is performed to compare the operational design data with the actual conditions. In the initial design operation, solid NaOH flakes were dissolved to obtain a 20% NaOH solution. monthly requirement of NaOH 20% are 6,048 liters. The solid NaOH was replaced with liquid NaOH with a concentration of 48% for ease of material handling. When converted to a 48% concentration, Theoretically, the NaOH requirement should be 2,592 liters per month for each unit.

The design operation calculation is based on the solubility of the gases, which are then neutralized. However, in this analysis, the calculation refers to the pH value of the condensate to determine the number of acid moles. The required NaOH moles are then calculated stoichiometrically. The acids formed are H_2SO_4 and H_2CO_3, which both have the same hydrogen coefficient. Therefore, in the calculation, it can be assumed that only one acid is neutralized with the total mole count of both acids. The pH of the condensate from the analysis is 4.58.

$$Ph = - \log [H+] \quad (3)$$

From the calculation results, it is known that the amount of acid moles to be neutralized is 4.9353 mol/h. The required NaOH moles are twice the amount of acid moles, which is 9.8706 mol/h, equivalent to 2,368.9456 liters per month

. Reaction of netralization

$$H_2SO_4 + 2\ NaOH \rightarrow Na_2SO_4 + 2\ H_2O \quad (4)$$

$$H_2CO_3 + 2\ NaOH \rightarrow Na_2CO_3 + 2\ H_2O \quad (5)$$

For comparison, calculations performed by a third party indicate that the NaOH requirement is 2467 liters per month.

Table 2: Comparison of NaOH Consumption.

Reference	Monthly consumption
Design Operation	2,592
Neutralization reaction	2,369
Third party	2,467
Actual consumption	7,000-7,500

Based on the table, the actual consumption is significantly higher compared to both calculation models and the analysis conducted by the third party.

The first possibility for the change in NaOH consumption is the change of NCG in steam quality. Comparing the steam quality over the last 6 months, there has been a change in the NCG content, although it remains below the operational design. Therefore, the current actual consumption value is still significantly higher than it should be, considering the steam quality.

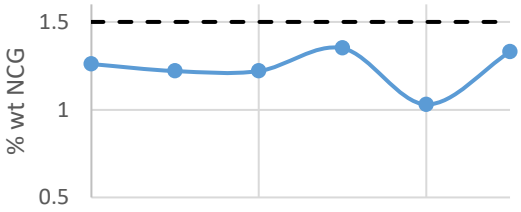
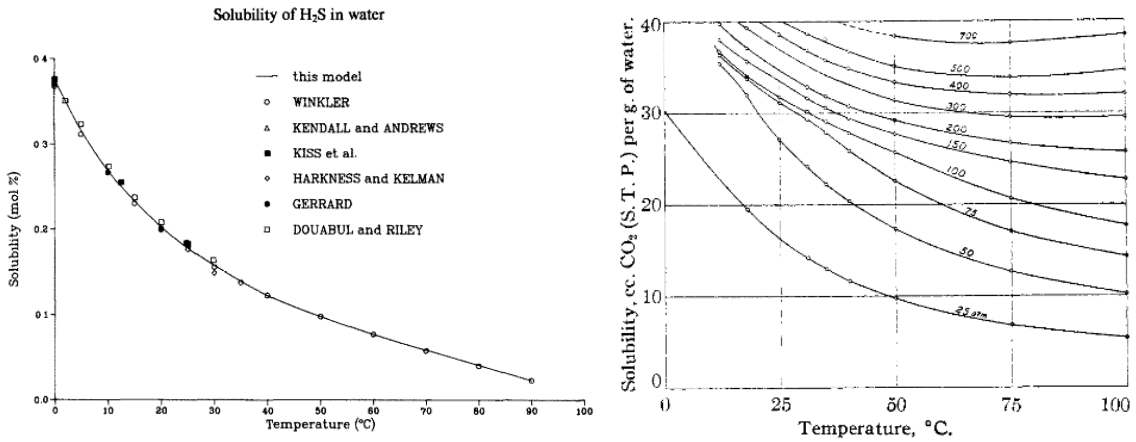


Figure 1: Change of NCG Percentage.

The next possibility is the change in operational conditions of the power plant. The solubility of gases in water is influenced by pressure and temperature. Since condensation occurs under saturated conditions, analyzing the changes in solubility based on temperature or pressure is sufficient. In the design condition, the condenser operates at a pressure of 0.08 bar or 41.50°C, while in the actual condition, the pressure at the condenser can reach 0.086 bar or 42.88°C.



(a) (b)

Figure 2: (a) solubility of H2S in water (Caroll, 1989), (b) solubility of CO2 in water (Weibe, 1940).

Based on the figure 2, it is known that as the temperature increases, the solubility of H_2S and CO_2 gases in water decreases, which means there is less possibility of acid formation. Therefore, the amount of NaOH required should decrease rather than increase.

The quality of the injected NaOH and the injection system can also affect NaOH consumption. Therefore, a test was conducted on the quality of NaOH to ensure it meets the desired concentration of 48%. The analysis results indicate that the NaOH quality is within the required specifications. Subsequently, an analysis was carried out on the injection system. Visual inspection of the NaOH injection line show no leaks. Additionally, a comparison was made between the existing flowmeter at the closest point to the NaOH injection pump discharge and the portable flowmeter at the nearest point of NaOH injection into the system, and the readings were relatively consistent. This further confirms that there are no leaks in the system.

Study was conducted to determine the Gibbs energy in the neutralization reaction. The objective was to assess the spontaneity of the reaction and identify whether any modifications to the system, such as additional agitation, heating, or relocation of the injection point, are required to ensure complete reaction between the reactants. From the Gibbs energy calculation, it is determined that the Gibbs energy is negative, indicating that the reaction occurs spontaneously. This means that the reaction does not require a long time to take place, nor does it require additional energy to ensure complete mixing or reaction. Furthermore, based on the Reynolds number calculation, it is known that the flow is turbulent since it exceeds 4,000. Therefore, it can be concluded that NaOH can react perfectly within the system.

In the condensate, there is a sulfate ($SO4^{2-}$) ion content of 0.58 ppm. The presence of Sulfur Reducing Bacteria (SRB) and Sulfur Oxidizing Bacteria (SOB) in the cooling tower can also contribute to the increase in NaOH consumption. SRB and SOB are acid-producing bacteria with the following reaction mechanisms:

Figure 3: Acid-Producing Bacteria Mechanisms.

The greater the presence of these bacteria, the higher the likelihood of acid formation. Analysis of SOB and SRB content is conducted by a third party responsible for supplying and evaluating biocide chemicals. The testing involves comparing the pH in the bottom and top of the cooling tower. It is assumed that if these bacteria are present in the system, the pH at the bottom of the tower will tend to be lower than the pH in the upper part of the cooling tower basin. Water samples are collected using a water sampler, and it is found that there is no significant difference in pH between the top and bottom. The third party did not conduct laboratory analysis of SRB and SOB or use reagents due to limitations in equipment and personnel.

The NaOH injection system is performed automatically based on pH meter readings. This means that the reliability of the pH meter readings will greatly affect NaOH consumption. A comparison was made between the existing pH meter and a portable pH meter, and a deviation of 0.46 in the readings was found. In the effort to increase pH, a difference of 0.5 in pH meter readings can lead to a significant increase in NaOH consumption. From the calculations, raising the pH from 4.12 to neutral and from 4.58 to neutral would result in 2.8 times increase in consumption. This value aligns with the observed increase in NaOH consumption.

Table 3: Comparison of NaOH consumption in Increasing pH.

Range	Monthly consumption
4 to 7	6832
4.5 to 7	2369

Both pH meters were calibrated, and the calibration results were relatively consistent. However, after retesting the samples, significant deviations in the pH meter readings were observed. While checking the existing pH meter, an error was found in the display ("error imp2 too high"). After Consultation with the pH meter provider, it concluded that there was damage to the pH meter electrode, leading to inaccurate readings. Therefore, a replacement of the pH meter is needed.

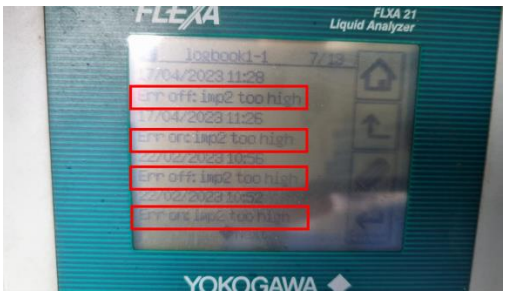


Figure 4: Error in pH Meter.

3. CONCLUSION

From the analysis, it is evident that several factors can contribute to the increase in NaOH consumption, such as changes in steam quality, operational conditions, injection systems, SRB and SOB microbial activity, and instrumentation. In the case of Ulubelu, it is highly likely that the increase in NaOH consumption is due to issues with the instrumentation of the injection system. Further analysis could involve a more detailed examination of SRB and SOB in the laboratory. It's important to note that conditions in other power plants may vary depending on the mentioned factors. Therefore, each power plant experiencing similar issues should conduct an analysis specific to their situation to implement appropriate improvements and ensure more effective and efficient system operation.

REFERENCES

Alvarez, M. G., & Galvele, J. R. (2010). Pitting Corrosion. Shreir's Corrosion, 772–800.

Bai, Y., & Bai, Q. (2014). Corrosion and Corroded Pipelines. Subsea Pipeline Integrity and Risk Management, 3–25.

Carroll, J. J., & Mather, A. E. (1989). The solubility of hydrogen sulphide in water from 0 to 90°C and pressures to 1 MPa. Geochimica et Cosmochimica Acta, 53(6), 1163–1170.

Tran, T. T. T., Kannoorpatti, K., Padovan, A., & Thennadil, S. (2021). Sulphate-Reducing Bacteria's Response to Extreme pH Environments and the Effect of Their Activities on Microbial Corrosion. Applied Sciences, 11(5), 2201.

Wiebe, R., & Gaddy, V. L. (1940). The Solubility of Carbon Dioxide in Water at Various Temperatures from 12 to 40° and at Pressures to 500 Atmospheres. Critical Phenomena*. Journal of the American Chemical Society, 62(4), 815–817.

Inconel 625 Laser Metal Deposition on Geothermal Steam Turbine Rotor

Andrianto Hapsoro, Rasyid Aziz, and Hepy Hanipa

SULZER

andrianto.hapsoro@sulzer.com, rasyid.aziz@sulzer.com, hepy.hanipa@sulzer.com

Keywords: LMD, welding, geothermal, repair

ABSTRACT

This paper explores the challenges associated with conventional methods of restoring damaged rotor geometry, namely thermal spray coating and arc welding. thermal Spray is commonly employed for mitigating relatively mild rubbing and damage, while arc welding is preferred for more severe damage. One drawback of thermal Spray is its restricted applicability due to the potential weakening of the mechanical bond between layers when too many layers are applied. On the other hand, arc welding entails the generation of substantial heat, necessitating stress relief measures and facing a risk of deformation. To address these challenges the use of Laser Metal Deposition (LMD) is developed as an alternative repair method. LMD utilizes laser technology to minimize the Heat Affected Zone (HAZ) and eliminate the need for Post Weld Heat Treatment (PWHT). This approach offers a shorter restoration process and reduces the risk of deformation on the shaft. By introducing LMD, we aim to bridge the gap between thermal spray and arc welding processes in restoring damaged rotor geometry especially when repair duration is one of major concern from customer. In this paper, thermal spray focus is on method known as High-Velocity Oxy-Fuel (HVOF), and for Arc welding, we will focus on Submerged arc welding (SAW).

1. INTRODUCTION

Damaged rotor geometry can be restored typically through weld build-up. The 2 conventional methods include HVOF coating and SAW. HVOF is typically suitable for small rotors with damaged depth less than 0.5mm, whereas SAW is used to restore shaft damage with more severe damage beyond the limitation of HVOF.

SAW has demonstrated its superiority in rebuilding rotor geometry without any dimensional limitations, making it extensively utilized in Sulzer Indonesia rotor repair. Several concern of high heat input, HAZ and potential of deformation or warping on the related area of the shaft during repair can be mitigated sufficiently using several techniques, including carefully put the HAZ on the low stress area and put additional welding overlay on possible affected area to add stock material so there will be enough machining maneuver during the repair process.

However, in certain instances, customers may demand faster repair cycles, particularly when spare rotor are unavailable, and the repair window is limited to the unit's major overhaul period. In such cases, alternative rotor repair options are sought to minimize the need for extensive welding and/or PWHT to expedite the repair process.

Sulzer Indonesia has taken the initiative to introduce LMD to bridge the gap between HVOF and SAW processes. LMD is an additive manufacturing process that uses laser technology with minimum heat input resulting in smaller HAZ compared to conventional SAW. Due to this fact, the restoration of dimensions using LMD typically does not require PWHT as well, thus shortening the restoration process and also reduce the risk of deformation on related part of the shaft due to small heat input.

2. HVOF, SAW AND LMD PROCESS

Several significant distinctions exist between the repair methods of HVOF, and LMD, key differences between repair method of HVOF, SAW and LMD will be explain in more detail as below point.

2.1 HVOF Process

HVOF spraying is primarily used to apply coatings of ceramics tungsten carbide and chrome carbide. The high velocity spray generates a velocity of molten powder. As kinetic energy goes up as the square of the velocity, the powder impacts the work piece being sprayed with high energy resulting in mechanical bonding. The powder particles flatten as they impact the surface and the coating is built-up, layer by layer, to achieve a fully dense structure. A schematic of a HVOF device is shown in Figure 1.

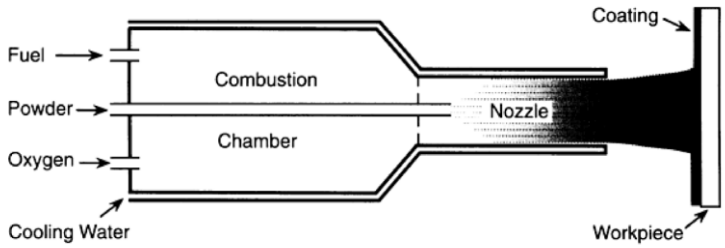


Figure 1: High velocity oxyfuel process illustration (ASM Handbook Vol. 5).

2.2 SAW Process

SAW is an arc welding process in which the arc is concealed by a blanket of granular and fusible flux. Heat for SAW is generated by an arc between a bare, solid-metal (or cored) consumable wire or strip electrode and the workpiece. The arc is maintained in a cavity of molten flux or slag, which refines the weld metal and protects it from atmospheric contamination. Typical setup for automatic SAW is shown in Figure 2.

A continuous electrode is being fed into the base metal by mechanically powered drive rolls. A layer of granular flux is being deposited in front of the arc. Electrical current, which produce the arc, is supplied to the electrode through contact tube. Figure 3 shows the melting and solidification sequence of SAW.

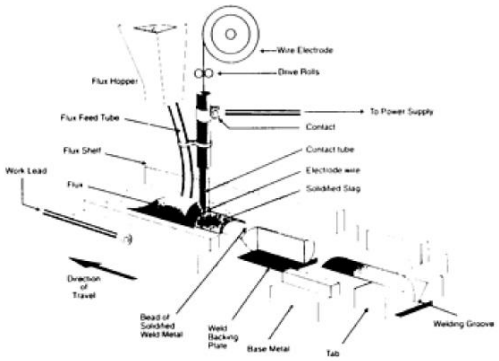


Figure 2: Schematic showing key components of automatic SAW setup (ASM Handbook Vol. 6).

2.3 LMD Process

LMD uses a laser as its source of heat. The control and concentration of heat from a laser source allows for a much lower heat input into a substrate. Despite this low heat input, the process produces a metallurgical bond and a fully dense deposit layer like welding processes. The lower heat input also contributes to low dilution, smaller heat affected zones, and minimal to no distortion.

LMD uses a high-powered laser beam that is focused on a small area. This high concentration of energy creates a melt pool in which metallic powder is then introduced, carried by gas, through a nozzle. The added powder fuses to the substrate creating a metallurgically bonded coating or cladding. With the use of the laser beam, the heat input and melt pool is very precise and localized compared to other welding processes. A schematic of LMD device is shown in Figure 4.

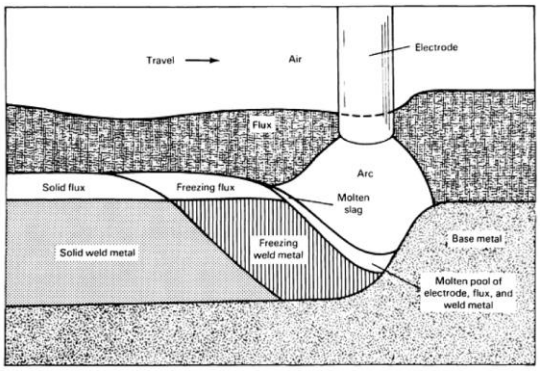


Figure 3: Illustration of weld pool dynamics of a Submerged Arc Welding (ASM Handbook Vol. 6).

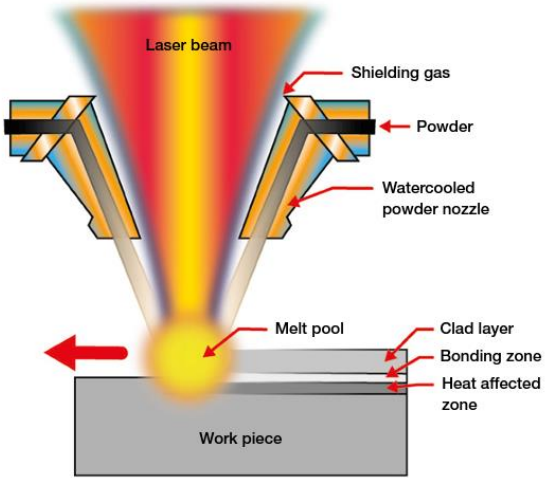


Figure 4: LMD process illustration.

3. COMPARATIVE SHOWCASE

When we want to make a comparison of a method, several cases are needed to better assess each method. Therefore, two cases are created as normal and special case as described below, both cases will be compared with the current conventional SAW method to repair the geothermal steam turbine rotor with LMD method:

- For Normal case is to repair the rotors on glands area only with erosion depth 1 to 4 mm
- For Special case is to repair blade interstage on barrel type rotors with erosion depth 1 to 4 mm, this barrel type rotor is typical on several Geothermal Rotor.

3.1 Normal Case of Rotor Damage

The usual case of damage on geothermal rotor is in gland seal, where the damage is caused by steam for sealing purpose, this can be seen in figure 5.

3.1.1 SAW Method

When facing with this problem, the normal geometry restoration repair is to overlay the damage area with SAW method. SAW method itself will consist of several step

- Prepare undercut
- Undercut (surface preparation)
- Preheat

- SAW weld build up
- Roughcut
- NDT inspection
- PWHT
- Final machining

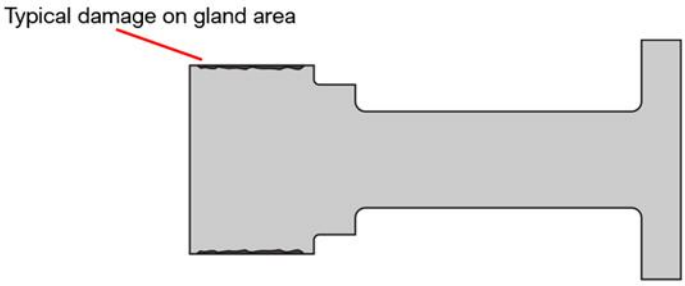


Figure 5: Typical damage on gland seal is of the geothermal rotor.

Although SAW repair methodology has reached a considerable level of maturity, one of the limitations associated with subjecting rotor dimensions to high temperatures in SAW is the potential for warping in certain regions, leading to alterations in the overall geometry. In the context of repairing the gland seal area, this implies that the journal may become warped, resulting in changes in the Journal run out and changes is coupling hole PCD relative to change of journal run out. Consequently, when addressing gland seal repairs, it is almost imperative to include the journal (by welding) and the coupling area (typically by rebushing or oversizing) in the repair process. In essence, there are going to be additional step from the above point as follow:

- Prepare undercut
- Undercut (surface preparation)
- Preheat
- SAW weld build up gland area
- SAW weld build up Journal area
- Roughcut
- NDT inspection
- PWHT
- Final machining on Journal and gland area
- Coupling correction

This can be visualized more on below figure 6.

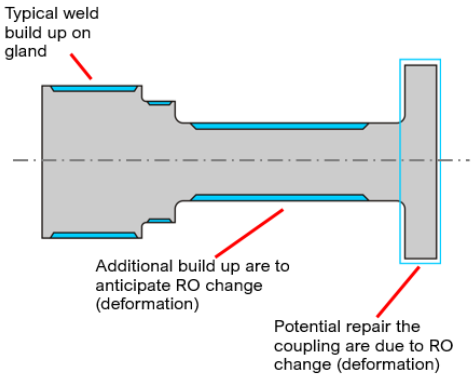


Figure 6: Additional area to be welded which are Journal and Coupling rebushing due to possible deformation after welding on gland area.

3.1.2 LMD Method

Approaching the geometry restoration repair using LMD will have somewhat different approach than SAW. The nature of LMD with low heat input will remove some of step requirement related to SAW such as PWHT sequences, thus the time to repair can be shorten compared to SAW. Low heat input also helps to reduce or even eliminate the possibility of warping in the close proximity area such as journal that additional step to correct the run-out on journal and reclaim the coupling PCD centerline is not needed anymore. The LMD step itself can be seen in below point:

- Prepare Undercut
- Undercut (surface preparation)
- LMD weld build up
- Final machining

This can be visualized more in below figure 7.

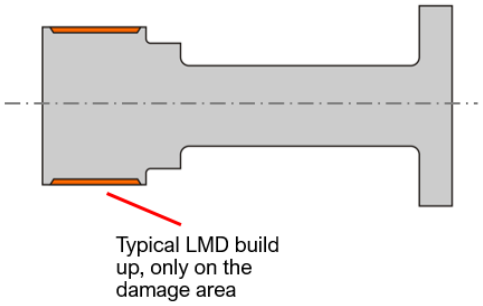


Figure 7: Typical LMD build up on gland area can be localized on the damage area only without any concern.

3.1.3 Cost and Duration Comparison

Based on above explanation, rotor repair duration when doing rectification work on Repair facility can be somewhat reduced. Considering that LMD eliminates the need for Journal welding, coupling rebushing and PWHT, this will be beneficial to Unit Owner especially when they need the unit back to operation as soon as possible to produce electricity. Comparison both method duration and potential loss saving can be seen in below table 1.

For calculation process, several key points were considered:

- Indonesian geothermal tariff for 2023 in Wilayah 1 (PERMEN ESDM) is set at 15 US cents per kilowatt-hour (USD cent/KWh) which is equivalent to 150 USD per megawatt-hour (USD/MWh)
- The best-case scenario for geothermal Levelized Cost of Energy (LCOE) is estimated at 55 USD up to 80 USD pe megawatt-hour (USD/MWh)
- The margin, which is the difference between the geothermal tariff and production cost, amounts to 70 up to 95 USD per megawatt-hour (USD/MWh)
- For a 50MW geothermal power plant, the range for potential daily margin can be calculated as follows:
    - Potential Margin = (70 USD /MWh x 24 hours x 50MW) up to (95 USD/MWh x 24 hours x 50MW)
    - Potential Margin = 84,000 USD - 114,000 USD

Table 1: comparison SAW and LMD Method Duration and potential Production Loss Saving.

General Step (repair only)	SAW	LMD
Reverse Engineering and generate drawing	7D	3D
Undercut	2D	2D
Preparation for welding	2D	2D
Preheat	0.5D	-
Build up process (Gland area)	2D	4D
Build up process (journal)	3D	-
PWHT	10D	-
Run out and Coupling Holes Correction	7D	-
Final Machining	7D	2D
Number of Day	40.5D	13D
Lead Time Saving	27.5 Days	
Potential production gain due to shorter repair duration (50MW)	2.1 up to 3.1 million USD	

3.2 Special Case of Rotor Damage

One of repair damage that also can be beneficial of using LMD is repairing interstage area of barrel type rotor. In geothermal environment, the condition of the steam sometime leads to heavy erosion in the area between the blades, this area can be seen as a critical area because the close proximity with the blades, where the blade attachment area is one of the highest stress locations in the rotor.

Typical damage on this interstage area, can be seen in below figure 8.

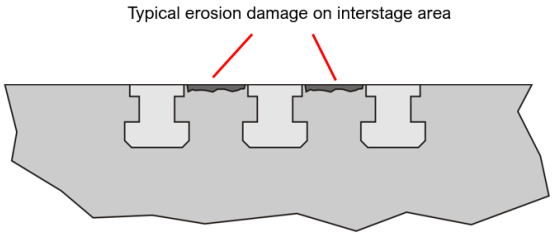


Figure 8: Damage area on interstage area.

3.2.1 SAW Method

Similar to the SAW method used for the gland seal, the steps involved in performing SAW welding on a barrel-type interstage are nearly identical. However, special considerations must be taken into account when welding in the interstage or in areas close to high-stress zones. Barrel-type steam turbines, in particular, have high-stress areas near the damaged section within the interstage plus the risk for possible dimensional collapse. Consequently, in most cases, the undercutting will be more extensive, including the blade attachment area with purpose of placing the HAZ on low stress area and to avoid mitigating the change in dimension or warping near the blade attachment area as illustrated in the figure 9 below.

This consequently raises concerns regarding blade replacement and the need to provide the customer with a new set of blades. Thus, the general step when doing SAW method for interstage area will be as below list:

- Remove existing blades
- Reverse Engineering existing blades and manufacture new blades
- Prepare undercut
- Undercut (surface preparation)
- Preheat

- SAW weld build up
- Roughcut
- NDT inspection
- PWHT
- Final machining on the blade root
- Install new blades
- Final machining new blades

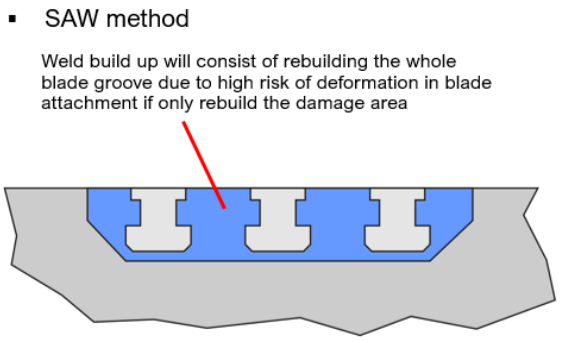


Figure 9: Overlay Design Plan for weld build up using SAW method, cutting through blade attachment area.

3.2.2 LMD Method

When repairing the same defect using the LMD (Laser Metal Deposition) method, several steps can be eliminated from the repair process. This is attributed to the low heat input nature of LMD, which results in negligible collapse of the blade attachment area and minimal heat-affected zone (HAZ) effects on the high-stress area.

The general steps involved in repairing using the LMD method are similar to those used in gland repair and are outlined below

- Prepare Undercut
- Undercut (surface preparation)
- LMD weld build up
- Final machining

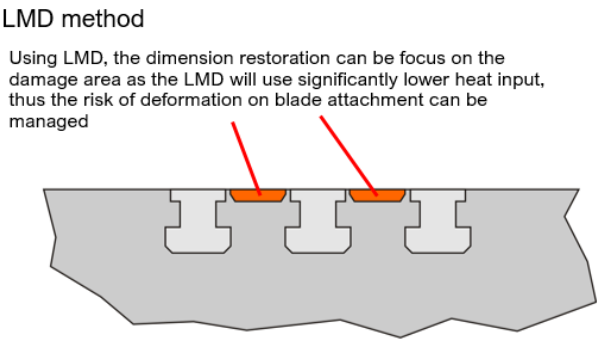


Figure 10: Overlay design plan for LMD Method.

3.2.3 Duration Comparison

When considering the specific case of repairing the interstage of a barrel-type steam turbine, a detailed comparison between the SAW (Submerged Arc Welding) method and the LMD (Laser Metal Deposition) method reveals significant advantages. These advantages are summarized in the table below, showcasing the substantial cost savings for the unit owner through reduced repair time and the elimination of the need to purchase replacement blades.

Table 2: comparison SAW and LMD Method Duration and potential Production Loss Saving.

General Step (repair only without reblading)	SAW	LMD
Reverse Engineering and generate drawing	14D	3D
Undercut	6D	2D
Preparation for welding	2D	2D
Preheat	0.5D	-
Build up process (all blade attachment)	10D	4D
PWHT	10D	-
Final Machining	14D	2D
Number of Day	56.5	13D
New blades set from customer (3 up to 5 row x 3 for double flow rotor)	230.000 USD (5 row x 2)	-
Lead Time Saving	43.5 Days	
Potential production gain due to shorter repair duration (50MW)	3.4 up to 4.9 million USD + 230.000 USD (for blade replacement)	

4. CONCLUSION

Through the application of LMD in rotor restoration, it becomes evident that the shorter lead time allows for a faster repair process. This accelerated repair duration contributes to the prompt installation of the rotor onsite thereby enabling customers to promptly resume their production operations. Consequently, this allows them to recover lost production time during downtime period.

Benefits

The concentrated heat input in LMD is not only creates significantly smaller HAZ thus generated much smaller residual stress but also reduces the risk of deformation due to heat treatment.

Impact

Typical welding jobs on a gland using SAW involve restoration on the gland and journal and may affect the runout of the coupling. These repair jobs can take about four weeks. By using LMD, the gland repair work can be reduced to only about two weeks.

Limitation

LMD generally offers a shorter lead time compared to SAW due to its more concise sequence scope of work. However, it is worth noting that the lead time for LMD can become longer when dealing with restorations involving significant thickness, as its deposition rate is considerably lower than that of SAW. Consequently, there exists a limitation on the thickness or width of the area for which LMD can be competitive in terms of lead time.

REFERENCES

2022 Electricity ATB Technologies and Data Overview, national Renewable Energy Lab, https://atb.nrel.gov/electricity/2022/index (2022)Jr., Robert C. Tuckers.: Thermal Spray Coatings, *ASM Handbook. Vol. 5: Surface Engineering*, 9th Edition, (1994), 1454–1455.

HARGA PATOKAN TERTINGGI PEMBELIAN TENAGA LISTRIK DARI PLTP OLEH PT PERUSAHAAN LISTRIK NEGARA (PERSERO), Lampiran PERMEN No. 17, (2014).

Ogborn, Jonathan S.: Submerged Arc Welding, *ASM Handbook Vol. 6: Welding, Brazing, and Soldering*, 10th Edition, (1993), 618–620.

Pardhi, Yogiraj: Laser metal deposition – developing new materials, *Sulzer White Paper*, (2022).

Inhibiting Co-deposition of Smectite and Calcite to Prevent Production Well Output Decline

Fritz Earwin Monterozo[1], Dinesh Mantri[2], and Tuğçe Şencan[3]

[1]Nalco Water, An Ecolab Company, CTP Asean Tower, Alabang, Muntinlupa City, Philippines
[2]Nalco Water India Ltd., Margarpatta Road Sade Satra Nali, Pune, India
[3]Nalco Water, An Ecolab Company, Istanbul, Turkey

fritz.monterozo@ecolab.com

Keywords: Mineral scaling, smectite, calcite

ABSTRACT

Smectite scaling was observed in different production wells with observable metal silicate formation due to aluminum, iron or magnesium ions. The type of smectite formed usually depends on the metal silicate present in the scale. In this particular case, the main issue observed was low enthalpy surface water intrusion with high content of magnesium ions. The projected deposition pathway is formation of magnesium silicate downhole which encourages smectite formation, particularly stevensite $(Ca,Na)_xMg_{3-x}(Si_4O_{10})(OH)_2$. After smectite formation, co-deposition with calcium carbonate may happen and subsequently, accumulation of these deposits at the surface (downstream of the master valve). At the flashpoint, well restriction was observed as confirmed by a caliper survey. The samples obtained were subjected to further analysis like X-ray diffraction, fluorescence and scanning electron microscopy (SEM). Elemental distribution graph confirmed co-deposition of smectite and calcite. Aside from downhole restriction, the deposits were being carried at the surface also, causing restriction in the downstream valves of the production wells.

To prevent further well output decline and surface scaling problems, an inhibition program was developed and executed. The inhibition program used has the capability to address calcite and smectite simultaneously through threshold inhibition of calcite and Mg-silicate inhibition. For the first well trialed, it was observed that the flowrate of the well was maintained at the design flowrate value and there was no significant decline observed for a period of one year. At the same time, calcium and magnesium ions were stable without any decline that may signify deposition somewhere in the system. Actual field inspection of the surface facility was conducted using gamma ray and on-site inspection. The state of the secondary valves was relatively cleaner (very minimal deposits observed, <1% blockage) compared to the prior treatment (10-20% blockage). The results of the program provided a positive impact to the plant in terms of output preservation and sustainable operations.

1. INTRODUCTION

Smectite scaling was observed in liquid-dominated production wells in Japan, Turkey and Philippines which poses a new challenge aside from the well-studied calcite scaling. These wells have a projected downhole inflow of surface water, bringing in Mg-rich stream that mixes with the geothermal fluid. Although smectite has many kinds depending on the incorporated metal ions, magnesium and iron-bearing smectite scales were the commonly observed scales in geothermal fields (Dulce et al., 2010).

Smectite is a group of phyllosilicate mineral species and members of this group differ depending on the metal ions incorporated in it. The common structures observed in geothermal systems are stevensite (magnesium), saponite (magnesium and iron) and nontronite (iron and aluminum). Based on experience, this does not occur as a problem on its own. In the observed geothermal fields mentioned, smectite co-deposits with calcite forming harder deposits compared to relatively pure calcite.

Threshold inhibition using polymer-based inhibitor was able to address calcite scaling but field data and observations shows that this approach is insufficient when dealing with smectite scales. Some observations that were gathered from the site were continuous pipe restriction build up even if calcite inhibition system is in place, deposition inside surface pipelines – particularly two-phase headers and

after the separator and decreasing trend of magnesium and calcium ions sampled at the surface which denotes deposition somewhere downhole.

This study aims to qualify a new inhibition program that can simultaneously target both calcite and smectite scaling. Several blends of potential active components were tested in the laboratory using standard qualification method and the potential chemistry was trialed in different geothermal sites where co-deposition of smectite and calcite was observed.

2. MECHANISM OF CO-DEPOSITION OF CALCITE AND SMECTITE

Calcite blockage can be attributed to the supersaturation of calcite upon flashing inside the wellbore. Boiling also reduces CO_2 partial pressure which in turn increases pH and strongly increases carbonate ion concentration. These parameter increases are the reason behind the supersaturation at the wellbore compared to its initial reservoir state (Siega et al., 2005). Another factor that adds up to the formation of calcite scales is the reaction of bicarbonates as shown in Equation 1:

$$Ca^{2+} + 2HCO_3{}^{-} \rightarrow CaCO_{3_s} + CO_2 \uparrow + H_2O \quad \text{(Equation 1)}$$

By following Le Chatelier's principle, the increase in bicarbonate concentration shifts the reaction forward, thus; facilitates formation of calcite scales.

For the perceived deposition pathway of smectite, the discussion will focus on Mg-containing type which are stevensite and saponite. The proposed first step in deposition is the formation of metal silicate components which will serve as "backbone" of smectite structure formation. In the case of Mg-containing smectite, the first step will be supersaturation of magnesium silicates downhole considering that the conditions conducive for scaling such high temperature, high pH and turbulent conditions are present (Kasai et al., 2000).

For the wells where smectite scales were observed, it was noted that samples taken after the flash point shows combination of smectite and calcite. The samples taken at the surface, prior to separator and after separator showed relatively more smectite scales than calcite scales. Below is an X-ray fluorescence analysis of a sample scale:

Table 1: Elemental Composition (XRF) of Scale Sample.

Element	Si	Mg	Fe	Ca	Mn	Al	P	Cu	Na
Weight (%)	25.3	16.2	12.82	2.49	3.01	0.32	0.31	0.099	0.082

The observed co-deposition of smectite and calcite suggests that the formation of smectite scales happen also at the flashpoint which is driven by increase in concentration of scale-forming particles due to flashing. As confirmed by Kasai (2000), mineral supersaturation and abundance of suspended materials in the liquid can serve as reaction nuclei. In the case of co-deposition, it follows both homogenous and heterogenous pathways for crystal nuclei formation.

3. TECHNICAL EVALUATION OF INHIBITION

Since the deposition issue is not just calcite, it was proposed that a new inhibition approach should be incorporated to address both calcite and smectite. The evaluation pathway followed for this trial is outlined Figure 1.

Geothermal fluid samples were analyzed using ICP to gather specific brine and steam chemistries. These were used to calculate the scaling potential using Nalco Water's Geomizer modeling software. From the results, it was confirmed that the well exhibits scaling potential for calcite, magnesium silicate and iron silicate. To further support the scale modeling results, scale samples from the last inspection was analyzed using XRF, XRD and SEM. From the results, it was confirmed that both smectite and calcite exists in this scale.

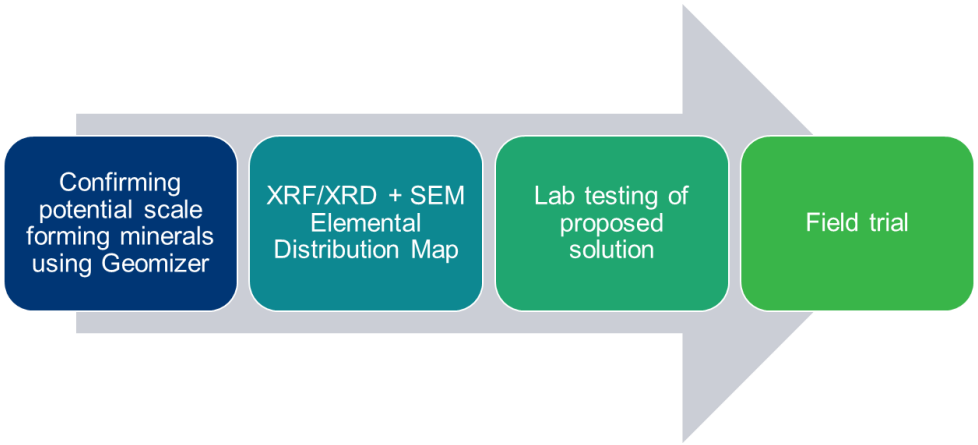


Figure 10: Evaluation pathway of the inhibitor program.

A new inhibitor blend, which can inhibit both calcite and smectite scales, was used in the testing. The proposed general mode of action will be threshold inhibition, general adsorption and dispersion of scale forming minerals and crystal modification of metal silicate particles. This inhibitor was tested using NACE TM0374 which is a standard method for screening potential inhibitors for calcite and anhydrite. For the proposed test, the brine chemistry is summarized below:

Table 2: Elemental Composition (XRF) of Scale Sample.

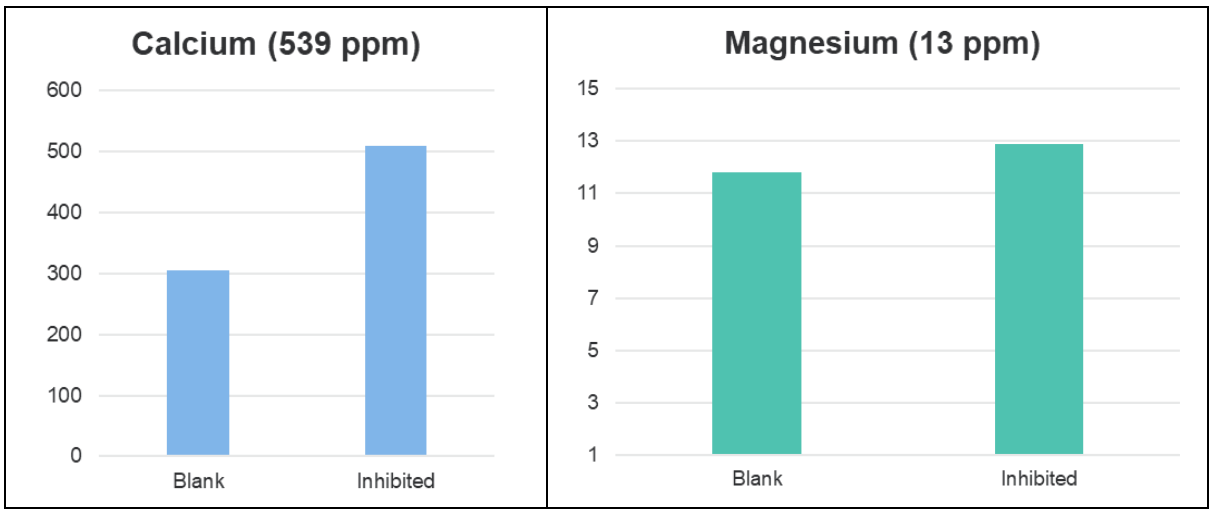
Component	$HCO3^-$	Ca	Mg	Cl	Na	Fe	Silica	Sulfate
Concentration (ppm)	124	539	13	12000	6341	1	319	88

Since the NACE standard test was carried out at 78 deg. C, pH of the sample was adjusted to 7.5 to achieve supersaturation with respect to calcite and also try to precipitate magnesium silicate. The monitored parameters are the following:

1. Calcium ion levels (inhibition performance)
2. Magnesium ion levels
3. Iron levels
4. Monomeric silica

4. LABORATORY TEST RESULTS AND FIELD APPLICATIONS

The parameters monitored during the lab trial showed good inhibition efficiency in terms of calcium retention. The following figures show the comparison of inhibited and uninhibited treatment conditions:



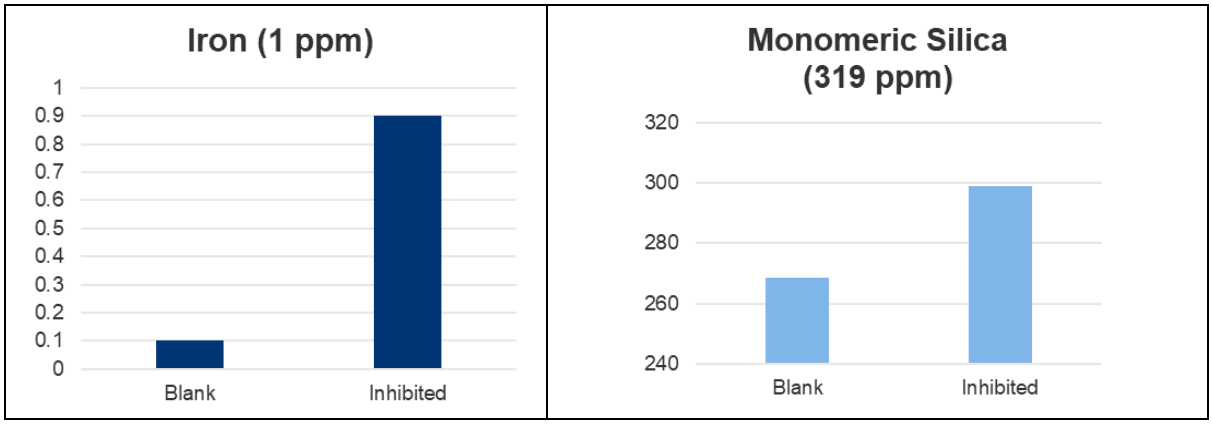


Figure 2: Results of the measured parameters.

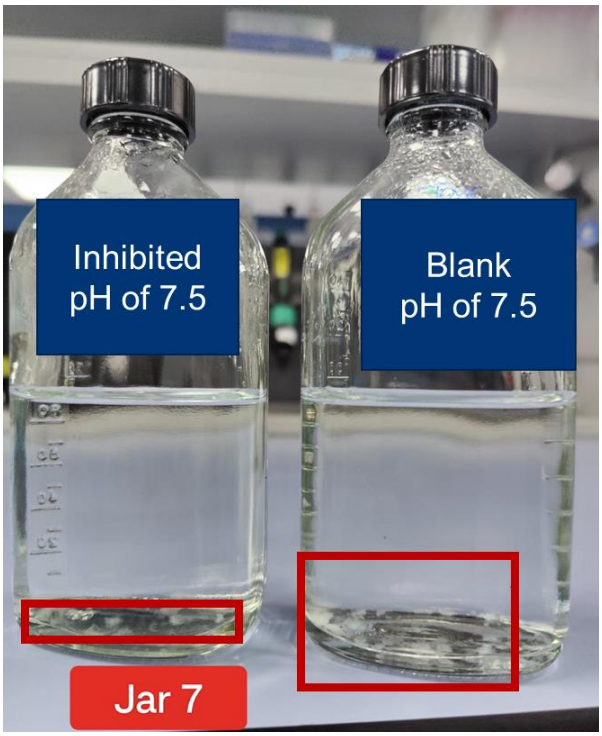


Figure 3: Visual manifestation of solid particles (scale formation) for both inhibited and blank.

The NACE test uses calcium retention to calculate for the inhibition efficiency. From the measurements done, the retention was at 95% which corresponds to inhibition efficiency of around 79% to 88%. It was expected that magnesium ion will show a decline in the blank setup, but this was not observed. Magnesium ion decline was not pronounced because the conditions for both the inhibited and blank are not conducive to scaling. Ideal conditions for scaling are high temperature, high pH and turbulent.

To be able to demonstrate the capability to affect metal ions, iron retention was also measured. Iron retention was ~95% for inhibited versus ~10% of blank which confirms metal ion inhibition/dispersion capability. Monomeric silica was maintained ~98% compared to ~84% of blank which confirms general dispersion on monomeric silica particles and preventing agglomeration because of metal ions.

After a promising laboratory evaluation, actual field runs were conducted in Japan and Turkey. For the first well trialed, it was observed that the flowrate of the well was maintained at the design flowrate value and there was no significant decline observed for a period of one year. At the same time, calcium and magnesium ions were stable without any decline that may signify deposition somewhere in the system. Actual field inspection of the surface facility was conducted using gamma ray and on-site

inspection. The state of the secondary valves was relatively cleaner (very minimal deposits observed, <1% blockage) compared to the prior treatment (10-20% blockage). The results of the program provided a positive impact to the plant in terms of output preservation and sustainable operations.

The field trial in Turkey also showed promising results versus the existing threshold inhibition program. From the previous treatment, deposition can be observed in a matter of days. After the program was instituted, no visible deposition was observed even just after one week of treatment and surface facility and equipment was kept clean.

Baseline Scale Coupon – Old Treatment (1 week)

Scale Coupon - Nalco Treatment (1 week)

Figure 4: Manifestation of co-deposition of calcite and smectite (comparing existing and proposed Nalco Water treatment).

5. CONCLUSIONS

We are now seeing more complex scaling phenomenon compared to simple calcite scaling. Addressing the problem is not "one-size-fits-all", each site will have different dosage strategy. Proper analysis of the brine and scale samples to confirm dosage and appropriate strategy. Successful field applications help us confirm that the proposed strategy is working. These applications help geothermal companies cope with challenging scale and maintain their production capacity. Ultimately helping them reduce total cost of operation.

REFERENCES

Brown, K., 2013: Mineral scaling in geothermal power production. *United Nations Geothermal Training Program.*

Dulce, R.G. et al, 2010: Genesis of smectite scales in Mindanao Geothermal Production Field, Philippines. *Proceedings World Geothermal Congress*, Bali, Indonesia

Kasai, K. et al., 2000: Characterization of smectite scale and scale inhibiton test by pH control at the Mori Geothermal Power Plant, Japan. *Proceedings World Geothermal Congress 2000.* Kyushu-Tohoku, Japan

Siega, F. L., Herras, E. B., & Buning, B. C. (2005). Calcite Scale Inhibition: The case of Mahanagdong wells in Leyte Geothermal Production Field, Philippines. *Proceedings World Geothermal Congress.*

Mechanical, Operation and Chemistry Approach in Monitoring and Controlling Deposition Control Program in Binary Power Plant

Muhamad Andhika, Nugraha Y. Arifpin, Tomy Suryatama, and Mona N. Siahaan

Ecolab International Indonesia, Pondok Indah Office Tower 5, 5th Floor,
Jalan Sultan Iskandar Muda Kav V-TA Jakarta, Indonesia

muhamad.andhika@ecolab.com

Keywords: Binary Power Plant, Binary Monitoring, Silica, Scale Inhibitor, High SSI

ABSTRACT

Binary power plant is prone with deposition of prograde solubility mineral such as silica and metal silicate. If left uncontrolled, the energy extraction performance will be rapidly declined and will lead to unscheduled shutdown that will reduce the reliability of binary power plant. Therefore, a proper monitoring program will be crucial to determine the performance of binary power plant. With proper monitoring program, any indication (early detection) of issue such as scaling deposition can be treated properly before the issue becomes more severe.

Performance of binary power plant is determined by multiple factors that might be intertwined between each other. For example, reduction in MW generation might be induced by scaling deposition, reduction in brine flow rate, secondary working fluid leakage, and others. To reclaim the MW generation, actions in handling the issues must be implemented properly to address specific issue. Based on this complexity, a series of monitoring protocol with mechanical, operation, and chemistry (MOC) approach should be implemented to properly identify the issue.

This paper will explain series of MOC approach analysis to monitor binary power plant performance. The analysis consists of physical measurement, such as flow rate, differential pressure, temperature rise, approach temperature, and log-mean temperature difference (LMTD); and chemistry measurement, such as % silica polymerization, % silica inhibition, % metal retention, and % soluble metal. With these monitoring, the issue will be properly identified, and the restorative or preventive action will be properly applied to recover the decline in MW.

1. INTRODUCTION

Geothermal fields in Indonesia, as in the world in general, have various enthalpy resources which lead to different strategy of geothermal power plant development. The most common system that widely exploited is high enthalpy system, which has temperature higher than 225 ^{O}C (Hochstein, 1990). This system only utilize steam to produce electricity and dump the hot brine directly to reinjection well which still has enough energy that equal to low-medium enthalpy geothermal system. As we know, low and medium enthalpy, still not applied in Indonesia since the produced geothermal fluid temperature, that can reach as low as 150 °C, will not be suitable to generate power using flash steam economically and efficiently (Hassan, 2022). One way to harness this energy is through binary power plants, which use a secondary fluid to generate electricity from geothermal hot brine. Recently, this idea of using binary power plant is becoming more popular in Indonesia as many fields that contain high enthalpy system is getting rare and geothermal companies would rather maximize existing fields rather than perform exploration in medium enthalpy geothermal system due to economic feasibility.

The aim of a binary power plant is to generate electricity using lower geothermal temperature resources as low as 50 °C which cannot be used in conventional steam turbines. Binary power plants work by using a secondary fluid with a much lower boiling point than water, such as refrigerant, isobutane or pentane. It will vaporize at a lower temperature than water and the secondary fluid will be used to generate electricity. The vaporized fluid is then condensed back into a liquid and then reused in a close loop system. This allows for extracting more electricity on high enthalpy geothermal system without drilling more production wells, which are costly and even riskier. However, in its development, binary

has several issues that need to be addressed properly to avoid potential revenue loss during operation. One of the obstacles is associated with silica and metal deposition.

Scale deposition occurs when minerals in the geothermal fluid precipitate out and form a solid layer on the surfaces of the heat exchangers, pipes, and other components of the power plant (Andritsos et al., 2002). This layer can reduce the efficiency of the power plant and eventually lead to equipment failure. To mitigate this issue, various methods are employed, such as chemical treatment, mechanical cleaning, and periodic shutdowns.

The most common scale deposition in high enthalpy geothermal system is Silica and metal silicate. Behavior of this scale is unique and not instantaneous. There are some phases that can be marked by certain pattern and can be monitored. The first step to prevent scale deposition is proper monitoring, not only the brine chemistry, but also fluid mechanics and operation side.

In this paper, we will present our best practice for monitoring binary power plant operation by using MOC approach. This monitoring method will guide us to inhibit scale deposition in heat exchanger properly hence reducing MW loss and cleaning frequency.

2. MECHANICAL AND OPERATION

As the biggest problem in binary plant operation, Silica scaling and deposition in heat exchanger should be our concern. Continues monitoring is the first important step to overcome this problem. The mechanics of fluid become basic knowledge to identify the flow regime and flow velocity that affect the kinetics of Silica scaling and deposition. The flow regime itself apply both in two-phase flow and single-phase flow.

Cacho stated in his paper (Cacho. 2015) that knowledge on two-phase fluid flow will help predicting the change in pressure in the production well more accurately which eventually give better predictions on mass flow or pressure in the well. The correlation between fluid flow and pressure has been studied and can be used to estimate the pressure drop in two-phase flow. The higher the fluid pressure drop occur; flashing will be higher which increase the saturation value of Silica thus increasing the possibility of Silica scaling at higher temperature at binary plant.

Fluid velocity in brine usually determined at 1 m/s, maximum at 1.2 m/s (Vieira, 2015) which will minimize pressure loss. Preserve fluid velocity will preserve high efficiency of heat transfer and at the same time reduce the risk of Silica polymerization (Pardelli, 2021). The exception of scaling event will occur at higher velocity when the particle size is larger and in colloid form, and velocity is 2.5 m/s (Brown, 2011).

Operating parameter also can be used to monitor scaling deposition event. The most common parameter is differential pressure (DP) and brine flow rate. Increasing DP with decreasing flow rate can indicate there is obstacle inside heat exchanger vessel. The limitation of this method is that the pressure gauge should be installed before and after vessel otherwise determination of specific location of deposit will be difficult. Flow rate and pressure also affected by brine booster pump and bypass line. The change of bypass opening valve can ruin flow rate differential interpretation while brine booster pump can create bias for DP monitoring in binary system.

Innovative approach should be used to overcome problem that exist in mechanical-operating parameter to monitor and controlling deposition in binary plant. One of important approach is LMTD method which stand for logarithmic mean temperature difference method. The basic principle is simple, it can be used for determining the temperature driving force for heat transfer in flow system such as heat exchanger. The illustration of LMTD countercurrent profile can be seen in Figure 2.

Figure 1: Silica scaling under controlled hydrodynamic and colloid particle size. From L to R: large particles - slow velocity, large particles - fast velocity, medium particles - low velocity, medium particles – fast velocity, small particles – low velocity and small particles – fast velocity (Brown, 2011).

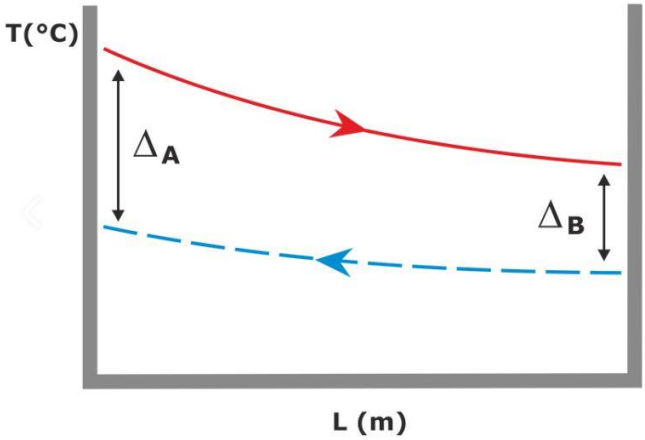


Figure 2: The LMTD illustrated in a countercurrent temperature profile (Wikipedia).

LMTD method is based on the heat transfer effectiveness, which is dimensionless parameter, defined as below (Almeshaal et al., 2023):

$$\varepsilon = \frac{Q_{tot}}{Q_{max}} = \frac{\text{Actual heat transfer rate}}{\text{Maximum possible heat transfer rate}}$$

Where the actual heat transfer rate can be determined by equation:

$$Q_{tot} = C_c\,(T_{c,out} - T_{c,in}) = C_h\,(T_{h,in} - T_{h,out})$$

However, to optimize the use of LMTD method, the measurement of the method should be real time to detect the decreasing of heat exchange effectiveness. Application holistic approach will reduce bias of DP and flow rate measurement since temperature sensor can be installed in each heat exchanger vessel.

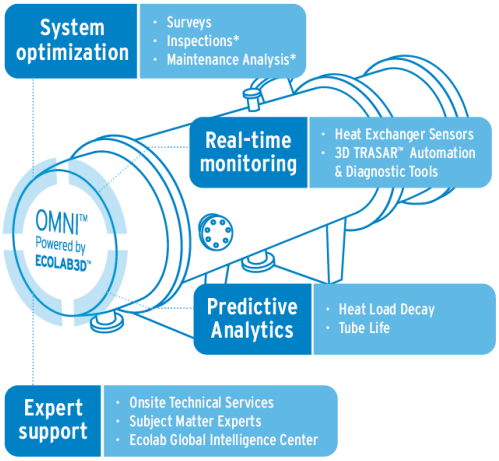


Figure 3: One of Application of LMTD Method (Ecolab bulletin).

The trial of this LMTD method in geothermal will soon be commenced. The benefit of this for geothermal industry is that the method is noninvasive, real time, and provide leading indicator for deposition event so that inhibition program can be adjust immediately. The figure below is one of the examples how the decrease of heat exchange effectiveness can be recovered immediately since the fouling is detected very fast and followed by corrective program to remove and prevent fouling from happen again.

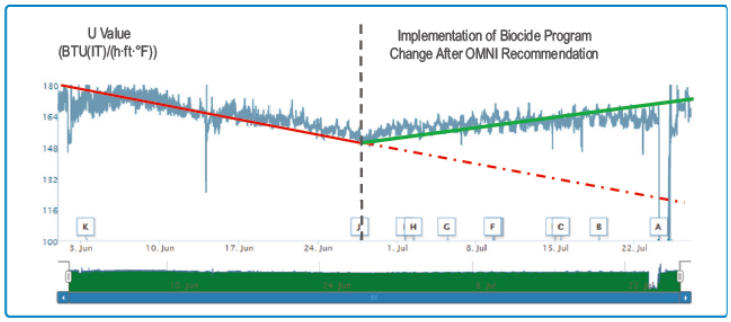


Figure 4: LMTD application to detect fouling event real time through change in U Value (Ecolab bulletin).

3. CHEMISTRY MONITORING

Chemistry monitoring is the main menu for controlling scale deposition in binary power plant. It can monitor the saturation condition of Silica and other metals through analysis of % monomeric silica retention, % metal retention, and scaling rate. Before going through the chemical monitoring method, the deposition mechanism will be exposed.

In general, amorphous Silica deposition occur through 2 different mechanism, formation of colloid and direct deposition on to solid surfaces. The most common pathway is the first mechanism. The formation of colloid can be achieved by 3 steps which is Nucleation, ripening and growth.

The most famous nucleation mechanism is polymerization. After supersaturation condition, monomeric Silica starts to form dimer, trimer, tetramer, etc. which catalysed by hydroxyl ions. That is why Hydrogen ion can slow down the polymerization since hydrogen ion will lower the concentration of hydroxyl ion concentration.

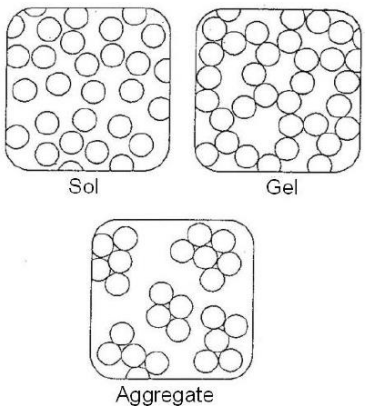


Figure 5: Form of Silica Coloid (Brown, 2011).

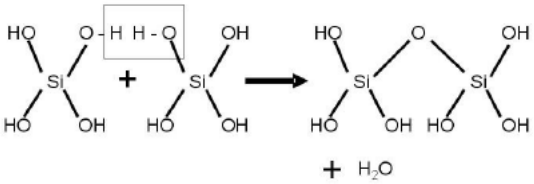


Figure 6: Polymerization Reaction (Brown, 2011).

3.1 % Monomeric Silica Retention

The first parameter in chemical monitoring method is % polymerization that can be derived from monomeric retention. The value of monomeric retention can be determined from brine sampling in upstream and downstream of binary system. % monomeric silica retention is an indicator of the amount of silica that remains in the monomeric form (equation 1). High % monomeric silica retention indicates that monomeric silica doesn't react with other monomeric silica to form polymeric silica or doesn't react with metal to form metal silicate.

$$\% \text{ Monomeric Silica Retention} = 1 - \frac{\text{Monomeric Silica at Binary Outlet}}{\text{Monomeric Silica at Binary Inlet}} \quad (1)$$

To understand the performance, below is the trend of % monomeric silica retention.

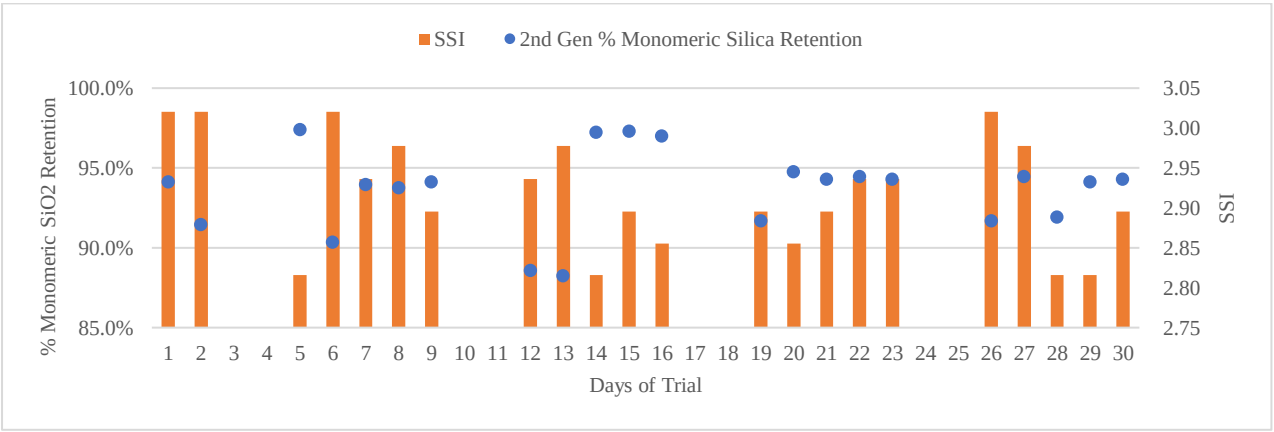


Figure 7: % Monomeric Silica Retention Performance (Arifpin et al., 2023).

Table 1: % Monomeric Silica Retention % Performance Summary.

SSI LSL	SSI USL	% of Data	Avg % Monomeric SiO2 Retention
2.78	2.85	18.2%	95.2%
2.85	2.92	31.8%	94.8%
2.92	2.99	31.8%	92.5%
2.99	3.06	18.2%	91.9%

It can be inferred from the data above that % monomeric silica retention can be used to monitor Silica condition. As the % monomeric silica declines, the risk of silica and/or metal silicate scaling deposition is increases. But, with this data alone, it is not enough to predict the scaling potential that might arises.

3.2 % Metal Retention

Metal retention determination method is similar with %monomeric retention. Brine sample from inlet and outlet binary system should be sampled and analyze using spectrophotometer to get metal concentration result.

The presence of metal ions in the brine can cause the formation of metal silicate which has a much lower solubility (Zarrouk et al., 2014). Therefore, it is crucial to understand and manage the risk of silica and metal silicate formation in binary heat exchangers. % metal retention indicates the amount of metal (aluminum, iron, manganese, etc.) that remains in the bulk water after it passes through the binary heat exchanger. High % metal retention indicates that most of the metal remains stable and does not react with silica to form metal silicate. This indicator will help to differentiate the scaling risk between amorphous silica and metal silicate in the binary heat exchanger.

$$\%\ \text{Metal Retention} = 1 - \frac{\text{Metal at Binary Outlet}}{\text{Metal at Binary Inlet}} \quad (2)$$

With the information of metal retention, the program can be adjusted to accommodate better metal silicate control if we found a situation where the propensity of metal silicate deposition risk is higher than silica deposition risk.

3.3 Scaling Rate

Scaling or deposition rate is a kinetics event and only can be determined empirically which affected by (Hirtz (2016), Pardelli et al. (2021):

1. Degree of supersaturation
2. Induction period
3. Flow velocity and turbulence
4. Ionic strength and salinity
5. pH
6. time
7. Availability of nucleation site

Typically, the binary power plant is designed to minimize the negative impact of the scaling formation by adjusting the parameter above. With this complexity, monitoring the leading chemistry indicators as above will not be sufficient to guarantee the system performance. Therefore, monitoring the scaling rate through coupon measurement is a good indicator to estimate the condition within binary heat exchanger. A good inhibition program will have to show good performance on both chemistry leading indicators (% monomeric silica retention and % metal retention) and deposition lagging indicators (scaling rate, MW declined, DP, etc.). To determine scaling rate, a scaling coupon can be installed in the downstream part of heat exchanger or between evaporator and preheater vessel. The weight different can be used to determined scaling rate.

4. CONCLUSION

The use of powerful Silica scale inhibitor will not be sufficient without proper monitoring and controlling system. Both will provide us with leading and lagging indicators to evaluate the condition of our heat exchanger vessel. The more accurate and consistent of monitoring result, the easier for geothermal developer to maintain their binary performance.

REFERENCES

Andritsos, N., Karabelas, A., & Koutsoukos, P. Scale formation in Geothermal Power Plants. (pp. 179-189). *International summer school on direct application of geothermal energy.*(2002).

Arifpin, N. Y., Hidayat, R., Andhika, M., and Suryatama, T.: Experience in managing High Saturation Index Silica Deposition in Brine ORC (Study Case Sorik Marapi Geothermal Field), *Proceedings*, the 8th Indonesia International Geothermal Convention & Exhibition (IIGCE). (2022).

Brown, K.: Thermodynamics and Kinetics of Silica Scaling, *Proceedings*, International Workshop on Mineral Scaling. (2011).

Cacho, Bryan. T. A Study On Different Two-Phase Flow Correlations Used in Geothermal Wellbore Modelling. *UNU-GTP Report.* (2015).

Hassan, H.. Utilization of Thermal Potential of Abandoned Wells. *India: Elsevier*. (2022)

Hirtz, P. V.: Silica Scale Control in Geothermal Plants – Historical Perspective and Current Technology, *Geothermal Power Generation*, (2016), 443 – 476.

Hochstein, M. P. Classification and Assessment of Geothermal Resources. *Dickson MH and Fanelli M (eds) Small geothermal resources* (pp. 31-59). Rome: Italy. (1990).

Pardelli, P. T., Tempesti, C., Mannelli, A., Kravos, A., Sabard, A., Fanicchia, F., Paul, S., Sengun, R., Sahiller, H. A., Halacoglu, U., Pekduz, I., Stefansson, A., and Galeczka, I. M., Design of a Scaling Reduction System for Geothermal Application, *E3S Web of Conferences*, **238**, (2021).

Vieira, Nuno. Steam and Brine Gathering System Design For Cachacos-Lombadas New Production Wells In RibeiraGrande Geothermal Field. *UNU-GTP Report.* (2015).

Metal Sulfides and Silicates Inhibition and Impact on Amorphous Silica Scaling

Fritz Earwin Monterozo[1] and Aarthi Narayanan[2]

[1]Nalco Water, An Ecolab Company, CTP Asean Tower, Alabang, Muntinlupa City, Philippines
[2]Nalco Water, An Ecolab Company, 1601 W. Diehl Rd, Naperville, Illinois, USA

fritz.monterozo@ecolab.com

Keywords: Mineral scaling, amorphous silica, metal silicates and metal sulfides

ABSTRACT

Silica scaling can be considered as one of the biggest challenges in utilizing geothermal energy for electricity production. It is often the thermodynamics of silica saturation that is considered in gauging the scaling tendency of a geothermal fluid. Aside from the thermodynamics, kinetics also plays a significant part and one factor not usually highlighted is the presence of metal ions. Small amounts of highly charged ions can drastically increase the agglomeration of colloidal silica. These ions act as bridges between colloidal silica particles, hastening the growth phase and thus, increasing rate of deposition. An inhibition program that targets both metal sulfide, metal silicate and amorphous silica scaling was tested on a brine from a binary plant. The test was carried out on a sidestream test that mimics the reduction of temperature in a binary plant targeting a silica saturation index of 2.0. Monomeric silica retention was calculated to be around 95% and the scaling spool installed showed minimal adherence of silica for the treated line. Even at the reduced outlet temperature, the deposit weight density is lower for the treated line (38 g/ft^2) compared to the untreated brine at the inlet temperature of 140 deg. C (55 g/ft^2). Exploratory analyses done on the scale deposits confirmed the presence of metal silicates and sulfides for the untreated line. The results of EDS elemental distribution map confirmed that the silica inhibitor program was able to disperse and prevent metal silicate and sulfide co-deposition with amorphous silica. Overall, the monomeric silica retention data complemented with physical observations suggest that the inhibitor program was effective in controlling the scaling even beyond saturation conditions. Actual field applications and trials were also conducted and confirmed that the scale management approach is effective.

1. INTRODUCTION

Amorphous silica scaling in different geothermal systems was proven to be a critical limiting factor in achieving operational sustainability. Amorphous silica, including its co-precipitation habits, causes extremely tenacious, highly insulating, and difficult to remove scales (Gill, 2011). In binary cycle geothermal power plants, further extraction of heat from hot brine that causes subsequent cooling leads to silica oversaturation, this condition will contribute to silica scaling which can minimize the heat transfer area of vaporizers and reheaters (Grassiani, 2000).

Currently, there are several methods being used to mitigate amorphous silica scaling in geothermal binary plants. These methods can be roughly categorized as reactive and preventive, both involving mechanical and chemical means. The reactive approach involves cleaning of amorphous silica scales that were already deposited inside the surface pipelines and heat transfer equipment. In an existing binary plant in the Philippines, the proposed cleaning methods were water blasting, mechanical clearing and chemical cleaning using hydrochloric (HCl) acid of hydrofluoric (HF) acid (Candido and Zarrouk, 2017). Water blasting uses high pressure water jet to dislodge deposits that clog the heat exchanger tubes. Mechanical clearing involves the use of drill bit to manually ream the deposits to recapture the capacity of the pipe. Chemical cleaning often involves the use of strong acids to dissolve existing silica deposits. The method is done by recirculating the acid inside the heat exchangers and disposing it through a dedicated HDPE pipe for reinjection. Acid cleaning method was used in binary plants in New Zealand to increase the brine flow. The impact of the cleaning minimizes pressure drop which is indicative of plugging reduction and increasing in temperature difference which means that heat was being transferred from the hot brine to the organic working fluid (Zarrouk, 2014).

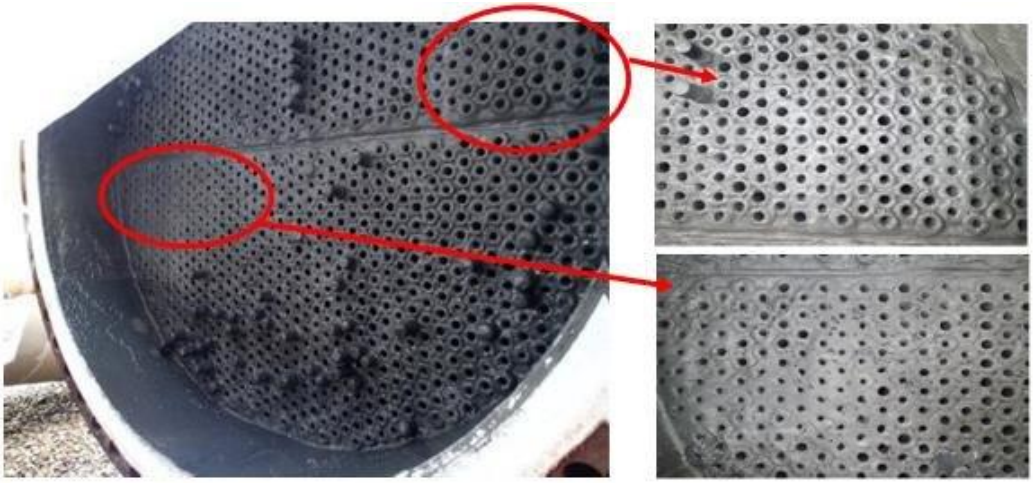


Figure 1: Scaled heat exchanger (vaporizer) tubes that contribute to reduced heat transfer efficiency (Candido and Zarrouk, 2017).

Preventive methods for amorphous silica deposition usually involve mechanical reconfiguration and chemical means of inhibition. For binary plants that do not meet the required brine flow by design, residence time inside the heat exchanger unit can be reduced by increasing the fluid velocity of the brine. This can be done by plugging the vaporizer tubes to not more than 10% (Telen, 2015).

Forced precipitation of spent brine using lime was also used in Salton Sea brines (USA). The principle behind is precipitating silica and undergoing clarification before injecting the treated water void of colloidal silica particles. Removal of silica using this method can be lucrative and research is still on-going (Brown, 2013).

In the industry, pH modification of the brine entering the vaporizer is one of the most widely used technique in minimizing the polymerization of amorphous silica; thus, minimizing the deposition tendency. The impact of decreasing the pH of geothermal fluids on silica scaling was documented in different sites (Grassiani et al., 2000). Akaku (1990) documented an acidic well discharge from one production site in Japan where the pH was at 3.9 and has the highest silica concentration among the other wells. This particular well has the least silica scaling compared to the other near neutral wells. A test in Svartsengi (Iceland) showed that spent brine used for power generation from a binary plant did not show any signs of polymerization for 60-80 mins after maintaining it at pH of less than 5.5. In a field test in New Zealand, rapid polymerization was observed at pH of 6 while at pH of 5, no polymerization was observed up to 200 mins. In the Philippines, field test in Mak-Ban geothermal facility used a pH setting of 5.5 to control silica polymerization (Gallup, 1996).

Although effective in delaying the polymerization of silica, Brown et al. (1983) do not recommend injecting the treated fluid because if the induction time is shorter than the perceived residence time downhole, scaling in the wellbore may happen which will plug the reinjection well. In some geothermal systems, scaling of antimony sulfide can be enhanced due to the low pH of the system from acid dosing. Recorded incidents of antimony sulfide scaling in binary plants were documented in Rotokawa and Ngawha (New Zealand) sites (Gill and Jacobs, 2018). Antimony sulfide or stibnite deposits can be tenacious as well and cause fouling of heat exchanger tubes. Aside from the tendency of stibnite precipitation, control of the acid dosing system is critical in achieving desirable results. Based on experience from different fields, insufficient acid dosing can lead to scaling while too much dosing can lead to corrosion and subsequently, surface equipment failure (Gallup, 1996).

The use of polymeric silica inhibitors is gaining interest in the geothermal community because of lower risk compared to pH modification. The challenge now is proving that the solution is technically and commercially viable alternative. Several studies were done to assess the performance of polymeric silica inhibitors. A study by Mejorada et al. (2000) involving a polymeric silica inhibitor was evaluated on a geothermal site in the Philippines. This inhibitor is phosphino-carboxylic co-polymer that was

specifically designed to retard silica polymerization. From the results, one ppm of the inhibitor was able to affect the morphology of the scales but was not enough to prevent the deposition completely. It was observed that the polymer was able to prevent the formation of hard, vitreous scales compared to the deposition documented in the untreated line. Another study on this polymer was carried out by Baltazar et al. (2014) in Leyte and Bicol (Philippines) steam fields. Visual inspection proved the favorable performance of the polymer on reinjection pipeline silica scaling mitigation. From the test, it was hypothesized that the proposed mechanism of the polymeric silica inhibitor is to disperse silica colloids – preventing agglomeration and react with corrosion products to minimize monomeric silica deposition.

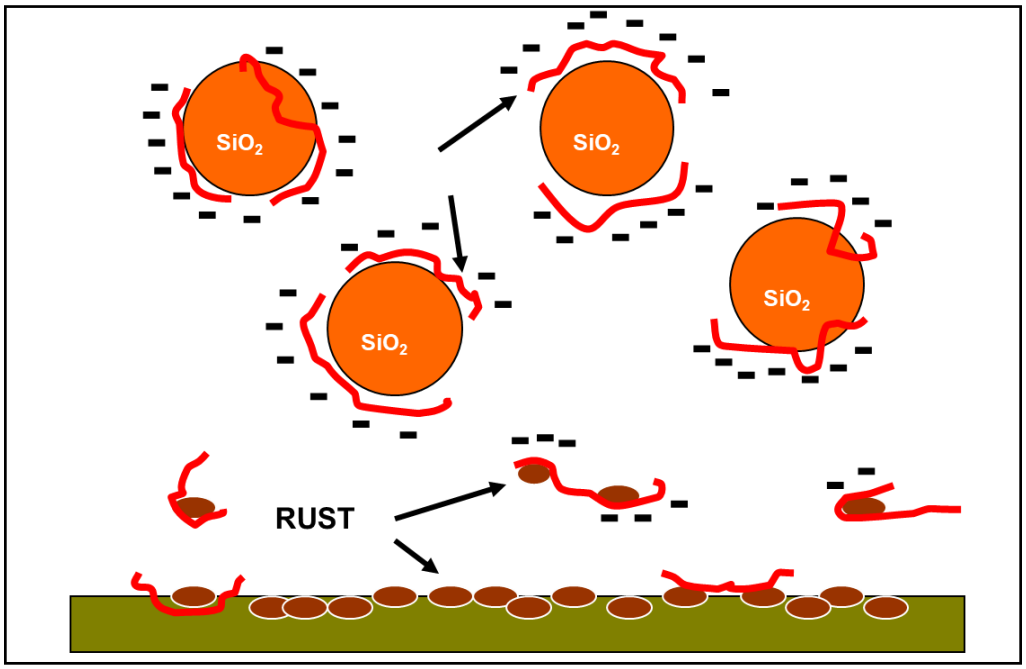


Figure 2: Proposed mechanism of polymeric silica inhibitor in dispersing colloidal silica particles and minimizing monomeric silica deposition (Mejorada et. al, 2023).

The carboxylic groups of the polymer attach itself to the silica molecules giving it a net negative charge which helps in preventing agglomeration and deposition on metal surfaces.

Polymeric silica inhibition studies were also conducted by Gill (2007) in both laboratory and field conditions. The active component of the polymeric inhibitor tested is a copolymer of acrylic acid. From the results of the laboratory tests, the perceived mode of action of this polymer are the following:

- Hydrophobic part of the active molecule prevents direct monomeric silica deposition on metal surfaces
- Acrylic acid helps in attaining a net negative charge among the silica molecules preventing nucleation; thus, polymerization retardation
- The same mechanism also happens with formed colloidal silica particles and in turn, prevents further colloidal particle growth
- Molecular adsorption or complexation also prevents formation of other scale like silicates

Field trials conducted in Heber facility (United States) showed promising results of the inhibitor based on visual inspection and final weights of the scale coupons installed in binary plant inlet and reinjection lines. For Cerro Prieto (Mexico) site, the results of field trial will help evaluate the feasibility of a binary cycle project (Gill, 2011).

Silica inhibition studies in a two-phase header using the same polymer-based inhibitor was also conducted by Jamero et al. (2021) and got promising results based on temperature profile.

In summary, for both laboratory and field trials, results should be evaluated based on monomeric silica levels read using spectrophotometer. Theoretically, yellow molybdate reagent is a colorimetric method that reacts particularly with monomeric silica (Franson, 1985). For inhibition to be deemed effective, the monomeric silica should be retained even past the induction time. Gill (2007) also used pre-weighed scale coupons to quantify the amount of silica formed and adhered on the metal surface. Mejorada et al. (2000) and Baltazar et al. (2014) used pre-weighed inspection spools to capture the amount of deposited silica. The spools are short carbon steel or stainless-steel pipe with 0.5-1-inch diameter. The amount of deposit formed can be used as a starting point to approximate the scaling rate per year. Aside from visual inspection, these measurements provide quantitative approach in assessing the performance of the mitigation technology selected.

Both pH modification and polymer-based silica inhibitors contribute to operational sustainability in terms of potential increase in the electricity generation capacity and preservation of pipeline flowrates (Gill and Jacobs, 2018).

Currently, the most common method being used to push the outlet temperature limitations is pH modification. This involves the use of acid to lower the pH of the geothermal brine, usually at pH 4-5, to delay silica scaling. This can help extract more heat from the inlet brine without causing significant scaling because of the lower outlet temperature setting. Typical challenge with this type of treatment is acid dosing control. In principle, too much acid will result to lower pH which can enhance corrosion of the system causing significant equipment damage. In contrast, too low acid dosing will not maintain the desired pH and will cause scaling.

The use of polymeric silica inhibitors is gaining interest in the geothermal community because of the minimal risk compared to pH modification. In the Philippines, some sites are using polymeric silica inhibitors to mitigate scaling in two-phase pipelines. The same principle can be explored and applied in binary plant operations where silica inhibitor will help extend the SSI operability even at reduced outlet temperatures. With the upcoming planned binary plant expansion facilities in the Philippines, this potential treatment method can be explored as a technically viable alternative to pH modification.

In the absence of an actual binary plant, testing of this potential technology can be challenging. Laboratory test may give idea on the mechanism and kinetics of the proposed solution but the actual field conditions that contribute to scaling propensity might not be factored in. A sidestream silica inhibition test may provide a better understanding of the inhibitor performance. By using a representative fluid from the actual plant, this gives a more approximate condition that can help capture different factors that may affect the performance of the proposed solution. Currently, previous sidestream tests done in the Philippines were either focused on understanding silica scaling behavior in reinjection systems or assessment of pH modification as potential treatment for binary plants. Previous sidestream studies on polymer-based inhibitors were aimed at finding a solution for maintaining reinjection well capacity. These studies only consider retention time and saturation as the dominating factors for scaling.

The study helped in understanding the mechanism of polymer-based scale inhibitors and its applicability on binary plant systems, specifically, the brine conditions similar to observed characteristics in the Philippines. The study also explored the impact of metal silicates and sulfides on the scaling behavior of amorphous silica which is often neglected when managing silica-saturated brines.

2. METHODOLOGY

A sidestream silica test skid was fabricated and installed in a binary plant in the Philippines. The schematic setup below outlines the process flow of the proposed study. Main brine inlet of the skid was tapped into the actual binary plant inlet where the incoming stream was divided into two, one is for the treated and the other is for the untreated line. For the treated line, polymeric silica inhibitor program (copolymer of acrylic acid and metal ion dispersant - supplied by Nalco Water) was used. The inhibitor program was composed of two separate chemistries. The silica inhibitor has the following physicochemical characteristics: hydrothermal stability at 320 °C, neat pH at 2.1-5.6, relative density at 1.06 (15.5°C) and kinematic viscosity around 194 mm2/s (at 20 °C). The metal ion dispersant or

metal silicate inhibitor has the following physicochemical properties: hydrothermal stability at 320 °C, neat pH at 2.5-3.6, relative density at 1.113 – 1.149 and kinematic viscosity around 39.93 to 42.69 mm2/s (at 20 °C).

The separated brine passed through individual coils (internal diameter: 3/8" stainless steel, length: 5.5 meters) where it was cooled to the target temperature of 100°C. An external cooling water supply and recirculation system helped maintain the target temperature and prevented thermal stratification. After reducing the temperature, the cooled brine passed through the retention vessels where the expected holding time was 90 mins. After passing through the retention vessels, the spent brine was collected in a holding tank and was pumped to a nearby sump. Figure 3 shows the proposed schematic diagram of the setup:

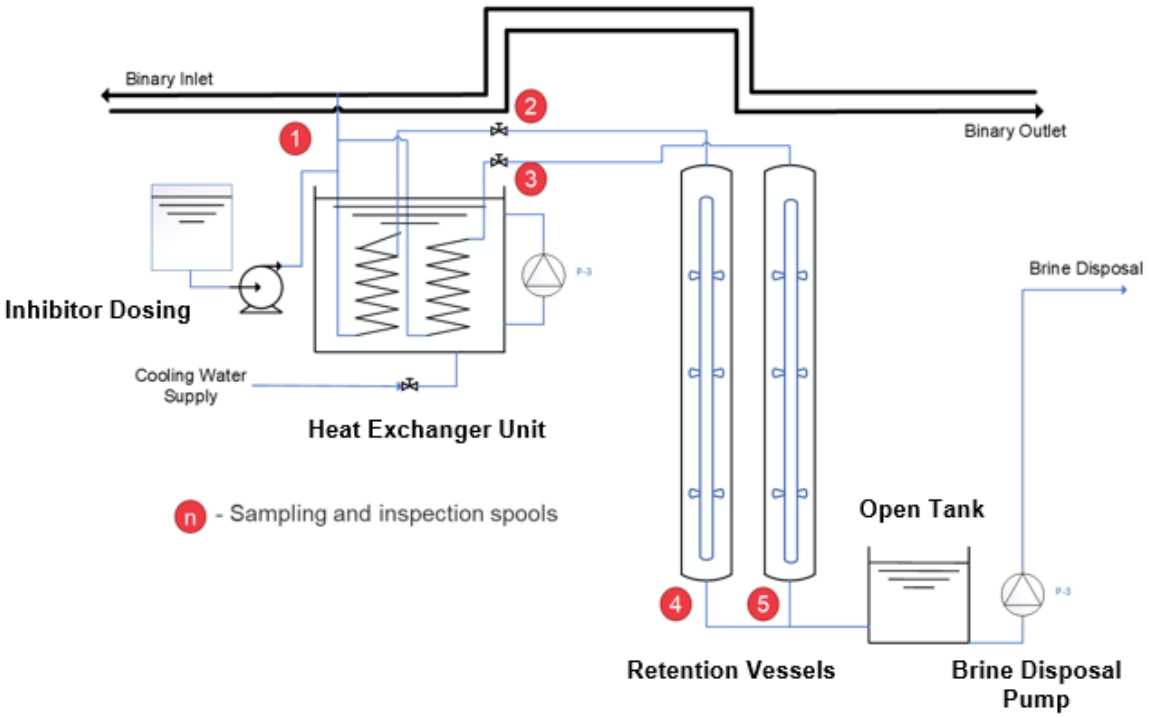


Figure 3: Schematic diagram of the sidestream setup (The numbers in red circles correspond the location of the brine sampling and inspection spools).

There were five sampling points for water analysis. Inspection spools (1-inch internal diameter and 5 inches length) were used to assess the physical manifestations of scaling,

The trial was conducted for 30 days to capture enough data points for analysis. The parameters that were monitored are the following:

Table 1: Monitored parameters, method of measurement and frequency.

Parameter	Measurement	Frequency
Monomeric silica	ASTM D859-16 (yellow molybdate method)	3x a day, 5 sampling points
Pressure	Analog pressure gauge	Manual logging, (3x/day)
Flowrate	Ultrasonic flow transmitter (Rosemount)	Logged automatically every 5 mins
Temperature	Temperature probes	Logged automatically every 5 mins
Total silica	Method 6020B - ICP	Once per week, (1st and 4th weeks only)

After the 30-day run, pre-weighed installed inspection spools were dismantled for visual inspection and deposit weight density measurement. Retention vessels and baffles were also inspected. Scale samples were submitted to an analytical laboratory in Singapore for XRF and XRD analyses.

For the experimental design, the only setting that was varied was the treatment condition, either treated or untreated. Variations in outlet temperature was minimized by controlling the cooling water supply to keep it constant. This is to maintain a constant silica saturation condition which is primarily driven by temperature. Inlet pressure was also fixed by throttling and adjusting the main isolation valve of the brine supply, thus keeping constant flowrates for both the treated and untreated lines. Dosage for the treated line was maintained at 14 ppm. The dosage was based on Nalco Water Geomizer® modeling software which uses Watch 2.4 speciation software to identify scale forming minerals and the corresponding saturation. The output was used by the modeling software to generate dosing suggestion based on the level of saturation of the brine. Monomeric silica, total silica, pressure, and flowrate were measured for both the treated and untreated streams.

3. RESULTS

Understanding the deposition behavior of silica particles in the trial conditions present can help understand the mechanism of inhibition. The inlet and outlet temperatures were 140°C and ~100°C respectively with pH at around 7. These translate to SSI values of 1.27 and 1.98 (considering 720 ppm actual silica measured at 160-165°C). At these brine conditions where SSI>1.0, nucleation is very rapid (Brown, 2012). Silicic acid molecules form dimers, trimers and so on until increasing to a significant particle size forming a single colloid – hence, the term polymerization. According to Iler (1979), the ionization of polymer species is much higher at pH of 6-7 and above 7 that the polymerization occurs rapidly causing decrease in concentration of monomeric silica. After the initial stages of polymerization, the colloidal silica particles will increase in size which is dependent on the oversaturation of the brine. The agglomeration of silica colloids contributes to surface deposition. According to Brown (2012), silica scaling happens because of interaction between like silica particles. With this condition, it is assumed that a monolayer of silica molecules exists on the surface of the metal pipes where the agglomerated silica particles will attach. The interaction of colloidal silica particles can be calculated with DLVO theory. Normal colloids in solution have a negative charge which causes electrostatic repulsion. As these colloidal particles grow, the distance between particles reduces (in terms of Angstroms) and the stable repulsive electrostatic force turns into attractive London and Van der Waals chemical forces (Brown, 2012). From the studies presented by Iler (1979) and Brown (2012), the hypothesized scaling process inside the pipe involves the following:

1. Formation of iron oxides on the surface of the pipe due to natural flow of geothermal brine and simultaneous slow direct deposition of monomeric silica.
2. In saturation conditions above 1, polymerization of silica happens which will eventually form into colloids and will grow.
3. Due to geothermal brines having high ionic strength, electrostatic repulsion of colloids was reduced, and this enhances the agglomeration of particles. The presence of metal ions also helps in increasing the agglomeration rate of colloid particles by acting as bridge.
4. Particle aggregates will attach to either the iron oxide particles or the slow-deposited monomeric silica. These can serve as either attachment point or seeds for other particles to attach.

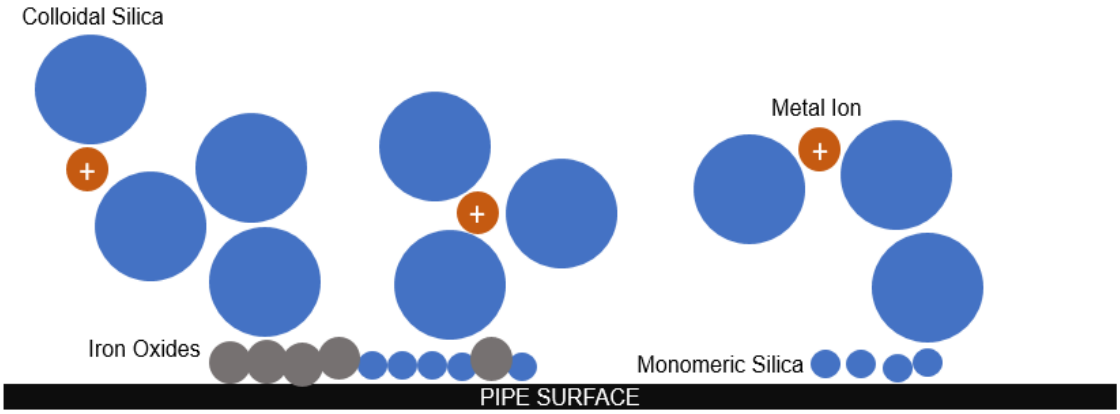


Figure 4: Proposed mechanism of scale deposition on the pipe surface.

According to Gill (2021), functionality of scale inhibitors can be divided into three: threshold inhibition, dispersion, and non-adherence. In the first functionality, scale-forming ions are kept soluble in the solution with the inhibitor being dosed at sub stoichiometric quantities in comparison to the target species. Dispersion functionality works on the particle structure, affecting changes on morphology, size and density, and surface charge. Consumption of inhibitor is significant since this must be adsorbed on the surface of the particles. The last functionality, non-adherence, creates a net negative charge on the particles that will be repelled by the metal surfaces. Based on the inhibitor selection criteria presented by Gill (2021), the most probable modes of action of the polymer-based inhibitor are dispersancy and non-adherence. Based on Gallup (2002), dispersion can be considered as the primary action of successful polymer-based inhibitors. These can impact the scale-forming minerals by increasing the induction period of growth, altering crystal forming habits and reducing potential for aggregation. Brown (2012) presented a mechanism by which dispersion functionality impacts colloid separation. For chemical inhibitors, it is possible that these can increase the energy barrier needed to overcome the electrostatic repulsive forces and turn into attractive forces. The succeeding figure shows the demonstration of the energy barrier increase:

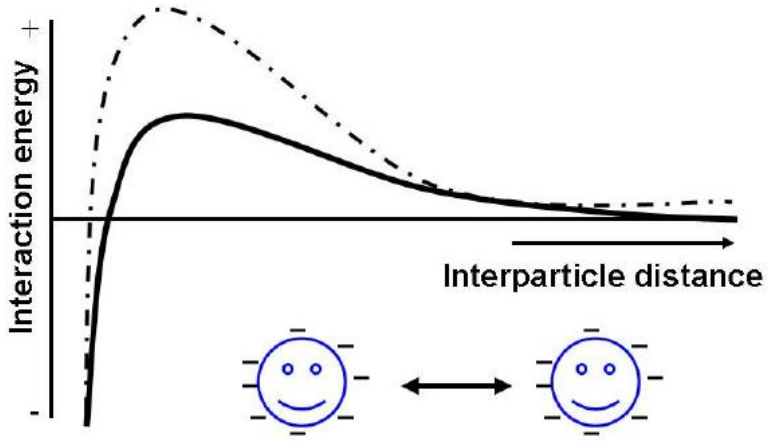


Figure 5: Increase in energy barrier that promotes colloid separation - as illustrated by Brown (2013).

With the learnings from the previous studies by Gill (2011) and Gill (2021), the proposed interactions of the inhibitor program are the following:

1. Affects the polymerization behavior of monomeric silica – results to increase in induction time.
2. Minimizes adherence of monomeric silica on pipe surfaces.
3. Enhances the electrostatic repulsive forces on colloidal silica particles by increasing the needed interaction energy to reverse these forces
4. Minimizes agglomeration of colloidal silica particles by effecting a net negative charge
5. Disperses metal ions by changing the surface charge to prevent it from acting as bridge between colloidal silica particles.

An important response that was measured during the trial was monomeric silica which was measured based on ASTM D859-16 (yellow molybdate method). For the trial, the measurement was done using a spectrophotometric determination of molybdate-reactive silica in the brine sample. The molybdate-reactive silica can be in the form of simple silicates, monomeric silica and silicic acid which are often referred to as reactive silica. Hach® high range silica reaction pillows were used, and the samples were read using Hach® DR900 multiparameter portable colorimeter.

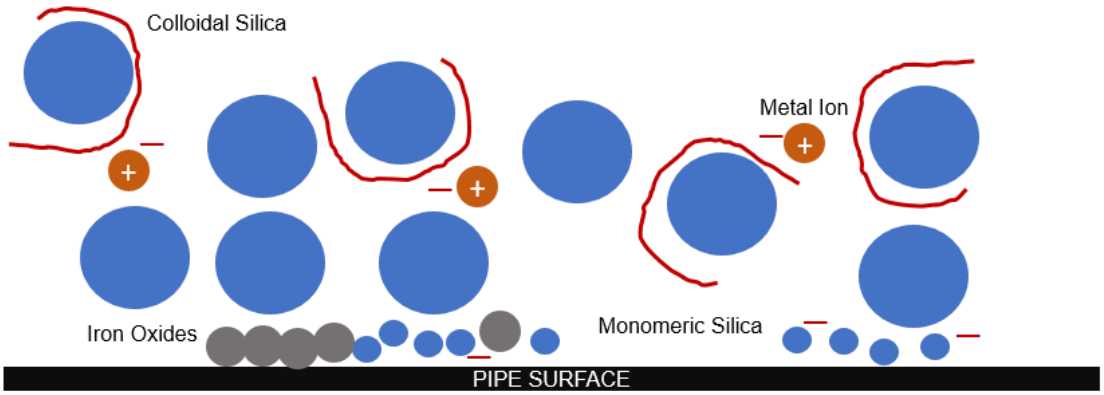


Figure 6: Interactions of polymer-based inhibitor on monomeric, colloidal silica and metal ions in the system.

Figure 7: Hach® silica high range reagents and Hach® DR900 portable colorimeter were used to monitor the monomeric silica levels.

For the analysis, a 1-mL brine sample was taken from the target sampling line and was diluted to 10 mL. The molybdate reagent will then react with monomeric silica in the brine sample forming a distinguishable yellow complex. The intensity of complex will be read against the original sample serving as blank.

There were five sampling points used to monitor the monomeric silica levels of different streams to determine how much was retained. The inlet brine monomeric silica level will serve as a baseline for both the treated and untreated lines. Samples were also taken after the cooling coils which captured the impact of temperature decline on monomeric silica retention. Furthermore, samples were also collected after the retention vessels to determine the impact on monomeric silica after holding the brine past its projected induction time.

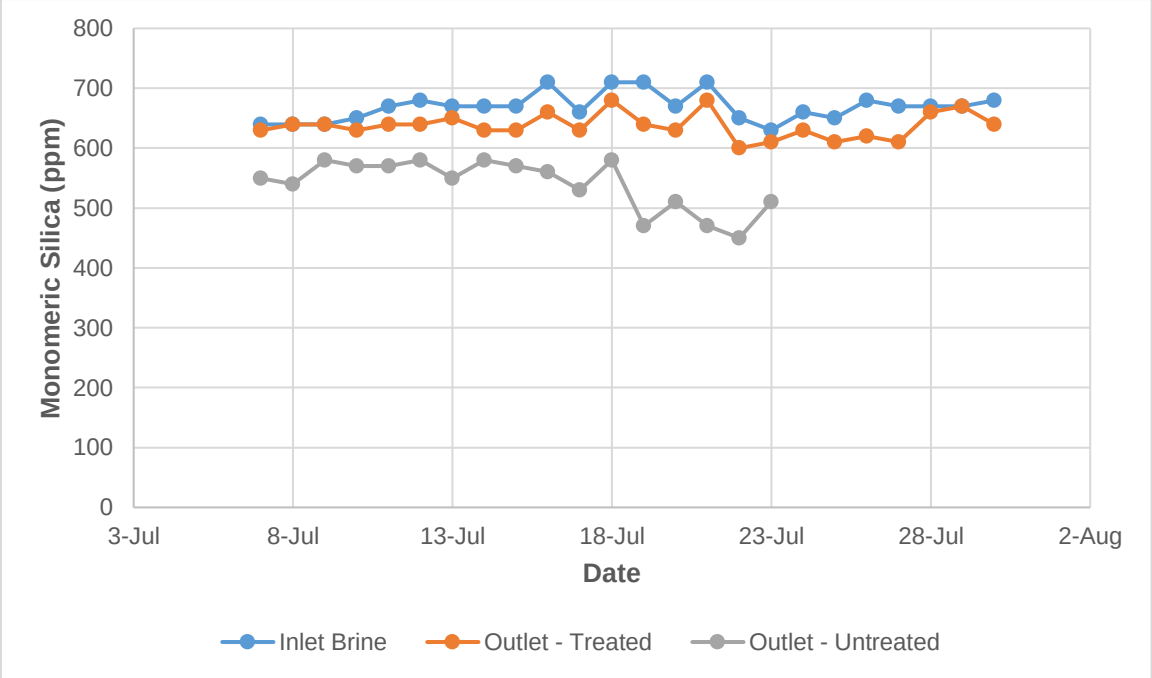


Figure 8: Monomeric silica readings of inlet brine, treated and untreated outlet streams after cooling to around 100 °C.

Using the average monomeric silica level of the inlet brine as the benchmark, the calculated percent monomeric silica retention for the treated and untreated lines were 95% and 80% respectively (using reduced data points for the untreated line). The monomeric silica trend observed on the treated line complements the proposed mechanism of inhibition. It can be noted that the inhibitor generally affected the polymerization behavior of monomeric silica; thus, keeping it soluble in the solution. Aside from the effect on monomeric silica, colloidal silica interaction leading to scaling was also reduced considering there was no significant drop in total silica (Table 2).

The attained monomeric silica retention for the treated line was higher than the target set by the plant which is at least 90%. Two-sample t-test between the treated and untreated monomeric silica levels was also done. The means of the two data groups were significantly different.

Aside from the effect of reduced temperature, there was also a significant impact on monomeric silica retention after holding the brine beyond its induction time. Figure 4.19 shows the monomeric silica levels at the inlet and outlet of the retention vessel.

Using the average values of the inlet and outlet monomeric silica levels, the projected percent retention was around 80%. For the untreated line, even with the reduced data points, the calculated percent monomeric silica level was around 70%. If the same benchmark of 90% monomeric silica retention will be used, the value obtained for the treated line may not be favorable, but the longer retention time should be taken into account. A study done in Kizildere geothermal field in Turkey captured the trend of monomeric silica levels with respect to pH and time.

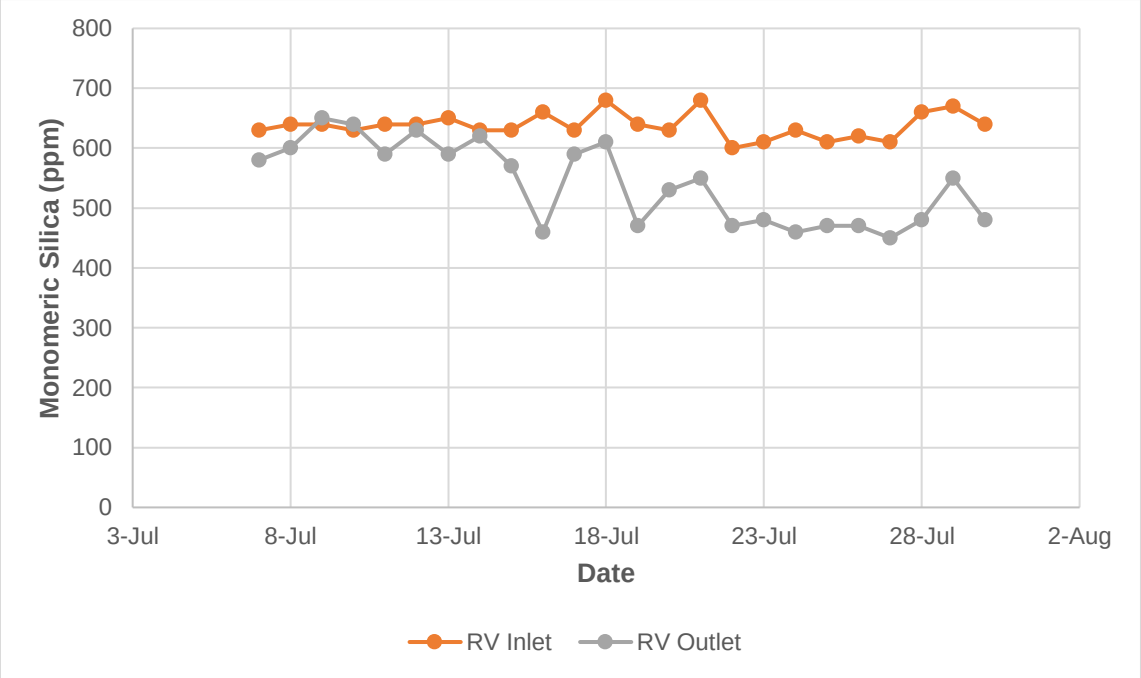


Figure 9: Monomeric silica levels before and after holding the brine in the retention vessel.

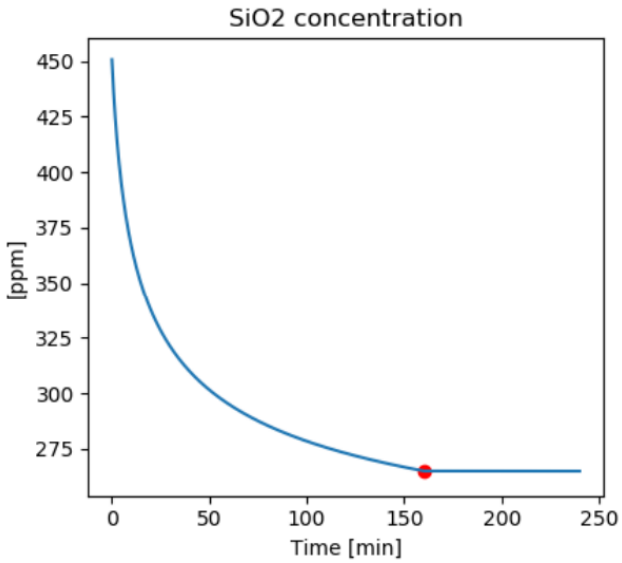


Figure 10: Trend of monomeric silica level versus time at pH of 7 and temperature of 50°C. (Pardelli et al., 2021).

It can be observed that time is a crucial parameter because aging geothermal fluids allow the polymerization of monomeric silica in excess of the equilibrium amorphous silica concentration. Longer retention time significantly decreased the monomeric silica concentration up to the equilibrium concentration. It can also be observed that monomeric silica levels will not fall below the equilibrium concentration despite holding the brine for longer periods of time hence a constant level after reaching the equilibrium concentration (Pardelli et al., 2021).

The reduced brine flow significantly increased the retention time towards the end of the trial. Plotting the monomeric silica levels at the treated line retention vessel outlet against the projected retention time based on flowrate, the observed trend is shown in Figure 11.

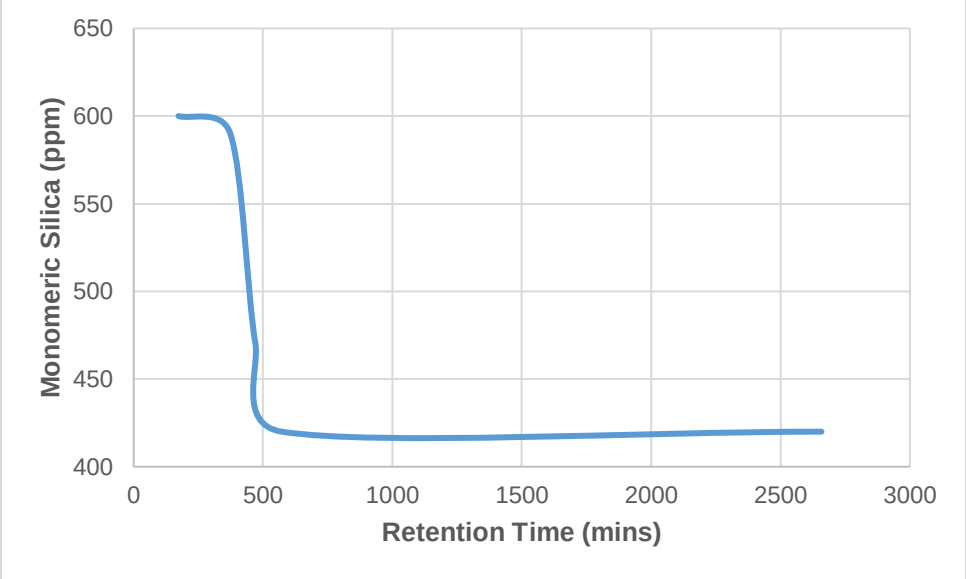


Figure 11: Treated line outlet monomeric silica levels at varying retention time.

Based on the obtained trend, it will take around 373 minutes before the monomeric silica will start to decline significantly. Iler (1979) also observed a drastic decline in monomeric silica past the induction time which was described as autocatalytic. Monomeric silica levels will stay constant despite the increased retention time once the equilibrium was reached based on solution temperature. The same general trend was observed in the study of Pardelli et al. (2021). It can be observed that the inhibitor can keep the monomeric silica soluble at 100 °C outlet temperature for more than 90 minutes. This means that even at the reduced temperature, the brine has enough travel time from the outlet of the binary plant to the target reinjection well.

Aside from monomeric silica, brine samples during the first and last weeks of the trial were sent to Nalco Water Analytical Laboratory in Singapore for ICP analysis. Ten mL of brine sample was diluted to 100 mL and was acidified by adding nitric acid until reaching a pH of 1.5. This will help delay polymerization while the sample is in transit. The total silica levels are summarized in the succeeding table:

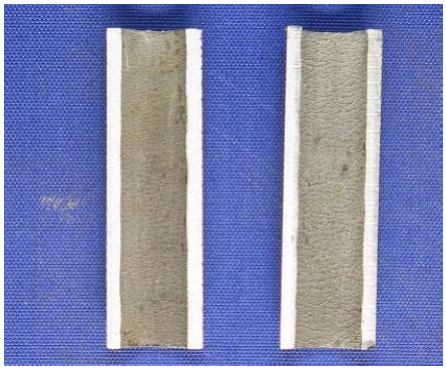
Table 2: Total silica levels during the first and fourth week of the trial.

Sample	Inlet (ppm)	Treated (ppm)	Untreated (ppm)	Retention Vessel – Treated (ppm)	Retention Vessel – Untreated (ppm)
1st week	720	710	650	650	600
4th week	720	680	190	630	170

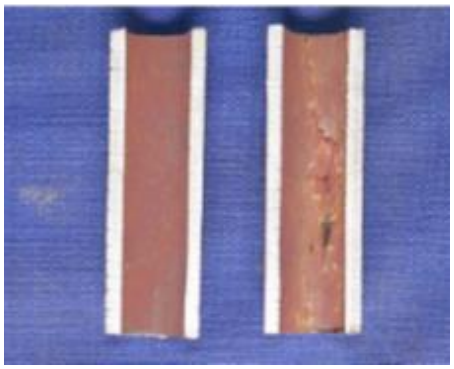
The results of the total silica during the last week of the testing further affirms that there was flow stagnation. If the stream of the untreated line is still flowing, the total silica in the system should still be close to the total silica during the first week. Significant decline in total silica for the untreated line means that the monomeric silica has already polymerized, formed colloidal particles and eventually, may have been co-deposited as iron silicates. The stagnation of flow may have depleted the monomeric silica in the system below the projected equilibrium concentration of ~364 ppm around 100°C.

The inspection spools used in the trial were submitted to Nalco Water Analytical Laboratory in Naperville, Illinois for deposit weight density measurement. Figures 12 and 13 summarized the condition of the inspection spools upon analysis.

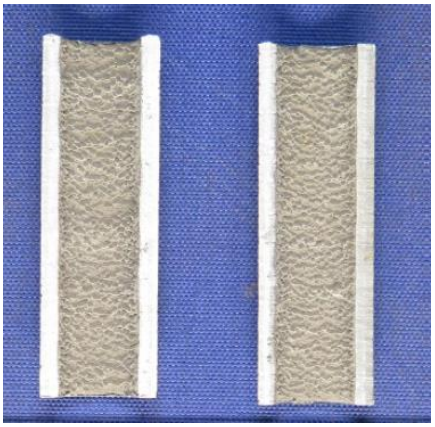
Figure 12: Internal condition of the inspection spool installed in the inlet stream.



(Treated – After Cooling)



(Untreated – After Cooling)



(Treated – After Retention Vessel)

(Untreated – After Retention Vessel)

Figure 13: Comparison of treated and untreated inspection spools installed after cooling and after the retention vessels.

Physical observations of the inspection spools for both the treated and untreated lines were consistent with the initial inspection of the cooling coils. Characteristic manifestation of surface corrosion was observed in the untreated line while the thin layer of deposits was observed on the surface of the treated line. The measured deposit weight density is summarized on the table below:

Table 3: Deposit weight density measurement of the spools.

DWD (g/ft^2)	Inspection Spool Location				
Pipe Side	**Inlet**	**Treated (after cooling)**	**Untreated (after cooling)**	**Treated (after RV)**	**Untreated (after RV)**
Lower	35	22	18	84	15
Upper	20	16	7	82	7

(Narayanan, 2022) – Nalco Water Analytical Laboratory – Naperville, Illinois

Generally, a higher deposit weigh density (DWD) means that there are more scales per unit of area in the pipe. In this case, the DWD values obtained from the untreated line cannot be used for comparison since it was observed that there was flow stagnation in the line that contributed to the depletion of monomeric silica; thus, having minimal deposits. The deposits measured in the treated RV spool was significantly higher than the spool after cooling because the retention time was more than the target 90 mins. Using the trend observed in Figure 11, significant decline in monomeric silica was observed past 373 minutes, this has favored colloidal silica formation, agglomeration of particles and deposition on the pipe surfaces. For the inspection spools after temperature reduction, possible impact on scaling tendency due to rapid cooling can be considered negligible. According to Brown (2012), rapid cooling of brine causes small colloidal silica particles and the corresponding deposition will be lesser. This rapid cooling should happen in matter of seconds. For the sidestream test, the temperature reduction happened within 3 – 5 mins, consistent to the projected time in the actual plant. This cooling time disregards the possible false positive outcome because of reduced colloidal silica size.

A helpful use of the DWD data obtained is the comparison of the inlet and treated line inspection spools. It can be observed that even with the increased saturation resulting from the decrease in temperature, the amount of deposits was lower in the treated line compared to the inlet line. This may suggest that the polymer-based inhibitor was effective in minimizing the deposition despite the increase in saturation.

However, the deposits on the internal surface of the spools were subjected to X-ray fluorescence (XRF) analyses to get further information on the elemental distribution. The XRF comparison of each spool deposit is shown in Figure 14.

It can be observed that majority of the scale composition of the treated line was amorphous silica while the untreated and inlet lines was iron. Sulfides in the deposit was also significant in the untreated line. There is also a considerable percentages of metal ions in both the untreated and inlet lines. This observation further validates the metal silicate inhibition capability of the polymer-based inhibitor used.

The inspection of the retention vessel of the treated line also showed minimal adherence of scale on the surface. Like the cooling coils and inspection spools of the untreated line, general corrosion was observed on the surface for both the vessel and the baffles.

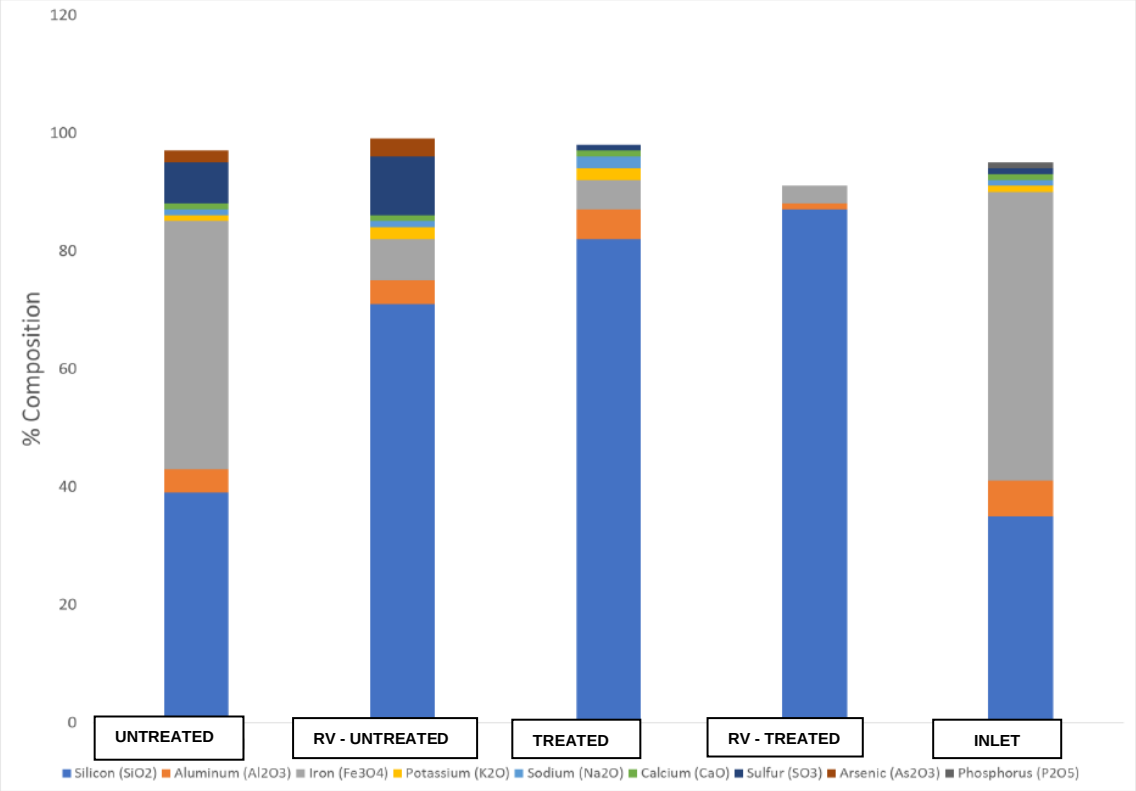
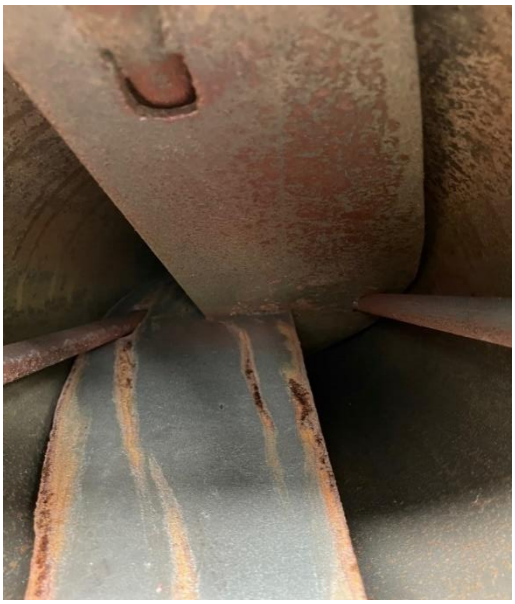


Figure 14: XRF analyses of the deposits found on the surface of the spools.

Opening of Retention Vessel (Treated) Opening of Retention Vessel (Untreated)

Figure 15: Inspection of the retention vessels after the 30-day run.

Baffles inside the retention vessel (Treated)



Baffles inside the retention vessel (Untreated)

Figure 16: Internal view of the baffles before pull out.

Scale samples were obtained by scraping the surface of the baffles. These were sent to Nalco Singapore lab to confirm the composition and structure. From the results of the XRF and XRF analyses, the dominant scale type on the treated line surfaces was amorphous silica with confirmed traces of magnetite. For the untreated line, majority of the deposits was iron silicates, amorphous silica and confirmed formation of hematite. The results of the XRF and XRD were consistent to the deposit analyses done on the inspection spools internal surfaces.

To explore the metal ion dispersion capability, an energy dispersive spectroscopy (EDS) was conducted on the adequate deposit samples found on the surface of the treated and untreated retention vessel inspection spools.

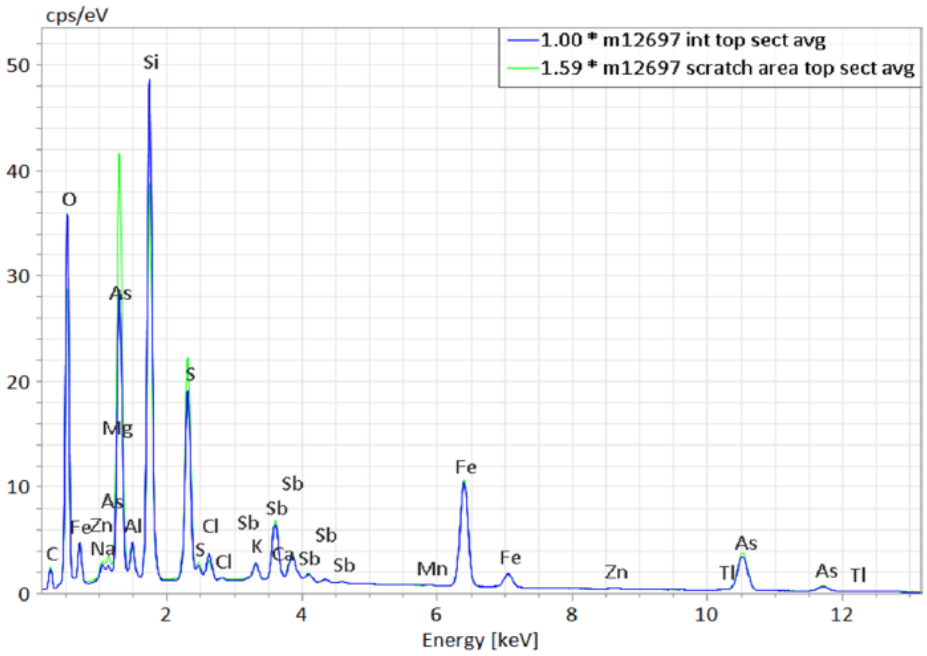


Figure 17: Elemental distribution map of the untreated RV inspection spool.

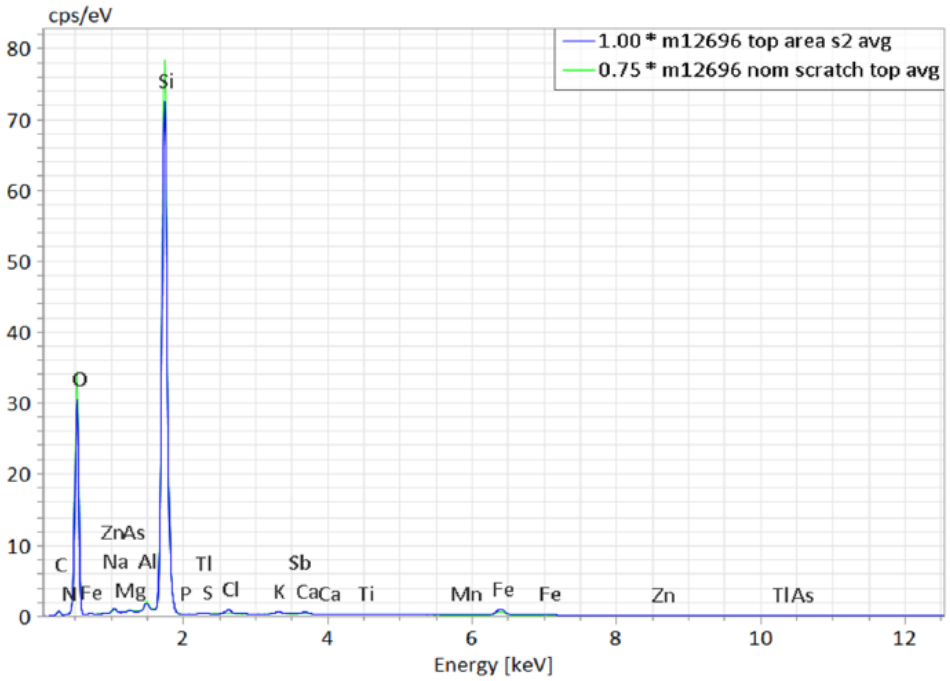


Figure 18: Elemental distribution map of the treated RV inspection spool.

The distribution map of the untreated deposit sample shows considerable peaks of metal ions like magnesium, aluminum, and iron. Toxic elements like arsenic and aluminum were also co-deposited with amorphous silica. A peak in sulfur was also observed which may indicate metal sulfides in the scale. Elemental distribution map of the treated deposit sample shows silica as the major composition. Very low peaks of metal ions were observed which confirmed the dispersive capability of the inhibitor.

4. SUMMARY

The main objective of the study is to evaluate a potential alternative for minimizing potential scale deposition in above-saturation binary plant conditions. This was done by fabricating a setup that can mimic the reduction in brine outlet temperature because of heat extraction. Consequently, holding the brine for a specific period was also done to simulate the travel of the brine from the outlet of the binary plant to the target reinjection well. The setup was able to reduce the outlet temperature of the treated and untreated lines close to the target value. Unfortunately, the brine flow going to the skid was erratic and gradually reduced because of pressure build-up and preferential flow to the main line. Since the retention time was based on the design flowrate, the projected holding time for the brine was increased to up to 2658 minutes. This was significantly longer than the target 90 minutes retention time.

The study utilized different information available to assess the performance of the polymer-based silica inhibitor. From the results of monomeric silica retention data from the dosed line, it showed the inhibitor program is effective in maintaining monomeric silica at around 95%. The achieved percent retention is promising in comparison to the empirical data obtained from different geothermal treatment sites. Examination of the inspection spools installed at the brine inlet and treated line cooling coil outlet showed minimal adherence of silica on the surface of the pipe. Even at the reduced outlet temperature, the deposit weight density is lower for the treated line (38 g/ft2) compared to the untreated brine at the inlet temperature of 140 deg. C (55 g/ft2).

The flowrate readings during the trial were lower than expected because of throttling due to limited cooling water supply. The impact of this was on the retention time which is longer than the projected 90 mins. At a much harsher condition, the dosed line monomeric silica retention after the holding vessel registered at around 81%.

Unfortunately, the untreated line cannot be used as a direct comparison because of the low velocity condition that occurred. The sudden spike in outlet pressure signaled an obstruction or deposition along the lines and the inspection after the trial confirmed the unforeseen condition. The presence of characteristic general corrosion and lower than equilibrium concentration total silica confirmed the flow stagnation. This has reduced the data points used for the untreated line monomeric silica readings and the deposit weight density measurement. Using the available data, the projected percent monomeric silica retention for the untreated line was at 80%.

Exploratory analyses done on the scale deposits confirmed the presence of metal silicates and sulfides for the untreated line. The results of EDS elemental distribution map confirmed that the polymer-based silica inhibitor was able to disperse and prevent metal silicate and sulfide co-deposition with amorphous silica.

Overall, the monomeric silica retention data complemented with physical observations suggest that the inhibitor program was effective in controlling the scaling even at a reduced outlet temperature.

REFERENCES

Angcoy, E. C. Jr., 2006: An experiment on monomeric and polymeric silica precipitation rates from supersaturated solutions. *UNU-Geothermal Training Programme Reports*, 5, 21-46

Baltazar, A. D. et al., 2014: Geothermal Silica Scale Inhibition and Control Using Phosphino Carboxylic Acid Copolymer in Bacon-Manito Geothermal Business Unit. *GRC Transactions*, 38, 663–668.

Bohlmann, E.G., Mesmer, R.E., and Berlinski, P., 1980: Kinetics of silica deposition from simulated geothermal brines. *Soc. of Pet. Eng. Journal*, 20, 239-248.

Brown, K., 2013: Mineral scaling in geothermal power production. *United Nations Geothermal Training Program.*

Brown, K. & Lichti, K., 2012: Some current challenges in production geochemistry. New Zealand *Geothermal Workshop Proceedings*, Auckland New Zealand

Brown, K.L., and Dunstall, M., 2000. Silica scaling under controlled hydrodynamic conditions, *Proceedings of the World Geothermal Congress 2000*, Kyushu- Tohoku, Japan, 3039-3044.

Candido, C. A. S. & Zarrouk, S. J., 2017. Scaling mitigations for the binary plant vaporizer: Upper Mahiao, the Philippines. *Proceedings of the 39th New Zealand Geothermal Workshop 2017*, Rotorua, New Zealand

Carroll, S., Mroczek, E., Alai, M., and Ebert, M., 1998: Amorphous silica precipitation (60° to 120°C): comparison of laboratory and field rates. *Geochim. Cosmochim*. Acta, 62, 1379-1396.

Fournier, R.O., and Rowe, J.J., 1966: Estimation of underground temperatures from silica content of water from hot springs and wet-steam wells. *Am. J. Sci*. 264, 685–697.

Franson, M. A., 1985: Standard Methods. For the examination of waste and wastewater (16th edition). *American Public Health Association*, 1268 pp.

Gallup, D.L., 1998: Aluminum silicate scale formation and inhibition (2): scale solubilities and laboratory and field inhibition tests. *Geothermics*, 27, 485-501.

Gallup, D.L., 2002: Investigation of organic inhibitors for silica scale control in geothermal brines. *Geothermics* 31, 415

Gill, J. S., 2011: New inhibitors for silica and calcium carbonate control in geothermal. *Proceedings International Workshop on Mineral Scaling*, 2011, 113-118

Gill, J. S. & Jacobs, G. T., 2018: Managing silica deposits in geothermal power plants- pros and cons of pH mod versus Silica Inhibitor. *GRC Transactions*, 42,

Gill, J.S., 2021: Simplifying the selection of chemical treatment for managing scale and corrosion in geothermal systems. *GRC Transactions*, Vol. 45

Geothermal Energy Basics. NREL.gov. (n.d.). Retrieved April 18, 2022, from https://www.nrel.gov/research/re-geothermal.html

Grassiani, M., 2000. Siliceous scaling aspects of geothermal power generation using binary cycle heat recovery, *Proceedings of the World Geothermal Congress 2000*, Kyushu- Tohoku, Japan, 3167-3171.

Gunnarsson, I. and Arnórsson S., 2005: Impact of silica scaling on the efficiency of heat extraction from high-temperature geothermal fluids. *Geothermics*, 34, 320-329.

Iler, R.K., 1979: The chemistry of silica: solubility, polymerization, colloidal and surface properties, and biochemistry. John Wiley & Sons

Jamero, J. et al., 2021: Mitigation of two-phase header scaling in an acidic system. *World Geothermal Congress 2021*, 27209

Liu, Y & Zhang, P., 2022: Review of phosphorus-based polymers for mineral scale and corrosion control in oilfield. *Polymers 2022*, 14, 2673

Mauren et al., 2020: Determination of reaction rate constant for increasing pH level in geothermal hot spring. *IOP Conference Series: Earth and Environmental Science*, 451 012088

Mejorada, A. V. et al., 2000: A silica scale inhibitor, Geogard SX, testing at the Southern Negros Geothermal Production Field. *Geothermal Resources Council Transaction*, 24, 503-507

Narayanan, A., 2022: PH trial spool analysis. Internal Report – Nalco Water Analytical Laboratory

Nasrazadani, S., 1990: Formation and transformation characteristics of magnetite (Fe3O4) under different lab and field conditions. *Corrosion Science*, 39, 1845-1859

Pardelli, P. T. et. al, 2021: Design of a scaling reduction system for geothermal applications. *E3S Web of Conferences*, 238, 01014

Telen, C. (2015). Upper Mahiao Brine Plant Rehabilitation Program. Philippines: Energy Development Corporation.

United States Environmental Protection Agency, 1999: Geothermal direct heat return flow wells. The Class V Underground Injection Control Study vol 18

Villa, R. R. et al., 2005: Methods of recovering solids from the discharge of steam dominated wells in Leyte Geothermal Production Field, Philippines. *Proceedings of World Geothermal Congress 2005*, 24-29.

Weres, O., and Apps, J.A., 1982: Prediction of chemical problems in the reinjection of geothermal brines. *Geological Society of America, Special Paper* 189, 407-426.

Yousaf, M. N. et al. 200. A Comprehensive Study Report on Energy Crisis & Energy Resources of Pakistan.

Zarrouk, S., Woodhurst, B., & Morris, C. (2014). Silica Scaling in Geothermal Heat Exchangers and its Impact on Pressure Drop and Performance: Wairakei Binary Plant, New Zealand. *Geothermics* 51 (2014) 445-459.

ORC Online Cleaning to Improve Electricity Generation at Binary Geothermal System

Nur Choiri Amin[1], Arsyan Sasoni[2], Logan Muller[2], and Ebta Pasaribu[2]

[1]Solenis NEU Kimya AS, Istanbul, Turkey
[2]PT. Solenis Technologies Indonesia, Indonesia
[3]Solenis New Zealand, Aukland, New Zealand

nchoiriamin@solenis.com

Keywords: ORC, Online Cleaning, Silica Scaling, Binary Geothermal, Electricity Generation

ABSTRACT

In flash Binary geothermal, Organic Rankine Cycle (ORC) processing fluids from moderate to hot temperature reservoirs are prone to amorphous silica and silicate scaling in surface equipment and reinjection wells. Scaling can reduce power plant generation capacity factors and cause a loss in Well injectivity.

The Customer has experienced deposition of silica through pipelines from production wells to the heat exchangers, and reinjection well. They must stop operation and do a mechanical cleaning process.

Solenis has conducted ORC online cleaning process at one of Binary Geothermal's customers in Indonesia with the following result. At 10 (ten) minutes, online chemical cleaning lifted electricity production by 36% versus 3 (three) days offline mechanical cleaning, 451 kg of silica was removed from the system, and inlet pressure drops over 13 bar showing.

1. INTRODUCTION

Deposition and related phenomena were considered a major constraint on the development of geothermal energy worldwide (Gudmundsson, 1983). Among the minerals susceptible to deposition, silica and calcite are the most common and difficult to remove. However, while calcite has been mostly troublesome for production well management, silica is considered “dangerous” for reinjection wells and some parts of the surface conduits transporting the brine. The scaling problem is inherent to most liquid-dominated geothermal resources. Generally, as aquifer temperatures rise, scaling problems would be expected to occur along the extraction system.

Organic Rankine Cycle (ORC) is a technology that converts low-temperature heat sources into mechanical energy and can produce electrical energy in a closed system. The heat sources can be received from renewable energy such as geothermal, solar, and biomass. Furthermore, the ORC system can also be used to increase energy efficiency in industry by using the waste heat produced. Therefore, the ORC system has two classifications: a heat recovery system and a binary power plant. Recently, the ORC system has thrived in the geothermal power plant. The ORC system can be applied to resources with low to medium temperature characteristics (Hijriawan, 2019)

The development of the Organic Rankine Cycle (ORC or “binary”) technology for geothermal power plant applications at the beginning of the 1980s was limited to those cases where silica scaling would not be expected, such as in medium to low enthalpy sources. At East-Mesa, California, pumped geothermal brines produced light iron carbonate and iron sulfide scales (Grassiani, 1988) reducing carbon-steel corrosion, while iron silicate was scarcely present on cooling at temperatures less than 90ºC. At the same time, scientists and developers started to become more confident about the site-specific nature of silica deposition and the importance of the kinetics of such deposition. An increased understanding might allow further use of spent thermal brines issuing from moderate- to high-enthalpy, two-phase geothermal resources. The interest shifted from Silica Index (actual concentration), to “supersaturation (concentration ratio), to “induction” (or incubation) period, to “polymerization” (which is a major prerequisite to colloidal, amorphous silica generation and further massive deposition). Induction periods may vary from several minutes to several hours and in many cases are long enough to allow normal flow and heat transfer inside the critical heat exchanger of the binary plant unit.

Furthermore, design and operational experience have evolved in recent years to a point where scaling is managed on a routine basis.

In steam-operating geothermal power plants, silica deposition by steam carryover may become very troublesome. Even in small concentrations, silica affects the heat exchanger of ORC systems, steam turbines, valves, and separators. The prospect of silica deposition after the separation of two-phase geofluids inspired a conservative approach to the design of the silica saturation index in the geothermal fluid system. The ORC system at Binary Geothermal Power would be an extremely critical operation with high SSI.

This paper summarizes of field application of a combination between GeoSol™ GS1008 (Silica dissolver) and GeoSol™ GS1251 (Silicate based Metal dissolver) during the ORC online cleaning process at one of the Geothermal customers in Indonesia. which the silica at the surface area was to be a big major issue in decreasing electricity generation. A combination of both chemicals has been compared versus offline mechanical cleaning process to find the best methods to remove silica scale in the ORC system of Binary Geothermal.

2. BACKGROUND

Scaling has a dramatic impact on the long-term operational performance of geothermal heat exchangers system. Scaling affects both the flow hydrodynamics and the heat transfer resistance. A review of reported scaling problems in geothermal heat exchangers shows that silicate (pure silica and metal silicate) is the main deposited mineral.

Customer is one of the first ORC binary geothermal plants in Indonesia. The customer will stop operation to do an offline cleaning process to remove the silica scale formed in the heat exchanger of the ORC system. The offline cleaning process will take 1-3 days to stop the ORC system. It caused reduced plant reliability and reduced electricity production significantly. Please see below the detailed scale formation on the HE system of ORC.

Figure 1: Scale formation onto Preheater system.

Deposit Analysis Result

X-Ray diffraction analysis (XRD) is a nondestructive technique that provides detailed information about the crystallographic structure, chemical composition, and physical properties of a material. Deposit analysis is used to decide the strain, preferred orientation, crystallographic structure, and grain size of crystalline materials. XRD can determine the presence and amounts of minerals species in the sample, as well as identify phases. The final stage of XRD analysis is to decide what kind of typical chemical would be used to remove from the system.

Based on the deposited sample from each Pre-heater system, Figure 2 is the analysis result. It shows that the major content of scale formation is Silicon dioxide at an average number of 71% and the second major mineral is Aluminum oxide at around 6-9%.

SCHEME	ANALYTE CODE	DESCRIPTION	UNIT	D.L	Scaling A	Scaling B	Scaling B REP
XRFFWR	AL2O3	Aluminium Oxide	%	0.01	5.99	9.18	9.14
XRFFWR	AS	Arsenic	ppm	10	153	54	35
XRFFWR	BAO	Barium Oxide	%	0.01	0.02	0.01	0.01
XRFFWR	CAO	Calcium Oxide	%	0.01	0.94	2.00	1.98
XRFFWR	CR2O3	Chromium (III) Oxide	%	0.01	0.02	0.02	0.02
XRFFWR	CU	Copper	%	0.01	0.04	0.01	0.01
XRFFWR	FE2O3	Iron (III) Oxide	%	0.01	9.03	2.12	2.14
XRFFWR	K2O	Potassium Oxide	%	0.01	1.34	2.32	2.32
XRFFWR	MGO	Magnesium Oxide	%	0.01	0.73	0.42	0.41
XRFFWR	MNO	Manganese Oxide	%	0.01	0.09	0.04	0.04
XRFFWR	NA2O	Sodium Oxide	%	0.01	0.53	1.64	1.66
XRFFWR	PB	Lead	%	0.01	0.07	0.08	0.09
XRFFWR	P2O5	Phosphorus Pentoxide	%	0.01	0.06	0.02	0.02
XRFFWR	SB	Antimony	ppm	10	51	63	50
XRFFWR	SIO2	Silicon Dioxide	%	0.01	72.92	71.79	71.72
XRFFWR	SO3	Sulphur Trioxide	%	0.01	0.04	0.05	0.05
XRFFWR	SRO	Strontium Oxide	%	0.01	0.01	0.03	0.03
XRFFWR	TIO2	Titanium Dioxide	%	0.01	0.25	0.03	0.03
XRFFWR	ZN	Zinc	%	0.01	<0.01	<0.01	<0.01
XRFFWR	LOI	LOI @ 1000 DegC	%	0.01	7.02	9.58	9.48
XRFFWR	SUM	Sum of Major Oxides + LOI	%	0.01	98.99	99.25	99.05

Figure 2: Deposit analysis result.

3. EVALUATION METHOD

To evaluate the descaling process along the online cleaning program, both parties have agreed to conduct water analysis parameters before, during, and while the online cleaning process, pressure inlet and pressure outlet of the dosing pump system, and comparison between an electrical output from each ORC#A and ORC#B before and after the online cleaning process. The water sample will be collected from the discharge line after the injection of the chemicals cleaning agent. Solenis used two chemical products, GeoSol™ GS1008 as a Silica dispersant agent and GeoSol™ GS1251 as a Metal silicate-based dissolver. Both chemicals will be injected into the system intermittently based on the alkalinity level in the water system.

Brine Chemistry

Solenis's onsite technician will collect water samples from the discharge point from the online cleaning process. Dissolved silica (Si) analyses were checked periodically to assure the descaling process was happening and it will not settle down to another system.

Dissolved iron (Fe) analyses were checked on-site to assure there is no surface corrosion on the surface of the pipeline system. rates. The Fe sample was treated with nitric acid (1.5% HNO3) before the Total Fe is measured because the acid dissolves the insoluble Fe and converts it into soluble Fe. Any increase in Fe content in the surface plant shows corrosion of steel tubing. The brine pH was checked on-site using the pH meter.

We also collected the other related parameters from the brine chemistry to ensure that the descaling process happened as described in the next result.

4. RESULTS

The field evaluation was conducted for a view minutes trials process and the results are described below.

4.1 Brine Chemistry analysis results

Along with the online cleaning process, the Solenis technician was collecting samples and did analyses as below table.

Table 1: Brine chemistry analysis results along the online cleaning process.

Time	pH	Conductivity (m S)	Fe (ppm)	SiO_2 (ppm)	Al (ppm)
13:53:00	8.86	3.42	0.062	500	0.017
13:57:00	9.01	3.42	0.016	500	0.012
14:00:02	11	4.41	0.012	700	0.011
14:10:40	1.58	7.37	0.167	700	0.408
14:48:40	12.98	35.1	0.035	810	0.978
15:09:40	0.78	30.8	0.485	770	0.456
15:15:40	2.29	4.22	0.065	710	0.013
15:35:40	12.8	19.75	0.014	680	0.319
15:58:40	9.73	3.52	0.027	330	0.014

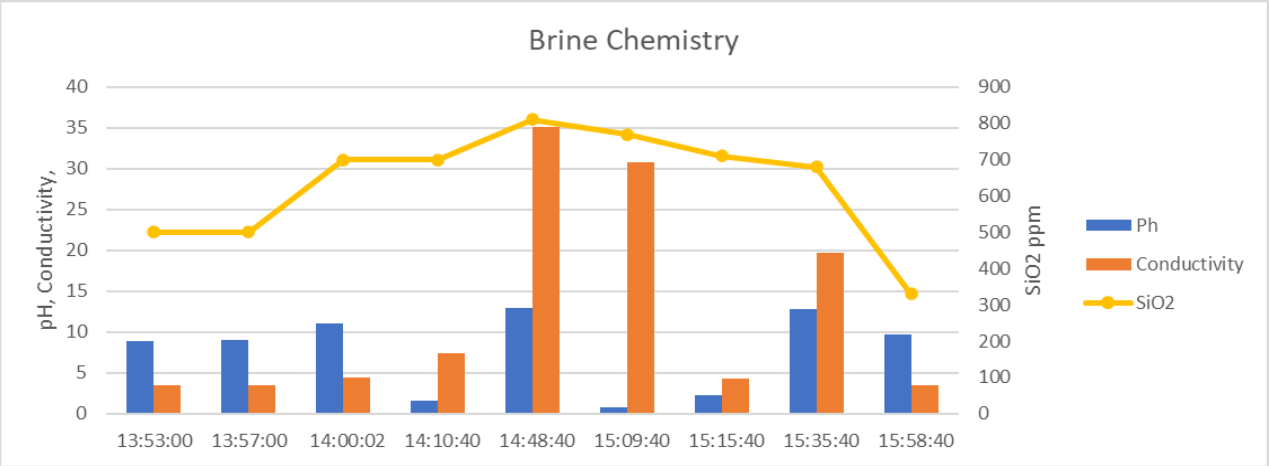


Figure 3: Brine Chemistry analysis results along the ORC online cleaning process.

When we started to inject GeoSol™ GS1008, the pH was lifted to an alkaline condition and the dissolution of silica was started on the ORC pipelines system. The highest level of silica dilution process was achieved after the 4th injection process of GeoSol™ GS1008. In the same way, the conductivity level tends to increase as the silica level was increased. We start to calculate the estimated silica removed based on the brine chemistry analysis result and flow rate indication from the process side. The silica dissolution stays in soluble condition as picture below (see Figure 4).

In another process, when injecting GeoSol™ GS1251, the pH tends to be acidic condition then metallic-based silicate starts to dissolve in the system. It was shown from the Aluminum level in the brine sample. The highest aluminum level was achieved after the 2nd injection of GeoSol™ GS1251 into the system.

The dissolved iron trend is to be stable before and after the injection of both chemicals into the system. It also shows there is no new corrosion process happening along the online cleaning process.

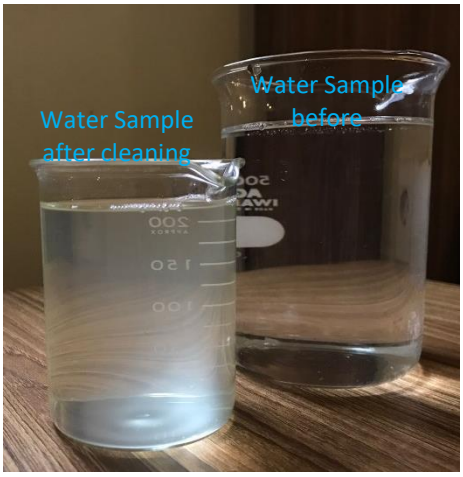


Figure 4: Water sample before and after the cleaning process.

4.2 Pressure indication at dossing pump injection system

Monitoring pressure inlet dosing skit pump as part of the indication of the descaling process along the online cleaning process. The below table (see Table 2) and figure (see Figure 4) give us the performance result of the online cleaning process.

Table 2: Inlet pressure and flow rate dosing pump skit.

Time	Inlet Pressure (Bar)	Flow (l/min)
13:53:00	23.6	464.5
13:57:00	23.4	474
14:48:40	16.5	455
15:35:40	13.8	415
15:40:40	11	425

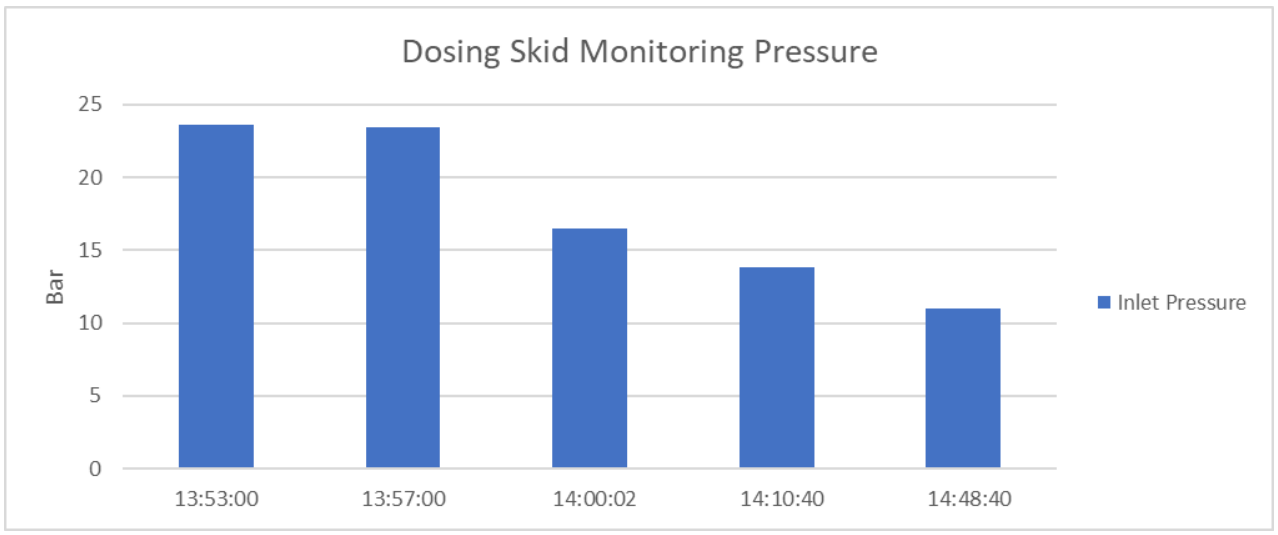


Figure 5: Inlet pressure monitoring dosing pump skit.

We found a high pressure in the inlet point during the initial injection up to 23 bar and it is reduced to 13 bar during the cleaning process, then the final pressure after the online cleaning process is shown at 11 bar.

4.3 Correlation of Silica removal and electric power generation

The primary goal of the short trial evaluation was to measure proof of concept and procedure to remove the silica scale without stopping the ORC system operation.

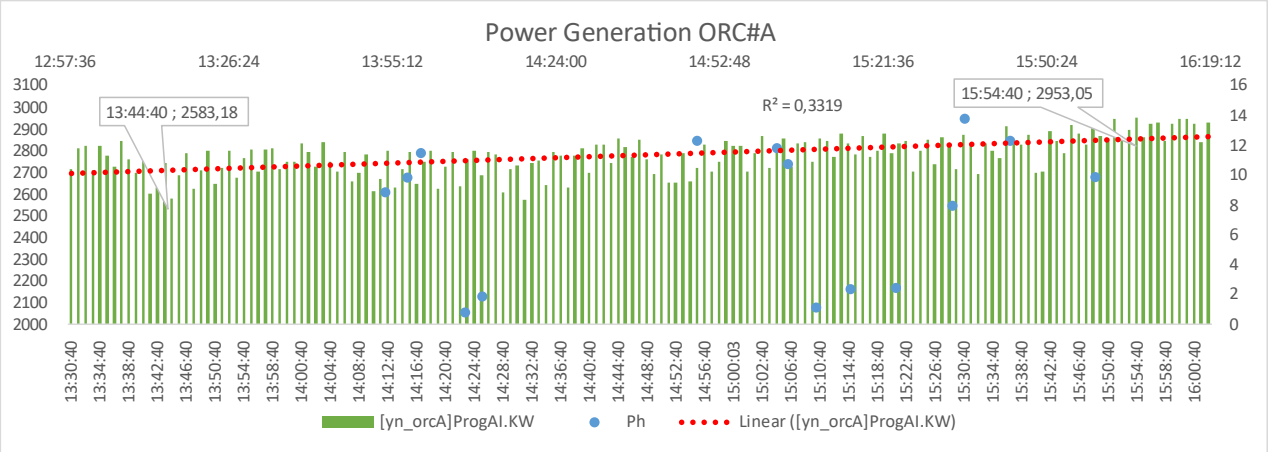


Figure 6: Power generation performance from ORC#A.

The regression line shows a moderately increasing trend of 0.3MW at ORC#A. It was lifted during the 10 mins of the online cleaning process. pH level reflecting the chemicals injection. During the high pH >10, GeoSol™ GS1008 works to dissolve SiO_2 whereas at the low pH <4, GeoSol™ GS1251 is working to dissolve Silicate based metal.

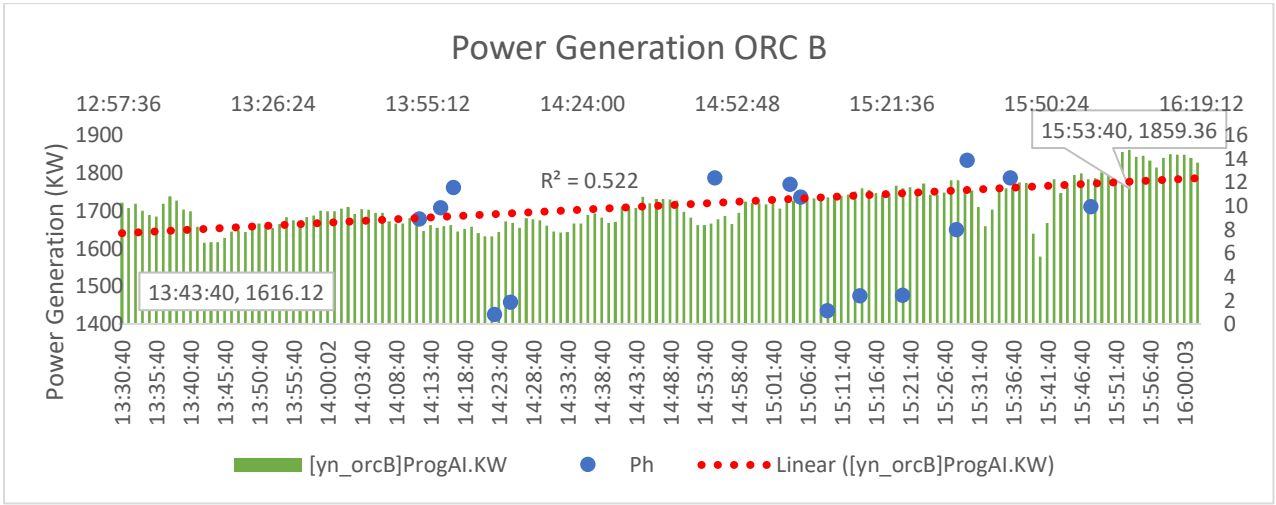


Figure 7: Power generation performance from ORC#B.

The regression line shows a moderately increasing trend of 0.2 MW at ORC#B. It was lifted during the 10 minutes of the online cleaning process.

5. CONCLUSION

Our conclusions from the field trials evaluation of the online cleaning ORC used GeoSol™ GS1008 (Silica dissolver) and GeoSol™ GS1251(Silicate based metal dissolver) are summarized as follows.

- The 10 mins online chemical cleaning process lifted production by ~36% of the last 3-day offline mechanical cleaning process.
- Based on the regression trend line, a total of 0.5 MW of electric power increased from both ORC systems.
- A total of 451 kg of silica was removed within ten minutes of operation.
- The inlet pressure dropped over 13 bars showing that the scale blocking the inlet was significantly reduced.
- The short trial was done in a small number of IBCs for proof of concept. The future action plan is to use a better rate per kg.
- Successful proof of concept needs to be applied to testing new chemicals for better performance to dissolve Aluminum silicate.

ACKNOWLEGDMENT

The authors thank the Solenis team and all data resource providers for making this technical paper complete.

REFERENCES

Gudmundsson J.S. 1983. Silica deposition from geothermal brine at Svartsengi, Iceland. Proc. Intern. Symposium on solving corrosion and scaling problems in geothermal systems, 72: 87, NACE.

Grassiani R. 1988. Scaling and corrosion in geothermal equipment: problems and preventive measures. Geothermics, 15: 839-856.

M.Hijriawan et al 2019. Organic Rankine Cycle (ORC) in geothermal power plants J. Phys.: Conf. Ser. 1402 044064.

Safe and Effective Online Cleaning Program, an Insurance for Reinjection Operation

Mona Natalia Siahaan, Rachmad Darmawan, Harita Cahyo Baskoro,
Yohanes Arifpin Nugraha, Muhamad Andhika, and Tomy Suryatama

Ecolab International Indonesia, Pondok Indah Office Tower 5, 5th Floor,
Jalan Sultan Iskandar Muda Kav V-TA Jakarta, Indonesia

Monanatalia.siahaan@ecolab.com

Keywords: Online Cleaning, Silica Removal, Silicate Removal, Chemical Cleaning

ABSTRACT

Scaling in geothermal surface facility is a common challenge that impacts the performance and longevity of the system, including in reinjection line. Once the scale has formed and impact to injectivity index, therefore, it needs to be removed. Silica scaling in geothermal systems is often treated with strong acids, such as HF and HCl. However, the use of strong acids can be corrosive, dangerous, danger in handling and environmentally harmful. Alternative methods, using redeposition agent, have been proposed to remove silica scale effectively and safely. A well-designed silica removal system can prevent scaling and optimize the plant's productivity. This study compares the observation amongst caustic + EDTA and redeposition agent treatments in removing silica scale through dissolution tests. The study involved conducting dissolution tests over 48 hours to determine the best chemical treatment that can effectively remove silica scale.

The dissolution test involves an introduction of specific chemicals to the silica scale formed in the reinjection system. The chemical is then left in contact with the scale for 48 hours. After the test period, the sample is analyzed to determine the extent of silica removal. The effectiveness of the treatment is determined by measuring the percentage of silica removed from the sample.

Redeposition agents are used in this study not to remove silica scale and meta silicate, but also to prevent for redeposition to happen by modifying the crystal structure of the scale-forming compounds. The results of the dissolution test indicate that some of the chemicals were effective in removing silica scale. However, the redeposition agent demonstrated the highest silica removal efficiency by 1796% compared to caustic with EDTA alone by 132%. The results of the dissolution test provide valuable insights into the selection of the best chemical treatment for silica removal in geothermal systems. The study can guide the optimization of silica removal systems to prevent scaling and optimize the plant's productivity. The use of the redeposition agent reduces operational costs and enhance the performance and longevity of the geothermal plant. Furthermore, the study emphasizes the need for careful monitoring of silica scaling in geothermal systems. Regular monitoring can identify early signs of scaling and prevent severe scaling problems. The development of a silica removal system can also reduce the risk of silica scaling and enhance the geothermal plant's productivity, especially since it can be done online.

1. INTRODUCTION

Scaling is a prevalent issue encountered in geothermal surface facilities, which has a significant impact on the system's performance and durability, including in the reinjection line. When scale deposits form and affect the injectivity index, they must be eliminated. When well injection capacity is reduced drastically, the well needs to be shut down (Zhang, 2022). For specific silica scale deposition, it can be conveniently formed by thermodynamics and kinetics process. The thermodynamics process provides valuable insights into the behavior of silica solutions by enabling us to predict the eventual outcome when the system reaches equilibrium. However, kinetics process seeks to explain the mechanisms and factors that influence the speed at which the system progresses towards its final equilibrium state (Brown, 2013). There are several factors contributing to silica deposition kinetics, they are degree of supersaturation, pH, temperature, flow rates, other ions, and other unknown factors.

Silica scale is difficult to remove once it formed. There are several ways to remove the scale deposit, either from mechanical or chemical ways (Monterozo et al., 2022). Mechanical methods involve physical means to remove scales from the well. These methods can be executed with or without the use of a rig, depending on the scale and complexity of the operation. Chemical methods often involve acid washing as a prevalent technique for cleaning scaled-up geothermal wells. Acid washing entails the use of specialized acid solutions to dissolve and remove the scale deposits. Acid washing aims to restore the permeability and efficiency of the well by eliminating scale obstructions. It is essential to consider the proper application, adherence to acceptance criteria, and thorough evaluation of potential risks associated with chemical methods.

In addition, according to McCartney et al. (2017) and Borrman et al. (2018), there are two widely recognized chemical approaches for silica dissolution: acid-based programs and alkaline-based programs. In acid-based programs, various chemicals are utilized, including hydrofluoric acid (HF), hydrochloric acid (HCl), and inhibited acids. Hydrofluoric acid, however, presents significant challenges. Firstly, it is highly toxic, both as a corrosive substance and as a contact poison. It can be absorbed through the skin, eyes, and inhalation. Exposure to HF can cause severe burns and damage to the nervous system, potentially resulting in cardiac failure and fatality. Moreover, HF reacts with other cations present in the system being cleaned, leading to the formation of secondary precipitates that are difficult to dissolve.

On the other hand, the alkaline program involves the use of alkaline chemicals such as caustic and caustic with EDTA. However, this approach also comes with certain risks, including:

a. Promoting the formation of metal oxides with low solubility at high pH, which can lead to scaling.
b. Selective dissolution of amorphous silica.
c. Environmental and transportation risks associated with the chemicals used.
d. The need for corrosion-resistant pumps.
e. The necessity of using condensate or fresh water due to the issue of redeposition.
f. Redeposition of dissolved materials, which can hinder the efficacy of the treatment.

To overcome these challenges, alternative approaches have been proposed for the effective and safe removal of silica scale. Several studies have explained how silica deposit can dissolve. Ueda et.al (2003) mentioned that it is crucial to remove excess silica before reinjecting. Fertani-Gmati et al. (2014) studied that using NaOH 8-11% can help to dissolve silica deposit. Chelating agents also play an important role in dissolving scale in EGS fields (Fukuda, et al., 25-29 April 2010). Conventional solution such as mixing NaOH and EDTA are effective in some ways to dissolve silica deposit.

Ecolab (Nalco Water) studies the factors that may contribute to silica deposition. In this dissolution test, methods involve removing the silica and metals, also prevent the solution from redeposition. Redeposition refers to the process where silica minerals, dissolved in brine or deposited as scale, tend to redeposit in the well or its equipment during the process of dissolution test. In the pipeline, this can lead to re-blockages and reduced well productivity. To prevent redeposition, redeposition agents are used. This specific chemical compounds as redeposition agent that can effectively inhibit the formation of new deposits or dissolve existing ones. The redeposition agents form a protective layer around silica particles, preventing them from reaccumulating on the well's surface. Selecting the right chemicals involves considering its compatibility with geothermal fluids, stability under varying conditions, and effectiveness in preventing or removing silica redeposition.

Thus, by employing these substances, a well-designed silica removal system can mitigate scaling issues and optimize the productivity of the geothermal plant. Dissolution tests will be conducted over a duration of 48 hours to determine the most effective chemical treatment for removing silica scale reliably. By identifying the best treatment option, this research will contribute to enhancing the performance and longevity of geothermal systems by addressing the persistent challenge of scaling. Moreover, by conducting this dissolution test, online cleaning in the pipeline is a safe and effective for

removing the scale and recover the reinjection effectivity without reducing or even shut down the generation.

2. DISSOLUTION TEST PROCEDURE

The test is a comprehensive procedure consisting of five distinct programs, each designed to evaluate the effectiveness of various chemicals under specific conditions (Table 1). To simulate real-world scenarios accurately, we employ a synthetic brine solution that closely replicates the actual conditions encountered in the field.

In each program, different chemicals are employed to determine their efficacy in dissolving deposits. The chemicals used in the programs are carefully chosen based on their known properties and potential for scale dissolution. These chemicals have unique compositions and mechanisms of action, allowing for a comprehensive assessment of their performance.

To initiate the test, the chemical solutions, which consist of caustic and redeposition agent, are prepared in a chemical tank by diluting the chemical agents with fresh water. It is crucial to ensure that the fresh water used is clean and exhibits low turbidity and suspended solid content to maintain the effectiveness of the cleaning process. The prepared chemical solution is injected into the system through an injection point using a 2-drum chemical system. The injection rate should be adjusted to achieve a concentration of redeposition agent and caustic following the actual total flow rate.

The experiment begins by heating synthetic brine using NaCl liquid without silica content to a temperature of 70°C (following highest SSI). This heated brine is then combined with a representative amount of scale deposit, which simulates the type of scale commonly encountered in the field. The scale itself is mostly consist as amorphous silica and aluminum silicate as it is found from the deposit analysis. Additionally, silica at a concentration of 700 parts per million (ppm) is also added into the solution. Thus, the pH level of the solution is gradually increased to a value of 12 using sodium hydroxide (NaOH). It is known that alkaline solutions are more effective than acidic solutions in dissolving scale, although the reaction itself is more complex (McCartney et al., 2017).

The chemical solutions, synthetic brine, and scale deposit are thoroughly stirred at predetermined velocities. This stirring process is crucial to facilitate effective interaction between the chemical and the scale. By ensuring proper distribution of the chemical within the solution, the dissolution process is optimized, leading to improved dissolution of the scale. Throughout the test, the dissolution process is continuously observed and monitored. We carefully record the changes in the deposit, noting the progressive dissolution of the scale over time. The observation period is predetermined and consistent across all programs, allowing for fair comparisons between different chemicals.

The test is considered complete when the entire deposit has been dissolved, indicating the successful performance of the chemical solution. The dissolution time may vary depending on the specific program and the chemical employed, providing valuable insights into the optimal conditions required for efficient scale removal. By conducting this comprehensive test, we gained valuable knowledge about the effectiveness of different chemicals in dissolving deposits. The results help inform decision-making processes and guide the selection of the most suitable chemical solutions for scale removal in practical applications.

3. EXPERIMENT RESULT AND DISCUSSION

The summary of dissolution test is shown at the table below. In the initial conditions of the experiment, which made to the real condition, the pH level is measured at 8, while the average total silica concentration is found to be 715 ppm. The levels of aluminum and manganese content are negligible at 0 ppm. Among all the tested schemes, scheme D, which is the one utilizing a chemical solution consisting of redeposition agent D at a higher dosage demonstrates the most significant silica dissolution. In comparison to the initial conditions, the silica dissolution rate is remarkably increased by 1796%. Additionally, the concentrations of aluminum and manganese content also show a notable

increase. Moreover, the weight loss from the deposit decreases by 31.4% in this scheme. By inhibiting the reformation of deposits, the efficacy of the chemical solutions in dissolving silica is enhanced.

Table 1: Summary of dissolution test.

	Result						
Parameter	**Initial Condition**	**A.1**	**A.2**	**B.1**	**B.2**	**C**	**D**
pH	8	13	13	10	10	13	13
Average Total Silica	715	1664.28	1181.78	597.6	539.98	541.5	13556.89
Average Aluminum	0	8.91	5.16	3.13	2.03	4.27	20.99
Average Manganese	0	0.89	0.57	0.77	0.80	0.18	0.57
Weight loss (%)	-	11.66	12.15	6.39	9.64	16.97	31.41
Test Condition	-	Caustic + EDTA	Caustic + Redeposition agent A	Caustic + Redeposition agent B1	Caustic + Redeposition agent B2 (higher dosage)	Caustic + Redeposition agent C	Caustic + Redeposition agent D

The second-best performing option is scheme A1, which involves the addition of both the deposit and a chemical solution containing an EDTA. This scheme results in a substantial increase of 132% in silica concentration and a weight loss reduction of 11.6%. The third option A2 involves the use of caustic combined with redeposition agent A. This scheme leads to a silica dissolution rate of 65% and a weight loss reduction of 12%.

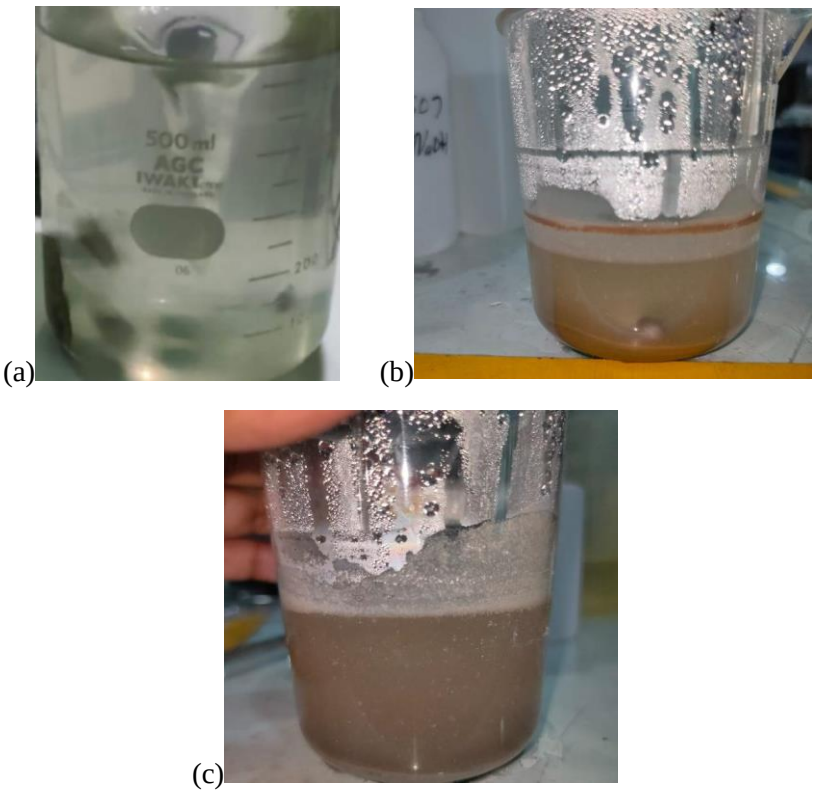


Figure 1: (a) scale deposit at the beginning of dissolution test; (b) variable D within 24 hours dissolution test with variable D within 24 hours; (c) dissolution test with variable D within 48 hours; The best result shown on Program D, with 31% deposit dissolved within 48 hours of cleaning program.

Nalco also studies the comparison between 2 (two) solutions, the 1st solution consists of caustic and EDTA, and 2nd solution, which is Nalco water program, consist of caustic and redeposition agent D, as showed the best performance in dissolution test (Figure 2). Both solutions have observed within 48 hours of experiment. As seen in the graph below, total silica from the 1st solution remains constant and for Nalco water program silica concentration is increased until certain amount of time or keep dissolved as silica solution.

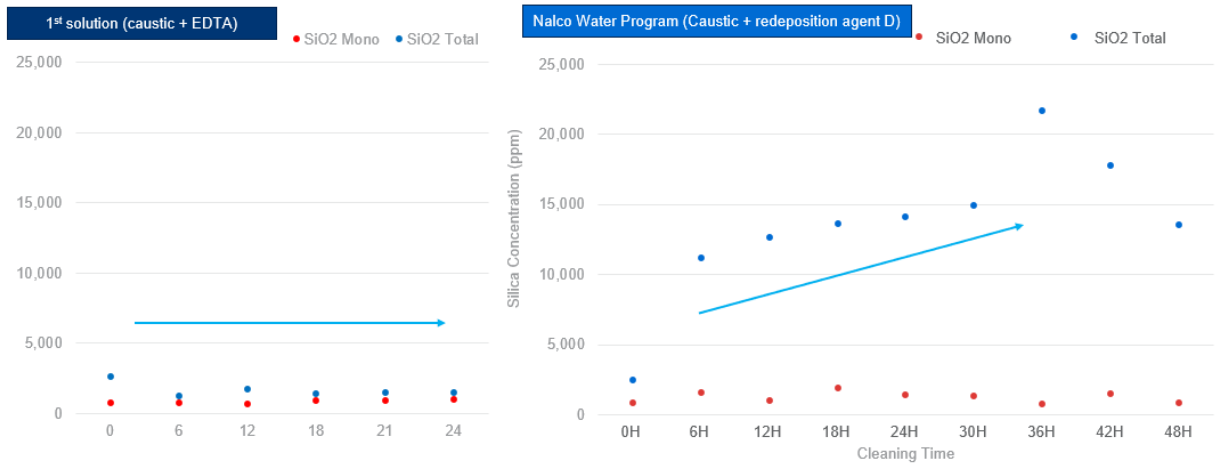


Figure 2: Silica concentration during dissolution test; (a) using caustic + EDTA and caustic (b)using caustic + redeposition agent D.

4. CONCLUSION

Nalco water has conducted an extensive dissolution test over a specific timeframe using a range of chemicals. From the experiment, it is revealed that maintaining a high pH level is crucial in effectively dissolving silica and silicates. By employing redeposition agent D, the resulting solution demonstrates an enhanced capability to dissolve deposits and facilitate the dispersion of metals. The elevated pH level in the solution promotes the breakdown of silica and silicate compounds, leading to their dissolution. This dissolution process is essential for preventing the redeposition of dissolved materials during the cleaning procedure.

The presence of these redeposition agent plays a vital role in preventing the formation of redeposits. This solution functions by inhibiting the reformation of silica and silicate scale. By impeding the redeposition process, this solution ensures that the cleaning process remains effective and long-lasting.

Overall, the combination of a high pH environment and redeposition agent creates a synergistic effect in the geothermal system. The results of the dissolution test indicate that some of the chemicals were effective in removing silica scale. However, redeposition agent D demonstrated the highest silica removal efficiency by 1796% compared to caustic with EDTA alone by 132%. This effect promotes efficient dissolution of silica and silicates, and redeposition agent D has powerful role to prevent the solutions to be redeposited. Through careful application of this scientific approach, geothermal systems can effectively manage scale-related issues and maintain optimal performance without reducing or even shutting down the generation.

During this writing, based on this dissolution test, one clean-out program has been successfully applied and increased flow more than 50%. Other clean-out programs are going to applied in other fields. However, each program needs to have its dissolution test first, before applied in the field.

REFERENCES

Borrman, T., Schweig, M., Cairns, M. J., Johnston, J. H., & Gray, A. K. (2018). Removing silica from geothermal water - Year One of Pilot Plant Operation with a Focus on Carbonate and Silica Analysis. Proceedings 40th New Zealand Geothermal Workshop.

Brown, K. (2013). Mineral Scaling in geothermal power production. Reykjavik, Iceland: UNU-GTP.

Fertani-Gmati, M., Brahim, K., Khattech, I., & Jemal, M. (2014). Thermochemistry and kinetics of silica dissolution in NaOH solutions: Effect of the alkali concentration. Elsevier, 58-67.

Fukuda, D., Watanabe, M., Arai, F., Sasaki, S., Sako, O., Matsumoto, Y., & Yamazaki, S. (25-29 April 2010). Removal of Anhydrite and Mg-Silicate Scales from Production Wells Using Chemical Agents at the Mori Geothermal Field in Hokkaido, Japan: An Application of Chemical Well Stimulation. Proceedings World Geothermal Congress 2010. Bali, Indonesia.

McCartney, T., Gharaibeh, S., & Shank, R. (2017). improved methods for removal of silica deposits. Heat Exchanger Fouling and Cleaning, 235-239.

Monterozo, F. E., Gica, G. R., & Mantri, D. (2022). Recovery of Reinjection Well Capacity Using Online Scale Dissolution. The 8th Indonesia International Geothermal Convention & Exhibition (IIGCE). Jakarta.

Ueda, A., Kato, K., Mogi, K., Mroczek, E., & Thain, I. (2003). Silica removal from Mokai, New Zealand, geothermal brine by treatment with lime and a cationic precipitant. Geothermics, 47-61.

Zhang, L., Geng, S., Chao, J., Yang, L., & Zhao, Z. (2022). Scaling and blockage risk in geothermal reinjection wellbore: Experiment. Journal of Petroleum Science and Engineering; Elsevier.

Silica Kinetics Test to Prevent Scaling in Hululais Geothermal Field

Ferdinan Rianto Sipayung, Edy Sudarmadi, and Jodhi Pramuji Giriarso

Pertamina

ferdinan.sipayung@pertamina.com, edy.sudarmadi@pertamina.com, Jodhi.Pramuji@pertamina.com

Keywords: brine, geothermal, scaling, silica

ABSTRACT

The Hululais project is one of several geothermal development fields owned by Pertamina Geothermal Energy. Hululais Field is a two-phase field located in Lebong Regency, Bengkulu Province, Indonesia. The field is projected to have 110 MW installed capacity generated from Condensing Unit and 60 MW generated from Binary Unit. Hululais production wells have an average silica content ± 750 ppm which has an impact scaling issues on production facilities. From the brine chemistry simulation, it is predicted that there are some minerals that oversaturated thus will have high deposition potential. The minerals are Silica, Iron Silicate, and Manganese Silicate.

Field testing (site stream test) was conducted to determine the method of scaling prevention. The challenge on that test were the lowest deposition in heat transfer area (highest heat transfer) and highest deposition in Central Cooling Pond (low scaling at cold reinjection facilities & reinjection wells). The chemistry that tested is combination of silica inhibitor, general metal dispersants, and metal sulfide dispersant. The chemistry combination tested with several testing conditions such as brine outlet temperature variance 90, 85, 75, 65 °C. Holding time 4 days at each temperature gradient was carried out to analyze the scaling rate on facilities. The inhibition program was Untreated (blank), pH modification, and Silica Inhibitor. The procedure of sampling and analysis were sampling, acidification, dilution, retention, and analysis. Analysis gives the % SiO2 polymerization. Desired output from the test were scaling rate < 1 mm/year, %Polymerization < 10%, and fastest deposition in Retention/Jar test/Central Cooling Pond.

The side stream test unit was designed to mimic the temperature reduction in binary power plant by reducing the brine temperature with cooling water. The temperature reduction was conducted in 2 states to duplicate both evaporator and preheater function in binary power plant. The unit has 2 parallel lines which enable conducting two tests simultaneously with different treatment programs. Testing was carried out on October 26th – December 17th, 2022. Fresh brine from HLS-G1 which represents two-phase production well (SiO2 content 839 ppm) flowed into the testing unit with adjusted inlet temperature 180 deg C.

SSI varies from 2.53 – 3.57 as an impact of decreasing temperature during testing. As the result of the test: % SiO2 polymerization for silica inhibitor is better than pH mod and untreated (blank). Both pH mod & inhibitor program delivers good results (<10%). For

scaling rate, silica inhibitor give significant improvement compares to pH mod, both program delivers good result (< 1 mm/year). % Fe reduction for silica inhibitor has significant improvement than untreated. The testing can provide the estimated cost of inhibition for operational steam field and binary unit to mitigate scaling on facilities.

1. INTRODUCTION

The Hululais geothermal field in Indonesia is in the Bukit Barisan Mountain Range, which is an NW-SE volcanic arc of Sumatra (Nurseto et al., 2021). The field is influenced by regional geological structures, including the NW-SE volcanic axis in the Hululais Volcanic Complex (HVC) (Nurseto et al., 2021). The HVC is a Quaternary volcanic complex consisting of six crown units: Bukit Resam, Suban Agung, Bukit Beriti, Bukit Gedang, Bukit Lumut, and Bukit Pabuar (Nurseto et al., 2021). The

manifestations in Hululais are distributed in accordance with the NW-SE geological structure and volcanic activity (Nurseto et al., 2021).

2. FLUID CHEMISTRY

Hululais geothermal field was identified as a volcanic geothermal system. Hydrologically, Kawah Suban Agung is interpreted as upflow. Fluid flowed relatively to the north in Semelako region that has several hot springs (Budiarjo, 2001). Temperature estimation from various geothermometers have been confirmed by development wells about 230-280 degC. Almost all fluid wells are neutral pH, some of it slightly acid. This kind of characteristic had made its silica content slightly different. In neutral fluids, silica content ranges around 580-830s ppm, in slightly acid fluid ranges around 750-950s ppm. Slightly acid fluids leached more silica from rock-mineral interaction than neutral fluids. In the graph below, shown silica content in normalized pressure each well,

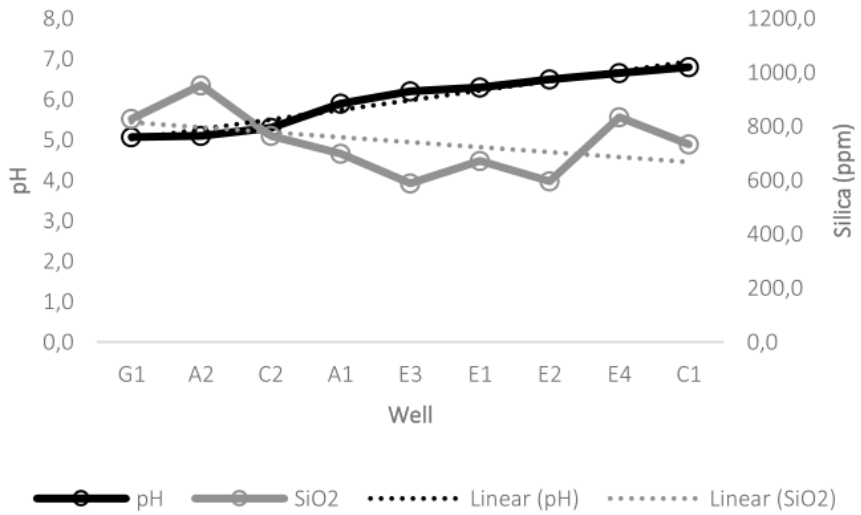


Figure 1: Fluid Chemistry of Hululais well.

3. SCALING RISK

Geothermal water contains many dissolved substances. Mineral deposition can happen when a solution approaches equilibrium and continues to do so until it is supersaturated. The existence of inhibitors, sufficient surface area for contacts, sufficient time for intermolecular interactions, and of course temperature all contributes to mineral deposition despite the abundance of dissolved chemicals (Nordstrom, 1994).

Silica is one of the substances that abundantly in geothermal brine. Its concentration depends on local lithology and its heat occurred in the fluids. Higher temperatures of fluids, higher solubility in water. Its solution is very complex and difficult to predict. Precipitation of silica mineral and/or other metal silicates mineral depends on several other factors such as pH, water chemistry and system operating condition. Polymerization of amorphous silica begins soluble breakdown then via anionic polymerization (Zuhl in Amjad, 2013) as follow:

$Si(OH)_4 + OH^- \rightarrow (OH)_3SiO^- + H_2O$

$Si(OH)_3– + Si(OH)_4 \rightarrow (OH)_3Si–O– Si(OH)_3– + OH^-$ (dimer)

Dimer → Cyclic → Colloidal → Amorphous silica (scale)

The value of the Gibbs free energy change at equilibrium is zero. The equilibrium constant (K) serves as a representation of the activity coefficient at constant temperature.

$$\Delta G_r^0 = -RT \ln K$$

The equilibrium constant of the reaction aA + bB = cC + dD in solution is,

$$K = \frac{(a_C)^c (a_D)^d}{(a_A)^a (a_B)^b}$$

Since the solute in the solid phase has an activity value of 1, only ionized solutes are used to calculate activity levels. The product solubility constant (Ksp) and the equilibrium constant are equivalent under these circumstances.

The product solubility constant (Ksp) is calculated to be proportional to the product ion activity (IAP) at equilibrium, and the ratio,

$$\frac{IAP}{Ksp} = 1, in\ equilibrium$$

Some references use logarithmic expression.

$$\log \frac{IAP}{Ksp} = 0, in\ equilibrium$$

These two kinds of expression largely acceptable, in this study, we use non-logarithmic expression.

While ion activity products (IAP) are represented by silica from analytical chemistry in laboratory. All concentration silica in ppm. The product solubility constant (Ksp) can easily calculate from amorphous silica solubility as a function of temperature as follows:

$$t°\text{C} = \frac{731}{4.52 - \log SiO_2} - 273.15$$

$$t°\text{C} + 273.15 = \frac{731}{4.52 - \log SiO_2}$$

$$4.52 - \log SiO_2 = \frac{731}{t°\text{C} + 273.15}$$

$$-\log SiO_2 = \frac{731}{t°\text{C} + 273.15} - 4.52$$

$$\log SiO_2 = -\left(\frac{731}{t°\text{C} + 273.15} - 4.52\right)$$

$$\log SiO_2 = \frac{-731}{t°\text{C} + 273.15} + 4.52$$

$$SiO_2 = 10^{\left(\frac{-731}{t°\text{C} + 273.15} + 4.52\right)}$$

The calculated scaling risk for wells G1 and A2 appears to be the highest based on the silica content of each well. According to thermodynamics, scaling is more likely to occur when there is a high silica content. The saturation index calculation can provide an initial indication of the potential of scaling in a fluid system. To be more comprehensive, we require a kinetic study that will determine silica's tendency to precipitate at a particular flow rate and temperature. We chose one of the two wells with the highest scaling risk to conduct this kinetic study as the geothermal field has not yet become operational. Due to their distance from one another and production facility, the two wells are unable to

be utilized simultaneously. Well G1 was chosen as the well to be studied for its silica kinetics due to production facility conditions.

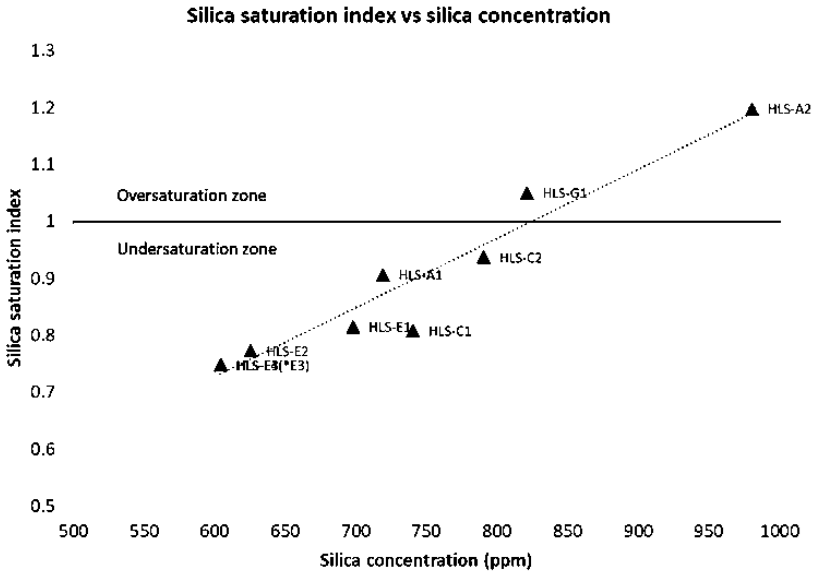


Figure 2: Silica saturation index vs silica concentration.

We utilize the Geomizer software to assess the trend of mineral precipitation when carrying out the side stream test. By changing the temperature utilized in the simulation, this application can be employed. We anticipated the precipitation of iron silicate and aluminum silicate in addition to simulating the precipitation of amorphous silica. We also adjusted the temperature in this simulation as low as possible, up to 60 degrees Celsius. This is to account for heat exchange circumstances in a binary system that permits up to that temperature. Amorphous silica tends to precipitate at low temperatures, according to the simulation results. The other two minerals, however, behave in the opposite manner. Low temperatures are the major focus in relation to the binary system implementation plan to explore the limits of where we can extract the most optimal energy.

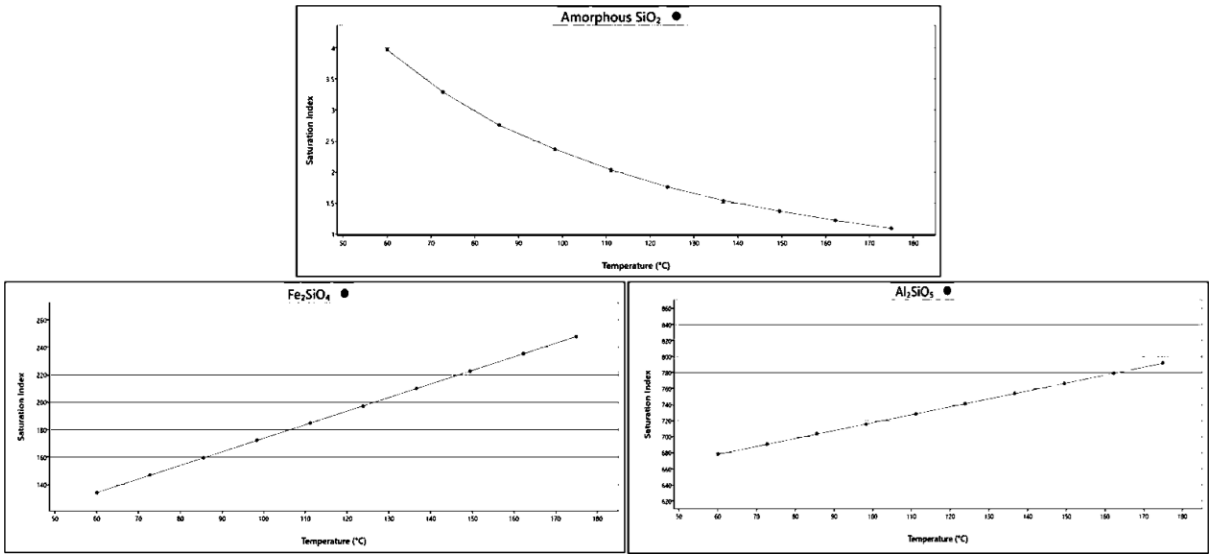


Figure 3: Geomizer simulation for Amorphous SiO2, Fe2SiO4, Al2SiO5.

4. SIDE STREAM TEST

Two phase geothermal fluid produced from HLS-G1 production well flowing to existing production test facilities. Separator set at pressure 9 barg to separate the steam and brine. The steam flowing to Rock Muffler and the brine flowing to Atmospheric Flash Tank (AFT). Brine flowing through open channel to pond brine and continue reinjected to reinjection well using reinjection pump. Production flow rate adjusted at the minimum flow to minimize the reinjected brine. Brine line on production facilities have the drain valve. Some modification was conducted at the brine line to connected the existing production test facilities to Side Stream test facilities. The tapping point modified from 2 in gate valve combined with 2 in carbon steel pipe. The outlet test facilities (brine side) tapping to the open channel and mix to the brine from AFT. At the other side cooling water transferred from pond water cooling at the existing production facilities to side stream test facilities. The outlet test facilities (cooling water side) recirculate to water cooling pond to reduce the temperature.

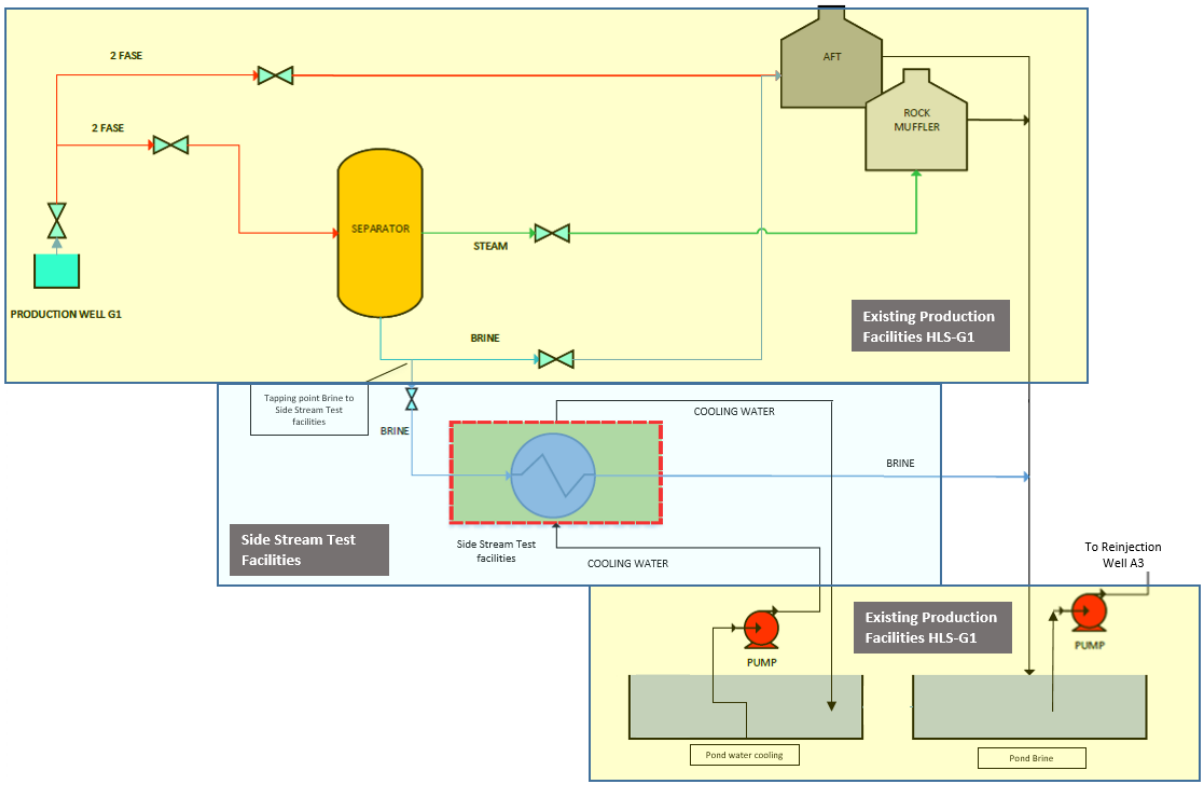


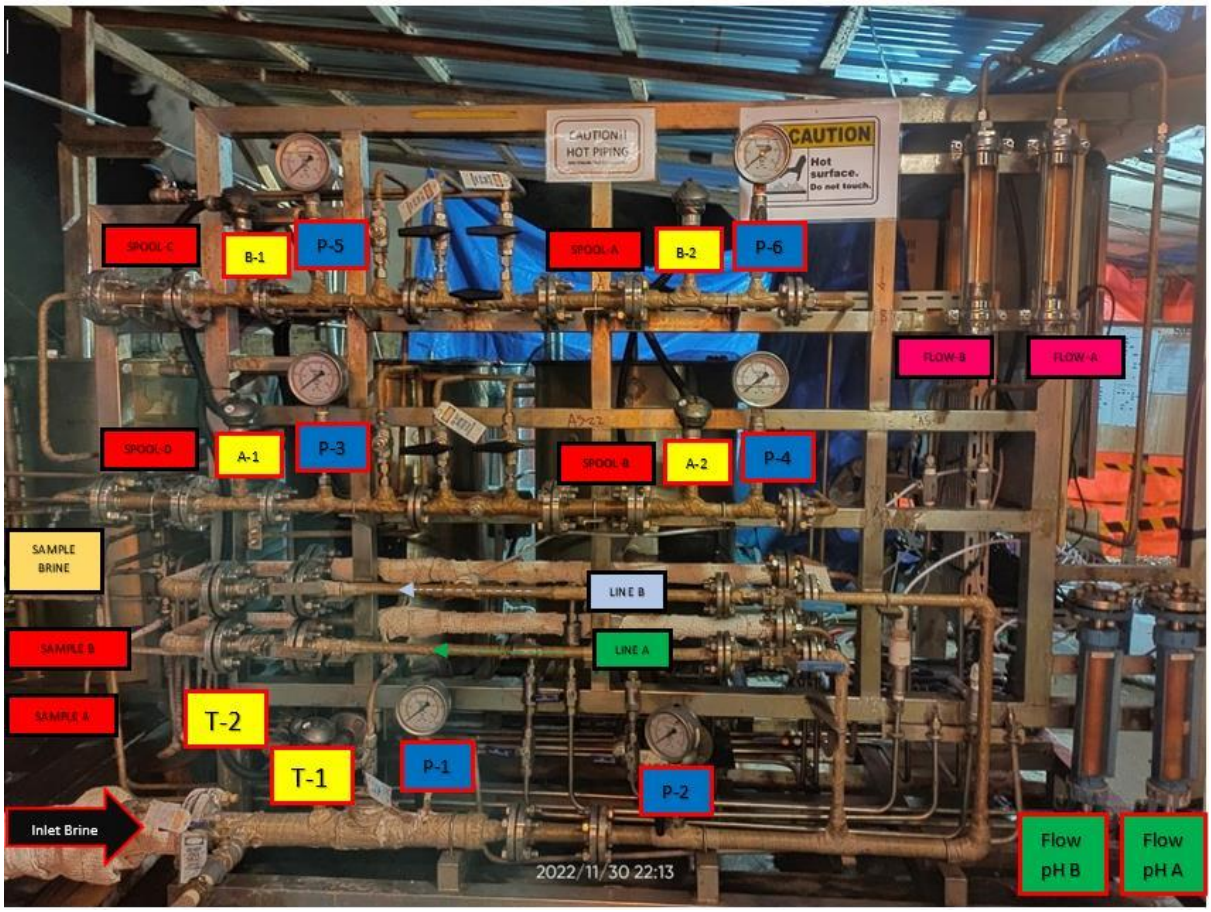
Figure 4: The schematic Equipment.

The side stream test unit is designed to mimic the temperature reduction in binary power plant by reducing the brine temperature with cooling water. The temperature reduction conducted in 2 stages to duplicate both evaporator and preheater function in binary power plant. The unit has 2 parallel lines which enable conducting two tests simultaneously with different treatment programs. The sample conditioning unit takes a continuous stream of geothermal brine, from 90 deg C in temperature. The sample supply is typically via ½" stainless steel tubing into the inlet of the test unit. This line isolated at the surface to minimize temperature loss and have a strainer to prevent any large particles entering the unit. This flow of geothermal brine then enters the sample conditioning unit and immediately splits into two lines. Each of the two streams goes through a stainless-steel tubing that is immersed in a cooling water bath. The cooling water temperature is controlled to maintain a pre-selected temperature that indirectly controls the outlet temperature of each coil. The flow through each coil is to be kept constant and is measured by flow meters and adjusted by valves on the outlet of the coils after the water bath. It is very important to keep the flowrate that through the coils are the same and daily adjustment. The unit

has a manual gauge on the brine inlet for both temperature and pressure. The unit has temperature sensors for the brine inlet, as well as at the outlet of the two coils. Each coil also has a flow transmitter.

The impact of unstable brine chemistry also shown in the trend result in each scheme and temperature variance as it may not be linear as the temperature was decreased. The chemistry condition plays an important role, and it was still not stable yet then the chemistry trend fluctuation was still occurred from brine chemistry analysis. The cooling water temperature is measured by a temperature sensor immersed in the bath. The hot incoming geothermal brine in the coils heats the cooling water and once the cooling water temperature reaches the selected cooling water temperature set-point the cooling water valve adjusted manually.

The make-up water source criteria are clean and cold which is typically water from cooling pond with the constant flow rate and able to overflows to a drain. This temperature control allows the hot geothermal brine (180 deg C) to be cooled to a consistent outlet temperature (90, 85, 75, 65 deg C) that is identical for both coils. This mimics the temperature drops across a geothermal power plant heat exchanger such as a binary plant pre-heater or series of heat exchanges. This temperature drop significantly increases the silica saturation index (SSI) and increases the rate of silica polymerization and deposit potential downstream.



T-1	TEMPERATURE INLET BRINE	P-1	PRESSURE INLET BRINE BEFORE SPOOL-E	SPOOL - A	SPOOL LINE B BEFORE FLOW - B
T-2	TEMPERATURE OUTLET WATER COOLER - 2	P-2	PRESSURE INLET BRINE AFTER SPOOL-E	SPOOL - B	SPOOL LINE A BEFORE FLOW - A
A-1	TEMPERATURE LINE A AFTER COOLER - 2	P-3	PRESSURE LINE A AFTER COOLER - 2	SPOOL - C	SPOOL LINE B AFTER COOLER - 2
A-2	TEMPERATURE LINE A BEFORE FLOW-A	P-4	PRESSURE LINE A BEFORE FLOW-A	SPOOL - D	SPOOL LINE A AFTER COOLER - 2
B-1	TEMPERATURE LINE B AFTER COOLER - 2	P-5	PRESSURE LINE B AFTER COOLER - 2	pH - A	NILAI pH LINE A
B-2	TEMPERATURE LINE B BEFORE FLOW-B	P-6	PRESSURE LINE B BEFORE FLOW-A	pH - B	NILAI pH LINE B

Figure 5: Side Stream Test unit installed on Hululais Field.

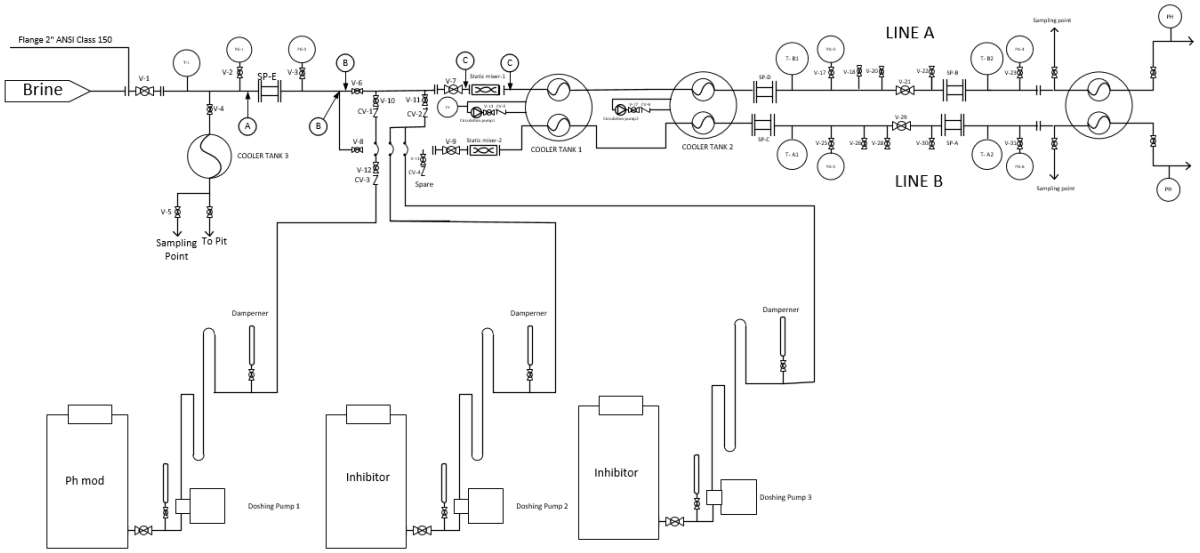


Figure 6: Schematic Piping & Instrumentation Diagram side stream test.

This side stream project located on Cluster G (HLS-G1) and conducted on some scheme variance that will change every period (depends on scheme) as below:

- Scheme 1: Blank vs pH Mod (with 4 temperature variances (90, 85, 75 & 65 deg C that change every 4 days). The test for Scheme 1 is being conduct Between October 26 – November 13, 2022, by keeping the constant outlet temperature 90, 85, 75 & 65 deg C, temperature variance will change after 4 days with constant pressure (8.6 Barg), and constant flow rate (300 L/hr). The treatment of this scheme is using pH Mod. For the pH Mod on Scheme 1 we maintain on 4.2 – 4.6.
- Scheme 2: Blank vs Silica Scale Inhibitor (with 4 temperature variances (90, 85, 75 & 65 deg C that change every 4 days). The test for Scheme 2 is being conduct Between November 14 – 30, 2022 by keeping the constant outlet temperature 90, 85, 75 & 65 deg C, temperature variance will change after 4 days with constant pressure (8.6 Barg), and constant flow rate (300 L/hr). The treatment of this scheme is with silica inhibitor consisting of Inhibitor A 14 ppm (silica inhibitor) & Inhibitor B 5 ppm (metal dispersant). The silica inhibitor on scheme 2 the pH on the range of 6.2 – 6.8.
- Scheme 3: pH Mod vs Silica Scale Inhibitor + Inhibitor C (with 2 temperature variance (90 & 65 deg C that change every 4 days). The test for Scheme 3 is being conduct between Dec 01 – 09, 2022 by keeping the constant outlet temperature 90 & 65 deg C, temperature variance will change after 4 days with constant pressure (8.6 Barg), and constant flow rate (300 L/hr). The treatment of this scheme is with silica inhibitor consisting of Inhibitor A 14 ppm (silica inhibitor) & Inhibitor B 5 ppm (metal dispersant) + Inhibitor C vs pH Mod. The silica inhibitor on Scheme 3 the pH on the range of 6.2 – 6.8 and for the pH mod the pH maintains on 4.2 – 4.6.
- Scheme 4: Blank vs Silica Scale Inhibitor (increase dosage) (with 2 temperature variance (90 & 65 deg C that change every 4 days). The test for Scheme 4 is being conduct between Dec 10 –17, 2022 by keeping the constant outlet temperature 90 & 65 deg C, temperature variance will change after 4 days with constant pressure (8.6 Barg), and constant flow rate (300 L/hr). The treatment of this scheme is with silica inhibitor consisting of Inhibitor A 14 ppm (silica inhibitor) & increase dosage of Inhibitor B to 10 ppm (metal dispersant). The silica inhibitor on Scheme 4 the pH on the range of 6.0 – 6.5.

Table 1: Scheme variance for line A and line B, duration, pressure inlet, temperature inlet and temperature outlet.

Parameters	Scheme 1	Scheme 2	Scheme 3	Scheme 4
Line A	pH Mod	Inhibitor	Inhibitor	Inhibitor
			Cheleating Agent	(Increase Dosage)
Line B	Untreated	Untreated	pH Mod	Untreated
Testing Time	26 Oct - 13 Nov 2022	14 - 30 Nov 2022	1 - 9 Dec 2022	10 - 17 Dec 2022
Temp Inlet	180 deg C	180 deg C	180 deg C	180 deg C
Pressure Inlet	8,6 Barg	8,6 Barg	8,6 Barg	8,6 Barg
Temp Outlet	90, 85, 75, 65 deg C	90, 85, 75, 65 deg C	90, 65 deg C	90, 65 deg C

5. RESULT

Silica saturation index increased over decreasing temperature. Decreasing 25 degC had increased silica saturation index from 2.53 to 3.57. This effect commonly occurred because silica solubility depends on their system temperature. Without any treatment, we can see that deposition rate had over best practice threshold between 1,7-3,09 mm/year. Treatment with pH modification, in temperature 90 and 85 degC apparently has shown different behavior with the lower temperature. Treatment with inhibitor A 14 ppm + B 5 ppm has the best result with only averagely one to three times maintenance a year and lower cost than other treatment.

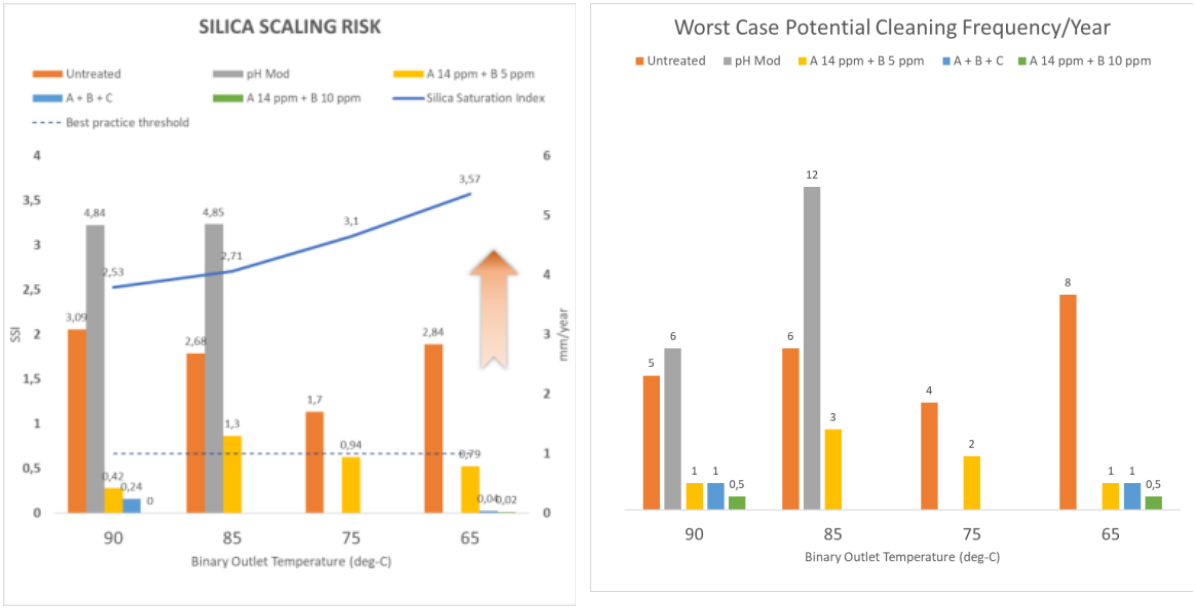


Figure 7: Silica Scaling Risk and Worst case potential cleaning Frequency/Year.

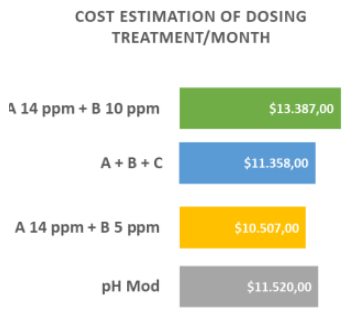


Figure 8: Cost Estimation of dosing treatment/month.

6. DISCUSSION

Over time there's a fluctuation (tends to decrease) on brine chemistry from HLS-G1 as we can see on figure 9. This could be due to one of the reasons that brine chemistry from HLS-G1 is still not stable in chemistry, it takes longer time for continuous flowing so that the chemistry is more stable. This fluctuation can be the factor of why the test result on some variation didn't get the linear conclusion.

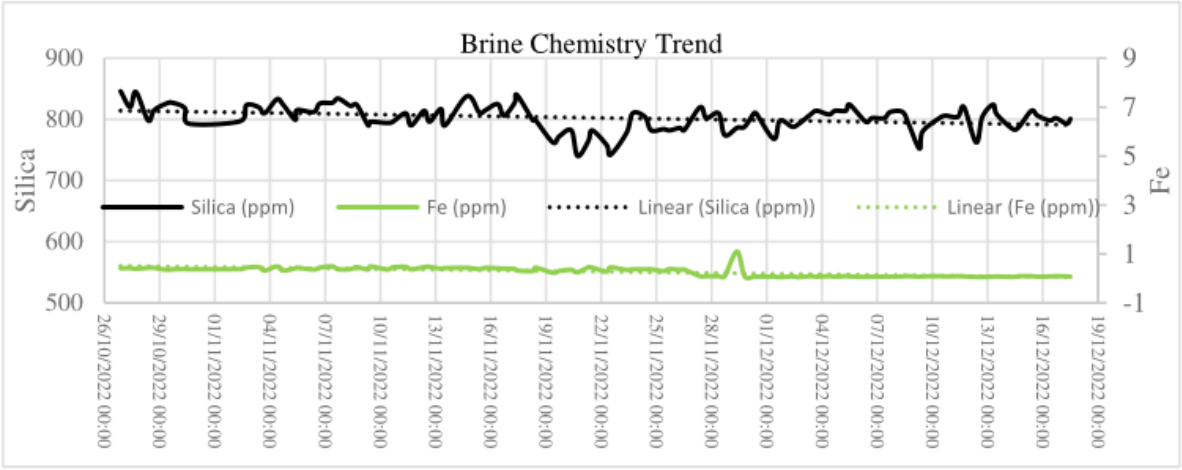


Figure 9: Brine Chemistry Trend.

7. CONCLUSION

To ensure the reliability of operation through minimizing the scale deposition, chemical inhibition program should be implemented. The cost of chemical inhibition program is varied and highly dependent on target outlet temperature, brine flow rate, and total silica concentration. Silica inhibitor provides the best scaling risk but will have an impact to the operational costs.

REFERENCES

Budiarjo, 2001

Nordstrom, 1994

Nurseto et al., 2021

Zuhl in Amjad, 2013

Slim Hole Drilling Performance Evaluation for Geothermal Exploration in Nage Field, Eastern Indonesia

Charlotte T. Mandagi[1], Darnisa Azzahra Nasution[1], Huda Nahrudi Ilham[1], Redha Bhawika Putra[2], Rizki Davidtri[2], Arif Munandar[3], and Robertus S. L. Simarmata[3]

[1]Arka Data Pratama, Gandaria Utara, Kebayoran Baru, Jakarta Selatan, 12140, Indonesia
[2]Jakarta Drilling Society, Gandaria Utara, Kebayoran Baru, Jakarta Selatan, 12140, Indonesia
[3]Pusat Sumber Daya Mineral, Batubara, dan Panas Bumi, Regol, Bandung, 40254, Indonesia

charlotte.tiffany@arkadata.net

Keywords: drilling, exploration, geothermal, slim hole

ABSTRACT

In 2021, the government of Indonesia has set a target to increase its geothermal power capacity to 3355 MW by 2030. However, only around 2347 MW have been achieved by 2022, indicating that substantial investments and development in the sector will be necessary to reach the remaining target.

As the country continues to develop its geothermal resources, slim hole drilling is expected to play an increasingly important role in the industry. Slim hole drilling is one of the choices that can be taken to verify the condition of geothermal reservoirs in the potential area. Slim hole drilling requires smaller rig requirements and has a smaller footprint compared to big bore drilling, enabling more flexibility in terms of location and maneuverability. As a result, slim hole drilling can be a more cost-effective option compared to big bore drilling methods, making it an attractive choice for exploration projects with budget constraints.

Based on the slim hole drilling activities conducted for geothermal exploration in Nage Field, Eastern Indonesia, between 2021 and 2022, several challenges were encountered, which led to a prolonged drilling time. Fortunately, the extended duration of this project did not impact the cost, as it was based on a lump sum payment. However, the extended duration of the drilling activities exceeded the planned timeline by more than 200%, indicating a significant need to optimize the drilling time. This paper will identify the problems that occurred during the slim hole drilling activities in the Nage field and analyze areas where improvements can be made to enhance the effectiveness and efficiency of future slim hole drilling projects.

1. INTRODUCTION

Geothermal energy is a renewable energy that has the potential to play a significant role in meeting the world's energy demands. While conventional drilling methods have been used for geothermal exploration, slim hole drilling has emerged as an alternative with the purpose of cost-effectiveness and efficiency.

In this paper, we will evaluate the performance of a slim hole drilling that has been done in the Nage field, Eastern Indonesia in 2021. We will present a comprehensive analysis of the technical aspects of slim hole drilling and compare the actual drilling operation with the ideal slim hole drilling performance from the literature study. This paper aims to provide valuable insights and lessons learned from previous experience to enhance the efficiency, effectiveness, and success rate of future slim hole drilling projects.

In this potential geothermal field, two wells were initially planned for drilling. The first well failed at a shallow depth, which led to the plug and abandons the well. Consequently, an additional well was drilled to replace the first well. Later, the planned second well (which become the third well) was drilled and did not reach the intended target depth. Therefore, only one well considered success in terms of meeting the planned drilling objectives. This well become the focus of this paper.

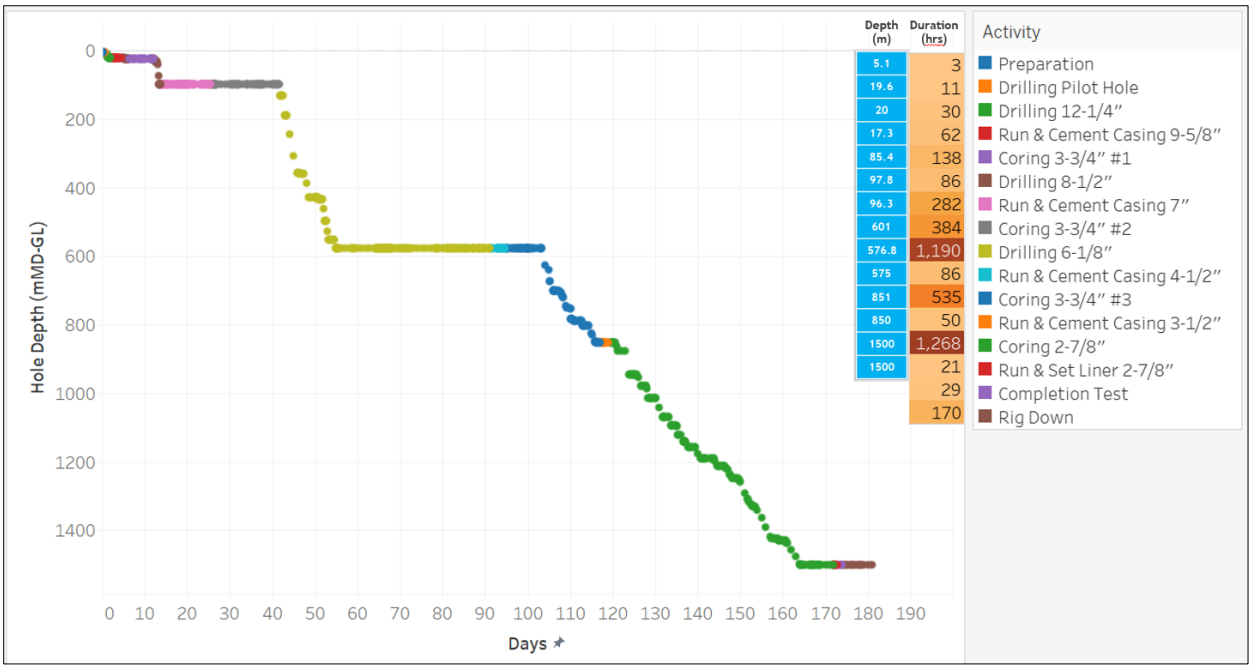


Figure 1: Day vs Depth Chart of Slim Hole Drilling in Field Nage.

In this slim hole drilling project, the drilling process was conducted in several stages to reach the target depth. The stages and their respective details are shown in Figure 1. There were five hole sections drilled down to a total depth of 1500 m.

2. METHODOLOGY

The data used in this research was sourced from the Daily Drilling Report (DDR) of a slim hole geothermal well in the Nage field. A total of 180 days of data were input and visualized using the Arka Data Dashboard, enabling the generation of valuable insights and an organized database for analysis. The research focuses on two key areas: Drilling Performance and Operation Problems.

Several steps will be undertaken to evaluate the slim hole drilling performance in the Nage field. Firstly, a literature study will be conducted to gain a comprehensive understanding of general slim hole drilling performance. Secondly, a detailed analysis of the identified problems indicated by the official non-productive time (NPT), will be carried out. Thirdly, an analysis of the productive time (PT) will be conducted to identify areas where performance improvement is possible. Fourthly, a comparison of slim hole drilling in Nage with other slim hole drilling in Indonesia will be presented to seek the best performer and insight that can be obtained from the operation. Lastly, recommendations for effective and efficient future slim hole drilling projects can be derived from the insights obtained through the previous analyses.

3. LITERATURE STUDY

3.1 Slim Hole Drilling Performances

Slim hole drilling has been used in different fields in Indonesia, but complete and publicly accessible information on these projects may be limited. However, the Darajat field stands out as an example where detailed information on slim hole drilling has been made available.

Riza and B. R. Berry (1998) summarized the performance of slim hole drilling in the Darajat field. One of the successful slim hole wells in Darajat reached a depth of 1438 m and was completed within a period of 56 days without encountering any hole problems. The achievement mentioned can be attributed to the lessons learned from previous wells. They decided to abandon coring in the 6-1/8" section, which proved to be beneficial in reducing the drilling time for this particular well and subsequent wells. This strategic adjustment significantly impacted the efficiency of slim hole drilling

operations in the Darajat field. According to Mackenzie et al. (2017), the average drilling rate for a slim hole drilled in the Darajat field was 39 days per 1000 m.

Another publication on slim hole drilling experiences is by Wilmarth et al. (2017), which focused on drilling activities conducted in Karkar, Armenia. According to their research, they successfully drilled two exploration slim hole wells and reached a depth of approximately 1600 m. The first well was completed in 76 days, while the second well was completed in 46 days. Notably, both wells were fully rotary drilled, eliminating the need for coring operations. In average, the slim hole drilling rate in Karkar was 38 days per 1000 m.

3.2 Slim Hole Drilling Schematics in Indonesia

In a study conducted by Jesslyn et al. (2022), it was observed that the majority of slim holes commenced with 13-3/8" and 9-5/8" conductor casings. Subsequently, casing sizes of 7", 4-1/2", and 2-7/8" were utilized. Regarding coring operations, it was noted that coring was performed at various depths, with some wells utilizing coring in the shallow zones while others focused on coring in the deeper zones.

3.3 Benefits and Challenges

According to Hosein et al. (2019), Mackenzie et al. (2017), and Abdirisak (2015), slim hole drilling offers several benefits and presents some challenges. Here are the key benefits and challenges of slim hole drilling:

Benefits of slim hole drilling:

- Cost savings: slim hole drilling requires fewer materials, equipment, and drilling fluids compared to conventional drilling, resulting in cost savings during the drilling process. Typically 25-40% of conventional wells.
- Reduced environmental impact: slim hole wells have a smaller surface footprint, minimizing the disturbance to the surrounding environment during drilling operations.
- Infrastructure:
    - Well pad size approximately 40 x 40 m, while the conventional drilling 100 x 70 m.
    - Access road of single lane track while the conventional drilling 2 lane road with no steep grades.

Challenges of slim hole drilling:

- Directional control: commonly slim hole well is vertically drilled.
- Increased risks of stuck: small tolerances between the drilling string and the hole due to the reduced size of the wellbore can increase the risk of stuck.
- Equipment compatibility: the smaller size and dimensions of slim hole equipment can result in limitations or difficulties in finding compatible equipment, potentially leading to issues such as drill string failures or tool joint failures.

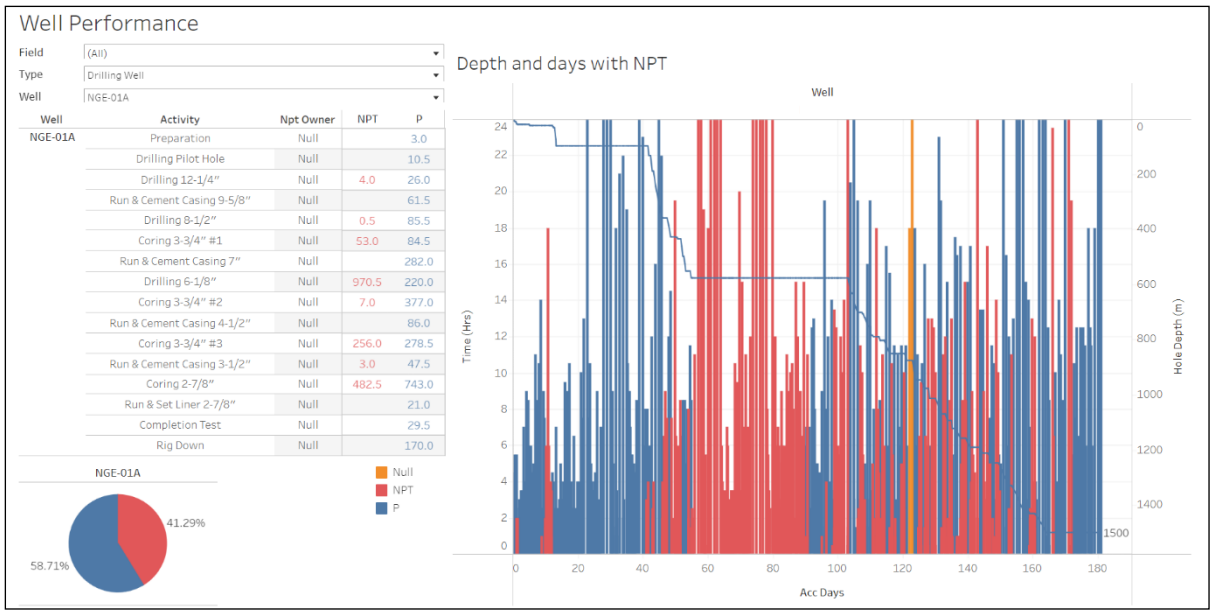
4. NON-PRODUCTIVE TIME ANALYSIS

To identify the non-productive and productive time, a total of 180 daily drilling reports (DDR) were inputted and visualized using the Arka Data Dashboard. While seems complex, the process only takes minutes with this machine. Figure 2 displays the results of DDR visualization.

Figure 2 shows the activities of drilling a slim hole well in the Nage field, which has been divided into 16 distinct activities. Each activity is labeled with its corresponding duration and classified as either 'productive time' (P) or 'non-productive time' (NPT) as indicated in the DDR. Additionally, the pie chart in the bottom left shows the percentage of total productive and non-productive durations during the drilling of the slim hole well.

The bar chart in the right figure represents the activity of each row in the DDR, with the length of each bar corresponding to the duration of the activity. This feature simplifies analysis, as hovering over a bar automatically displays its corresponding description. The blue bars indicate productive time, while the red bars indicate non-productive time.

According to the information presented in Figure 2, this well was completed within 180 days and reached a total depth of 1500 m. The NPT percentage is approximately 41% of the total drilling time, which contributes 74 days of non-productive activities throughout the drilling process.



Well	Activity	Npt Owner	NPT	P
NGE-01A	Preparation	Null		3.0
	Drilling Pilot Hole	Null		10.5
	Drilling 12-1/4"	Null	4.0	26.0
	Run & Cement Casing 9-5/8"	Null		61.5
	Drilling 8-1/2"	Null	0.5	85.5
	Coring 3-3/4" #1	Null	53.0	84.5
	Run & Cement Casing 7"	Null		282.0
	Drilling 6-1/8"	Null	970.5	220.0
	Coring 3-3/4" #2	Null	7.0	377.0
	Run & Cement Casing 4-1/2"	Null		86.0
	Coring 3-3/4" #3	Null	256.0	278.5
	Run & Cement Casing 3-1/2"	Null	3.0	47.5
	Coring 2-7/8"	Null	482.5	743.0
	Run & Set Liner 2-7/8"	Null		21.0
	Completion Test	Null		29.5
	Rig Down	Null		170.0

Figure 2: Well Performance Visualization on Arka Data Dashboard.

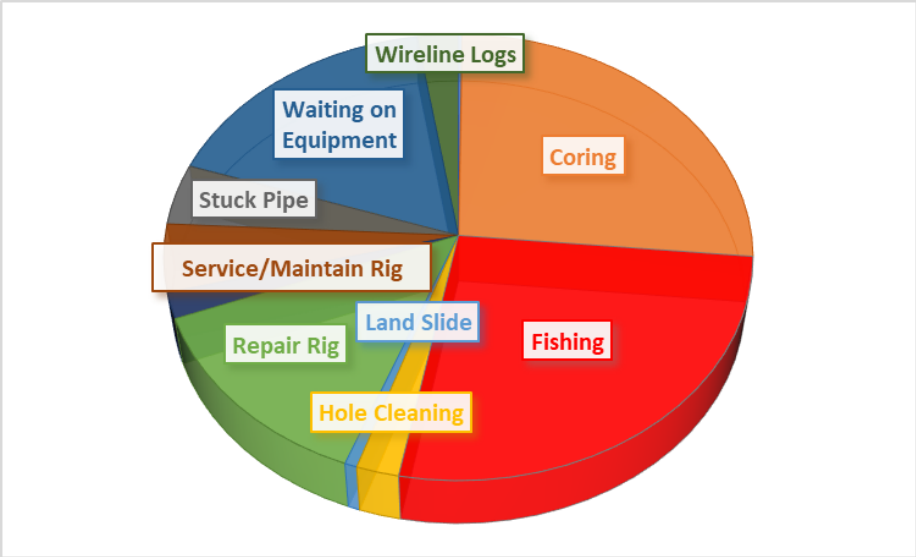


Figure 3: NPT Breakdown.

The detailed non-productive time (NPT) data was further analyzed to conduct a comprehensive analysis, as presented in Figure 3. The main objective of this analysis is to compare the duration of non-productive time for each NPT cause and to perform a more comprehensive evaluation of the top NPT contributors. Based on the findings from Figure 3, the main NPT contributors were identified as fishing, coring, waiting on equipment, and repairing the rig.

- Fishing

  The fishing operation was done while enlarging the 6-1/8" hole due to: 1. Broken connection between 4-3/4" DC and 6" String Stabilizer; and 2. Broken Floating Shaft TDS and loose

connection between TDS with 3-1/2" DP. This operation contributes 11% to the total days of drilling and 26% of the total NPT.

Tool joint failure is one of the problems in slim hole drilling. Because of small and thin tubular and joints, they are inherently weaker and tend to twist-offs, particularly in deeper holes. (Zhu & Carroll, 1994)

- Coring

  The reason for NPT due to coring is the failure in retrieving the inner tube, which led to work pipe operation. This operation contributes 11% to the total days of drilling and 26% of the total NPT.

- Waiting on Equipment and Repairing the Rig

  The NPT reason is due to waiting on the equipment as follows: Fishing Equipment, Floating Shaft TDS, PTS Tool, and Fabrication of x/o Running Tool Casing Spear to NQ Rod.

  Mud Pump and Top Drive System (TDS) are the main contributors to the repair rig NPT. The repair of the Mud Pump accounted for approximately 120 hours of downtime. The Top Drive System (TDS) repair duration was 59 hours.

5. PRODUCTIVE TIME ANALYSIS

The objective of the analysis is to compare the duration of productive time for each activity and to investigate further if any activity takes an unusually long time. According to Figure 2, the top three most time-consuming productive activities are Coring 2-7/8", Coring 3-3/4" #2, and Running Casing 7".

- Coring 2-7/8”

  This particular section is the longest in the well and faced various challenges during the drilling process. Interestingly, some of these challenges were categorized as productive time in the report, including issues such as tool joint leaks, difficulties in retrieving the inner tube, and broken strings.

- Coring 3-3/4” #2

  Coring 3-3/4” #2 was carried out in the 6-1/8” hole section, and the second longest section in this well. There were several problems labeled as productive time, which were mainly caused by attempts to retrieve the inner tube.

- Running Casing 7”

  The running casing encountered several obstructions that required actions to deepen it through work on the casing.

The analysis of productive time also involves evaluating the rate of penetration (ROP) during coring to identify potential areas for improvement. The actual ROP of coring in this well will be compared to the ROP reported in the literature study. Figure 4 presents the 3-3/4” coring ROP of this well.

According to Rachmadani et al. (2021), the maximum rate of penetration (ROP) for 3-3/4" coring using a full coring rig is reported to be 1.56 m/h. Figure 4 illustrates that the ROP for all the 3-3/4" coring activities in this well falls below the values reported in the literature study. This suggests that there is room for improvement in terms of ROP in future coring operations.

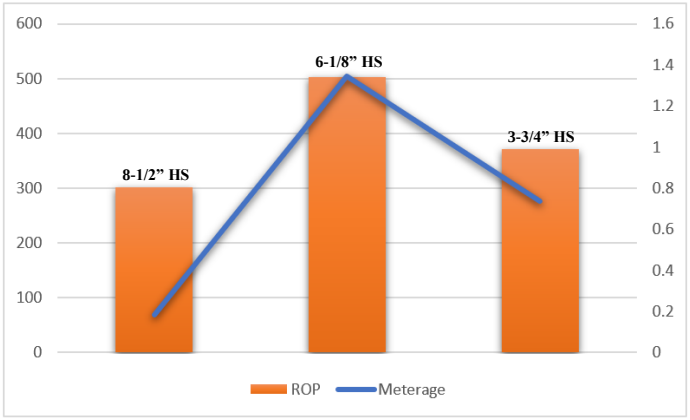
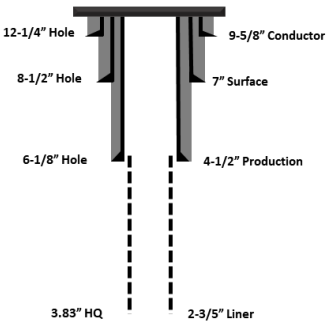
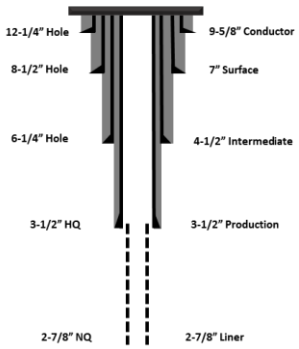
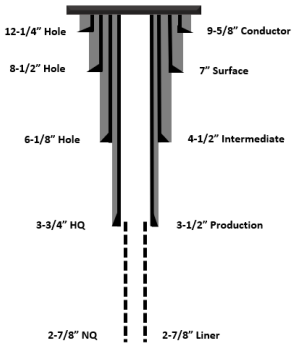


Figure 4: 3-3/4" Coring ROP of slim hole drilling in Nage field.

6. COMPARISON WITH THE DRILLING OF OTHER SLIM HOLE WELL IN INDONESIA

Slim hole drilling in the Nage has several similarities and differences with other slim hole drilling conducted in the Darajat and Ijen. Table 1 summarizes the drilling summary of those three slim hole drilling performances.

Table 1: Comparison of Slim Hole Drilling in Indonesia.

Description	Darajat	Ijen	Nage
Rig Type	Multipurpose Rig	Multipurpose Rig	Multipurpose Rig
Well Schematic			
Drilling Methodology	Rotary drilling until 6-1/8" section, continue with continuous coring to the total depth.	12-1/4" section was rotary drilled, continue with coring and drilling enlargement until 6-1/4" section, continue with full coring to the total depth.	Coring and continue with drilling enlargement until 6-1/8" section, continue with full coring to the total depth.
Total Depth (mMD)	1684 (avg 6 wells)	2000	1500
Total Duration (days)	61 (avg 6 wells)	169	180
Overall ROP (m/day)	27.5	11.8	8.3
Problems Encountered (Drilling)	lost circulation, fishing job	stuck pipe, rig equipment failure, total lost circulation	stuck pipe, fishing, rig equipment failure, total lost circulation
Problems Encountered (Coring)	high torque, unstable formation, fishing, total lost circulation, H2S gas		

Based on Table 1, all slim hole drilling began with the same section, a 12-1/4" hole, and cased with a 9-5/8" casing as the conductor casing. The next section was an 8-1/2" hole which was cased with a 7" casing as the surface casing. The hole continued with a 6-1/8" or 6-1/4" hole cased with 4-1/2" casing as the production casing in Darajat, while in Ijen and Nage as the intermediate casing. The next hole was HQ as the production zone in Darajat, while in Ijen and Nage it was cased with production casing. In Ijen and Nage, the hole was continued with NQ as the production zone. Those 3 slim hole drilling had a similar well configuration, but only one which stand-out as the best performer, slim hole drilling in the Darajat field.

The configuration of slim hole well in Darajat was fewer than the others, with the deepest well in this field reaching a total depth of 2275 mMD. While slim hole wells in Ijen and Nage require more sections to reach approximately the same total depth. The well schematic design is one of the factors that affect drilling performance, the more the hole section of a well, the longer the drilling duration.

The methodology of Darajat slim hole drilling utilized rotary drilling down to a 6-1/8" hole section and continued to perform continuous coring only at the production zone (HQ hole). The slim hole drilling in Ijen and Nage performed continuous coring from the first section down to the total depth and require hole enlargement using rotary drilling for the upper sections. This drilling methodology influences the drilling duration as the coring ROP is slower than rotary drilling and enlargement drilling for the upper section also requires more time to complete the section.

7. RECOMMENDATION FOR FUTURE SLIM HOLE DRILLING

Based on the analysis of the slim hole drilling performance, several recommendations can be derived to eliminate problems and improve productive time:

- Avoid Tool Joint Failure
    - Conduct a technical meeting before the drilling operation to inform the maximum parameter that can be applied safely within the technical limitations of the equipment (tool joint).
    - Seek high-quality tubular with strong material properties to withstand the drilling environment and reduce the risk of equipment failures.
- Equipment Spare Parts
    - Stock more spare parts for the equipment that has frequent problems.
    - Stock complete fishing equipment to be able to fish all of the BHA tool joints.
- Optimize Coring Practices
    - Evaluate the necessity of coring to reduce drilling time.
    - If required, consider coring in the deep sections only, where it is most critical for reservoir and geological evaluation.
    - Seek efficient coring techniques and equipment to maximize core recovery and minimize time spent on coring operations.
- Optimize Coring ROP
    - Evaluate the parameter of efficient coring:
    - There is a critical RPM that stabilized the coring process. If the applied RPM is less than the critical RPM, hence the coring might be slow because of a whirl.
    - Find optimum weight on bit (WOB) by conducting a drill-off test.

8. CONCLUSION

Slim hole drilling can be an alternative for efficiently evaluating reservoir conditions. However, the performance of slim hole drilling in Indonesia is currently not meeting the standards mentioned in the literature study, indicating the need for significant improvements. A comprehensive analysis of a slim hole drilling in the Nage Field was carried out, as the drilling process for this specific well took a considerable amount of time, spanning 180 days. To enhance operational efficiency, the research aims to address this issue by focusing on two key areas: reducing non-productive time (NPT) and optimizing productive time (PT). Based on the aforementioned objectives, the following general recommendations

can be made for future slim hole drilling projects: 1. Avoid Tool Joint Failure; 2. Stock Equipment Spare Parts; 3. Optimize Coring Practices; and 4. Optimize Coring ROP.

REFERENCES

Abdirisak (2015). Analysis of Slim Hole Drilling Operations. Norway: University of Stavanger.

Hosein et al. (2018). The Viability of Slim-Hole Drilling Onshore Trinidad. Trinidad: Journal of Petroleum Exploration and Production Technology.

Jesslyn et al. (2022). Summary of Geothermal Slimhole Drilling Operation in the Last 10 Years: Lessons Learned for Geothermal Exploration in Indonesia. California: 47th Workshop on Geothermal Reservoir Engineer.

Mackenzie et al. (2017). Use of Deep Slimhole Drilling for Geothermal Exploration. Jakarta: The 5th Indonesia International Geothermal Convention & Exhibition.

Rachmadani et al. (2021). Full Coring Drilling Operation Analysis to Improve the Exploration Drilling Performance of Geothermal Slimhole. California: 46th Workshop on Geothermal Reservoir Engineer.

Riza and B.R. Berry. (1998). Slimhole Drilling Experience at Darajat Geothermal Field, West Java, Indonesia. Jakarta: 20th NZ Geothermal Workshop.

Wilmarth et al. (2017). Karkar, Armenia – Slimhole Drilling and Testing Results. Utah: GRC Transactions, Vol. 41.

Zhu, T., and Carroll, H.B. (1994). Status Report, A Review of Slim Hole Drilling. Bartlesville: National Institute for Petroleum and Energy Research and BDM Oklahoma.

Penta Helix Approach for Geothermal Technology Research and Development in Indonesia: The Adoption from the United States

Vincentius A. Brilian[1,2], Dorman P. Purba[1,2], Daniel W. Adityatama[1,2], and Ferdino R. Fadhillah[1,2]

[1]PT Geoenergi Solusi Indonesia (GEOENERGIS), Cibis Nine 11th Floor, Jakarta, Indonesia
[2]PT Enerka Bhumi Pratama (ENERKA), Cibis Park, Jakarta, Indonesia

adven.brilian@geoenergis.com, dorman.purba@enerklaz.com

Keywords: geothermal technology, power plant, education, innovation, Penta Helix, research and development, Triple Helix, drilling, US, Indonesia

ABSTRACT

Technology maturation can be divided into five phases: discovery, development, system testing, demonstration, and commercialization. The U.S. government, businesses, and universities contribute to the process, with universities playing a significant role in concept discovery and component development. The government's Department of Energy and national laboratories contribute the most to system testing and demonstration phases, largely due to their federal funding and advanced research facilities. As technology matures, businesses contribute the most to demonstrating the technology in an operational environment and putting it into large-scale market use. The Triple Helix framework in the U.S. strongly influences technology innovations, and the interactions between government, business entities, and universities could be applied to the geothermal technology research and development (R&D) framework in Indonesia. Similar technology transfer mechanisms between the three elements could be adopted in Indonesia.

The Indonesian government could also conduct its own geothermal technology R&D through the national research and innovation agency, Badan Riset dan Inovasi Nasional (BRIN). BRIN, which includes the Indonesian Institute of Sciences, Agency for the Assessment and Application of Technology, National Aeronautics and Space Institute, and National Nuclear Energy Agency, can conduct R&D activities related to geothermal technologies. However, Indonesia has a unique social landscape compared to the U.S., with heterogeneous religions and cultural values, and most geothermal prospects located near community settlements and protected areas. The involvement of society and media in the framework of geothermal technology R&D in Indonesia is crucial, leading to the transformation from the Triple Helix framework to the Penta Helix framework. This study aims to analyze the current Triple Helix framework in the geothermal technology R&D in the U.S., how it could be adopted as the Penta Helix framework for the case of Indonesia, and the importance of involving the community and media in the Penta Helix framework.

1. INTRODUCTION

The United States government intends to ensure the nation's welfare and security by addressing its energy and environmental issues through transformative science and technology solutions (DOE, 2021). Similarly, Indonesian government also prioritizes energy development as one of the national strategic projects to improve the nation's welfare. Bin-Nun et al. (2017) identified that the need for "transformative science and technology solutions" for addressing energy and environmental issues is derived from at least the following three factors:

- **Economic growth:** new technology development is a driving factor of economic growth by increasing energy supply, maintaining geopolitical stability, securing national energy security, and diversifying the energy structure.
- **Energy security:** new energy technologies could improve the reliability of renewable energy and reducing the reliance on fossil fuels, enhance grid stability, and mitigate supply disruptions. Therefore, it could contribute to a more secure and resilient energy systems. Additionally, innovations in energy exploration, production, and distribution could lead to greater self-sufficiency and reduced geopolitical risks.

- **Climate change:** new energy technologies help address climate change issues by reducing greenhouse gas emissions and transitioning to low-carbon energy sources. Energy efficiency improvements in industries, transportation, and buildings also help cut emissions.

Since the first invention of geothermal power plant in Larderello, Italy, in 1904, innovative geothermal technologies have been produced through decades of research and development efforts globally. This innovation is mainly driven by the need of producing geothermal energy from a geothermal resource with site-specific characteristics in an economically-efficient manner. Similar to other technologies, the maturity of any innovative geothermal technologies increases gradually as those technologies are being developed. The "transformative science and technology solutions" could be delivered through research and development (R&D) activities in the field of energy and environmental technologies. The technology R&D of geothermal energy, which is one of the renewable and clean energy sources, could play its part in helping the government address national energy and environmental issues. In the U.S., the geothermal technology R&D is dominantly performed under the collaboration framework between the government, businesses, and universities. However, the unique social landscape in Indonesia might require beyond these three components; that is by involving the community and media in the geothermal technology R&D.

The research questions to be answered in this study are as follows:

1. What is the current geothermal technology R&D framework in the U.S.?
2. How could the geothermal technology R&D framework in the U.S. be adopted in Indonesia?
3. What are the importance of incorporating the community and media in the geothermal technology R&D in Indonesia?

2. TRIPLE HELIX FRAMEWORK IN THE UNITED STATES

The technology maturation could be divided into five phases: 1) discovery; 2) development; 3) system testing; 4) demonstration; and 5) commercialization (DOE, 2020). As shown in Figure 1, the U.S. government (through the DOE and national laboratories), businesses, and universities contribute an evolving level of effort as the technology maturation progresses. Universities contribute the highest level of effort during the technology concept discovery and component development, supported by the DOE's funding & grants and R&D efforts by the national laboratories. Businesses start entering the technology maturation effort when the technology's concept has been identified/proven at laboratory-scale and the technology component is being validated/integrated. As the maturation progresses, the university's contribution to the total level of effort decreases, while the government's and businesses' contributions increase. The government's DOE and national laboratories contributed the highest level of effort during the system testing and demonstration phases. This is largely due to the national laboratories' federal funding and advanced research facility, technology, and personnel that make them capable of conducting pilot-scale testing and demonstration. Furthermore, as the technology maturation approaches and enters the commercialization phase, businesses contribute the highest level of effort in demonstrating the technology in an operational environment and putting the technology into large-scale market use. The dynamic collaboration between the U.S. government, businesses, and universities in the technology maturation effort suggests that the technology innovations in the U.S. is strongly influenced by the Triple Helix framework.

The Triple Helix concept was introduced in 1995 to better understand the dynamic interaction between the government, businesses, and universities, which results in the fostering of innovation and entrepreneurship (Etzkowitz & Leydesdorff, 1995). Additionally, the concept may also become a policy formulation tool. Governmental agencies like the U.S. DOE have used Triple Helix for both objectives in the environment of energy technology innovations, including geothermal technologies. Figure 2 shows the Triple Helix concept that potentially represents the framework of current technology innovation environment in the U.S. The success of technology innovation in the Triple Helix framework is inseparable from the role of each element in the framework. Government makes policies to maintain stable interactions between three Triple Helix elements. Additionally, the government may conduct its own R&D through the national laboratories. Furthermore, universities are an environment of teaching

and learning, as well as the forum of academic scholars conducting basic and applied R&D activities. Subsequently, businesses aim for technology commercialization through pilot and field-scale testing and market use. In addition, businesses could generate capital through investments and technology market use to conduct other R&D activities.

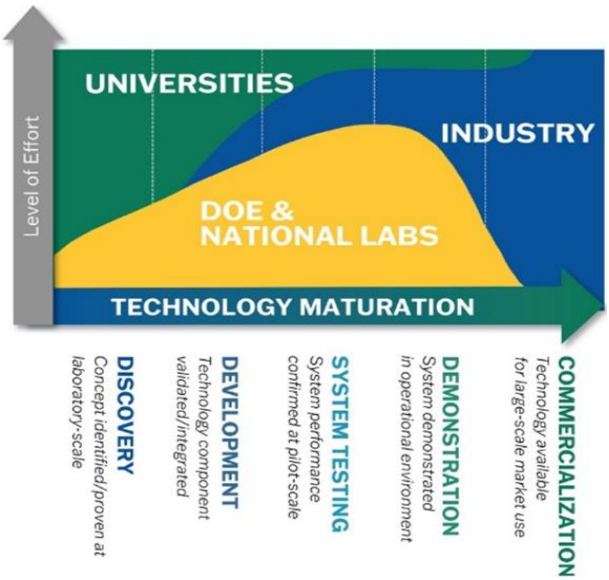


Figure 1: Relationship between the U.S. governments, businesses, and universities in technology innovation environment (DOE, 2020).

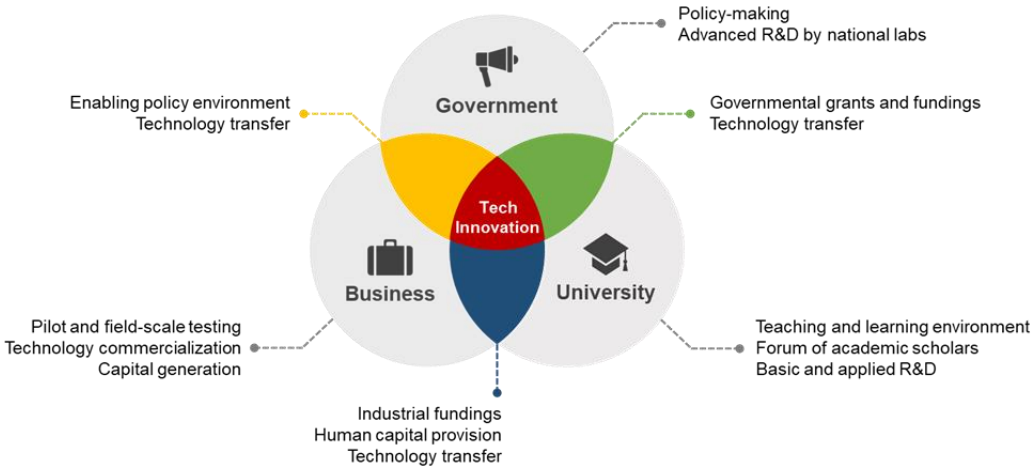


Figure 2: Triple helix framework in U.S. technology innovation environment.

Besides the contribution from each Triple Helix element according to its respective roles, the key for the success of technology innovations in the Triple Helix framework is the cohesive interaction between each element. The following section discusses how each Triple Helix element interacts with other elements, especially in geothermal technology R&D. It can be seen that the interactions between every element have a commonality in that each interaction always involves technology transfer, which occurs in a unique way for every interaction depending on the roles of each element. Additionally, the technology transfer does not occur unidirectionally. Instead, it resembles a mutual technology transfer for both parties.

2.1 Government-University Interactions

The interactions between the government and universities are in the form of two primary modes as follows:

- **Governmental grants and funding:** The U.S. governments provide more than 60% of annual university R&D funding. The federal funding for universities is mostly in the form of grants for a specific R&D topic conducted by individual faculties. Meanwhile, the state government funding primarily supports the general operation and maintenance of the university (Pew Charitable Trusts, 2015). The grants from the federal government for geothermal technology R&D are conveyed through the DOE's Geothermal Technologies Office (GTO). These federal grants are awarded to selected R&D projects, including those that are conducted by universities, such as the 46 million USD funding for University of Texas at Austin's effort in developing the optimized EGS hydraulic fracturing methods at the Utah FORGE's EGS (UT Austin, 2021). This, in return, helps the GTO's success in its Utah FORGE initiative. Therefore, the governmental grants not only give benefits to the university, but also creating reciprocal positive impacts to both parties.
- **Technology transfer:** Often, universities are taught to be the leading Triple Helix element in knowledge database and generation, while the government acts as a policy-maker that regulates the stable interaction between the three Triple Helix elements (THERG, 2021). However, the U.S. government has the privilege of being beyond policy-making, that is to conduct its own geothermal technology R&D through its national laboratories. It is even possible that national laboratories transfer their technology to the universities since the national laboratories may have a more sophisticated research infrastructure, technology, and personnel, thanks to the federal government's funding in these areas. An example of this case is the collaboration between Stanford University and SNL, in which the university's students perform research on inflow measurement in geothermal wells using the chloride measurement tool developed by SNL (Stanford University, 2021). In return, Stanford University transfers its technology to SNL by developing SNL's chloride measurement tools. This reciprocal impact may create a perpetual research facility and technology development, which could lead to more breakthrough geothermal technology innovations. Additionally, technology transfer between the government and universities could be in informal ways, such as personal communication, research publication, conferences, and educational initiatives. The mutual technology transfer between the government and universities is illustrated in Figure 3.

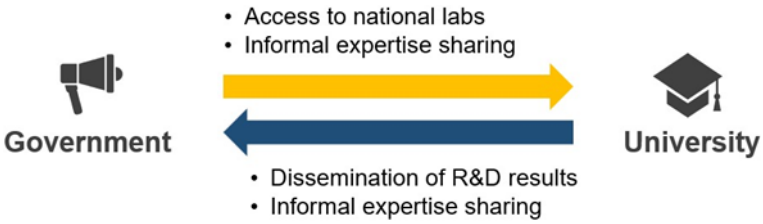


Figure 3: Mutual technology transfer between the government and universities.

2.2 Government-Business Interactions

The interactions between the government and businesses are in the form of two primary modes as follows:

- **Enabling policy environment:** The government could establish policies that enable geothermal technology R&D conducted by businesses. At the federal level, Energy Act 2020 authorizes 170 million USD per year from DOE for the EGS demo, FORGE initiative, and other geothermal technology research, development, and demonstration (Cunliff & Nguyen, 2021). These federal grants are awarded to selected R&D projects, including those that are conducted by businesses, such as the 2 million USD grant award for GreenFire Energy to investigate the possibilities of CO_2-based low-temperature geothermal electricity generation in eastern Arizona (Richter, 2010). Furthermore, both the federal and state governments may impose business taxes and offer R&D tax incentives in the forms of federal research credits,

state research credits, or tax depreciation allowance. Additionally, the government could erect efficient business bureaucracy, especially for new business establishments. The U.S. are among the countries with the shortest number of days needed to establish new business and hence U.S. achieved the highest year-on-year percentage in new business applications in 2020 (Djankov & Zhang, 2021). The efficient new business establishment could promote the growth of startups conducting geothermal technology R&D.

- **Technology transfer:** To support the energy technology commercialization and adoption by energy producers and consumers, DOE's national laboratories have provided various technology transfer mechanisms to business entities. Therefore, businesses may concurrently benefit from the R&D technologies and core competencies of every national laboratory. Various regulatory mechanisms have been developed to create lab-industry commercialization strategies as a result of the complexity of knowledge transfer between national laboratories and businesses. As an example, GreenFire Energy acquired the access to Lawrence Livermore National Laboratory's expertise and facility through the Small Business Voucher (SBV) mechanism to develop the company's closed-loop supercritical CO_2 geothermal system (Richter, 2010). Conversely, national laboratories could acquire the expertise from business entities for a specific area. For example, National Renewable Energy Laboratory (NREL) partnered with TPL Inc. to acquire its expertise in dielectric materials to support NREL's project of developing high-temperature electronics for drilling in hot and hard crystalline rocks (Richter, 2019). Additionally, technology transfer between the government and businesses could be in informal ways, such as personal communication, research publication, conferences, and educational initiatives. The mutual technology transfer between the government and businesses is illustrated in Figure 4.

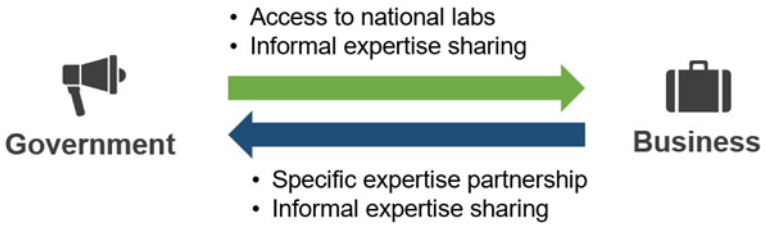


Figure 4: Mutual technology transfer between the government and businesses.

2.3 Business-University Interactions

The interactions between businesses and universities are in the form of three primary modes as follows:

- **Industrial fundings:** Universities could receive funding from business entities for technology R&D that has the potential for commercial application. Consequently, businesses could cut their effort on the first half of the technology maturation effort (concept discovery and component development) and instead focus on the demonstration and commercialization of the technology. In the last decade, industrial funding accounted for 5-10% of the total R&D funding of U.S. universities (Ward et al., 2020). In terms of individual universities, the proportion of industrial R&D funding may vary, depending on how the R&D activities in each university could attract industrial participation. Duke University managed to become the U.S. university with the highest industrial R&D funding proportion of up to 22% in FY 2016 (ITIF, 2018).
- **Human capital provision:** Human capital is a set of knowledge, skills, talents, and abilities possessed by individuals (ETF, 2021). Both the universities and industry require human capital to perform their own roles. Universities need human capital to conduct high-quality education and research. Meanwhile, businesses require human capital to perform effective management, increase productivity, and acquire optimum economic benefits. Businesses could acquire human capital from the universities by recruiting university graduates through hiring processes. After the graduates are recruited, they will combine the knowledge they gained in the university with the knowledge they gained through professional experiences and training. Additionally, university could provide consultancy services to the industry by utilizing the university faculty's expertise. Conversely, industry practitioners could become a human capital for

universities to provide a balanced theoretical and practical teaching, learning, and research environments.

- **Technology transfer:** As the success of technology innovations depends on the commercialization of the technology and its adoption by energy producers and consumers, the technology transfer between businesses and universities becomes important. Universities could conduct their own R&D activities using the university laboratories, which is a privilege that most business entities do not have. Business entities could propose accessing university laboratories facility and personnel to perform certain R&D activities according to the industry's needs. Furthermore, business entities and universities may form a commercial partnership, such as consultancy projects delivered by the university for the business entity. For example, University of Texas at Austin's Bureau of Economic Geology provided feasibility study consultancy for Sage Geosystems for a closed-loop geothermal development project at Ellington Air Base (Sage Geosystems, 2023). Additionally, technology transfer between business entities and universities could be in informal ways, such as personal communication, research publication, conferences, and educational initiatives. The mutual technology transfer between businesses and universities is illustrated in Figure 5.

Figure 5: Mutual technology transfer between businesses and universities.

3. PENTA HELIX: THE POTENTIAL ADOPTION OF THE FRAMEWORK FROM THE U.S. IN INDONESIA

The interactions between the government, business entities, and universities in the geothermal technology R&D framework in the U.S. could be adopted as the foundation for the geothermal technology R&D framework in Indonesia. Additionally, similar technology transfer mechanisms between the three Triple Helix elements in the U.S. could be adopted in Indonesia. Similar to the U.S. government, the Indonesian government could also conduct its own geothermal technology R&D through the national research and innovation agency called Badan Riset dan Inovasi Nasional (BRIN). Based on the Presidential Regulation No. 33/2021, BRIN becomes the umbrella for the pre-existing four research agencies in Indonesia: 1) Indonesian Institute of Sciences or Lembaga Ilmu Pengetahuan Indonesia (LIPI); 2) Agency for the Assessment and Application of Technology or Badan Pengkajian dan Penerapan Teknologi (BPPT); 3) National Aeronautics and Space Institute or Lembaga Penerbangan dan Antariksa Nasional (LAPAN), and National Nuclear Energy Agency or Badan Tenaga Nuklir Nasional (BATAN). Through the acquisition of these four agencies, BRIN possesses tens of research laboratories with various research areas that can be used to conduct R&D activities related to geothermal technologies. Prior to the acquisition by BRIN, BPPT conducted two pilot tests of geothermal binary plants in Kamojang, West Java (3 MW installed capacity; started operation in 2016), and Lahendong, North Sulawesi (500 kW installed capacity; started operation in 2019) respectively (EBTKE, 2016; BPPT, 2019). The pilot binary plants in both locations are shown in Figure 6.

However, Indonesia has a distinctive social landscape to the U.S. since Indonesia has a heterogeneous religions and cultural values in every region and most of the geothermal prospects are located in the vicinity of community settlements and protected area (Meijaard, et al., 2019). The adjacency of geothermal projects to the community has proven to be able of causing social rejections to the project. Moreover, the public perceptions to geothermal energy technologies are largely influenced by media. Therefore, the involvement of society and media in the framework of geothermal technology R&D in Indonesia becomes vital. This yields the transformation from the Triple Helix framework used in the U.S. into the Penta Helix framework that should be used in Indonesia, as illustrated in Figure 7.

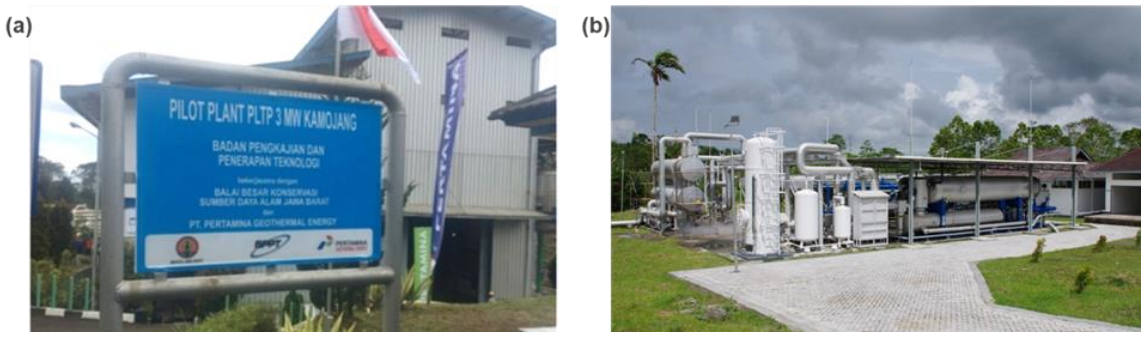


Figure 6: (a) 3 MW pilot binary plant in Kamojang, West Java (EBTKE, 2016); (b) 500 kW pilot binary plant in Lahendong, North Sulawesi (BPPT, 2019).

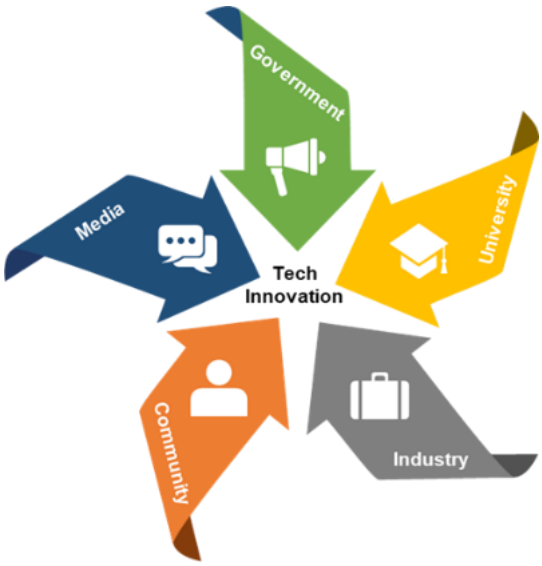


Figure 7: Penta helix framework for technology innovation environment in Indonesia.

3.1 The Importance of Community Involvement

Conventional geothermal power generation projects in Indonesia could be divided into five phases: 1) preliminary and 3-G (geology, geophysics, geochemistry) surveys; 2) exploration drilling; 3) development drilling; 4) surface facility construction; and 5) operation and maintenance. The term "conventional" is used to differentiate between conventional geothermal power plant projects and new geothermal technology R&D projects. According to Poernomo et al. (2015), the company that wins the concession of a "green" (unexplored) geothermal working area has around 5-7 years to conduct exploration activities, which includes 3-G surveys and exploration drilling. The most crucial stage of the whole project stages is the exploration stage, during which the company must conduct exploration drilling and delineation drilling to verify the geothermal conceptual model derived from the 3-G survey, hence significantly reducing resource uncertainty. The outcome of the exploration drilling will determine whether to proceed with development drilling or relinquish the geothermal area for future development. The outcome will also affect the decision regarding power plant size and type that will be built (Adityatama et al., 2019).

Conventional geothermal power generation projects are faced with both technical and non-technical challenges. The biggest technical challenge is the resource uncertainty during the exploration stage. Meanwhile, the non-technical challenges may include community rejection, incompetitive electricity tariff compared to fossil fuels, and land-use conflicts (Fadhillah, et al., 2023). As one of the non-technical challenges, social unrest and rejection may significantly delay or even halt a geothermal power

generation projects (Wallquist & Holenstein, 2015). The typical causes of society concerns could be categorized into three: 1) cultural; 2) economics; and 3) environmental (Fadhillah, et al., 2023). Recent social unrest events in geothermal projects in Indonesia are listed in Table 1, in which it is evident that social unrest often begins when the concession holder is about to perform exploration drilling at the end of exploration phase. This situation is concerning since the failure to conduct exploration drilling will cause the concession to be revoked and the Indonesian government will conduct re-tendering (Adityatama et al., 2019). Furthermore, delays due to social unrests could financially burden the company. A single day of delayed exploration drilling activity could cost the company up to 100,000 USD due to idle workers, rig, and heavy equipment (Fadhillah, et al., 2023).

Table 1: Recent social unrest events in conventional geothermal power generation projects in Indonesia (Fadhillah, et al., 2023; Adityatama, et al., 2019).

Field	Province	Exploration Period (EBTKE, 2017)	Unrest Date	Society Concern	References
Wae Sano (Government Drilling)	Eastern Nusa Tenggara	**Exploration** (No SK WKP* yet since exploration drilling is performed by the government)	February 2022	**Cultural:** • Disturbed local settlement complex. **Economics:** • Limited local agriculture production potential **Environmental:** • Threatened water sources	(VoxNtt.com, 2022)
Dieng (PT Geo Dipa Energi)	Central Java	**Development** (Expansion of the existing GPP)	January 2022	**Environmental:** • Proximity to villages • H_2S leakage and blowout during drilling	(OpiniJateng.com, 2022)
Bittuang (Government Drilling)	South Sulawesi	**Exploration** (No SK WKP* yet since exploration drilling is performed by the government)	January 2021	**Cultural:** • Disturbed sacred places. **Economics:** • Loss of agricultural areas **Environmental:** • Threatened water sources	(MakassarChannel, 2021)
Mount Lawu (PT Pertamina Geothermal Energy)	Central and East Java	**Exploration:** • SK WKP*: 13 August 2012 • End of exploration period: 2019	January 2018	**Cultural:** • Disturbed sacred places. **Economics:** • Limited economic benefits to local society **Environmental:** • Disturbed ecological preservation. • Threatened water sources	(Ibrohim, Prasetyo, & Rekinagara, 2019)
Mount Talang (PT Hitay Daya Energy)	West Sumatra	**Exploration** • SK WKP*: 3 June 2014 • End of exploration period: 2017	November 2017	**Economics:** • Limited local agricultural potential **Environmental:** • Threatened water sources • Human-induced disasters (e.g., micro-earthquake during drilling) • Abandoned assets in case of project failure	(Anggreta, Somantri, & Purwanto, 2022)
Sokoria (PT Sokoria Geothermal Indonesia)	East Nusa Tenggara	**Exploration** • SK WKP*: 30 January 2019 • End of exploration period: 2019	February 2017	**Economics:** • Untransparent land acquisition process	(Adityatama, Umam, Purba, & Muhammad, 2019)

Field	Province	Exploration Period (EBTKE, 2017)	Unrest Date	Society Concern	References
Baturaden (PT Sejahtera Alam Energy)	Central Java	**Exploration** • SK WKP*: 8 April 2010 • End of exploration period: 2017	November 2016 – October 2017	**Economics:** • Loss/change of occupation • Disturbed tourism areas **Environmental:** • Threatened water sources. • Disturbed forest ecosystems • Human-induced disasters (e.g., landslide, flood)	(Qorizki, Permadi, Yuwono, & Rohman, 2021)
*) SK WKP: Certificate of Geothermal Working Area					

Technology maturation could be divided into five stages: 1) discovery; 2) development; 3) system testing; 4) demonstration; and 5) commercialization (DOE, 2020). By learning from conventional geothermal power generation projects in Indonesia, addressing social issues is vital to employ successful geothermal technology innovations, especially on technology maturation stages that potentially brings impacts to society and environment. To facilitate the mapping of potential social impact on every geothermal technology maturation stage, the conventional geothermal power generation project stages could be made as an analogy to technology maturation stages, as shown in Figure 8. Technology concept discovery and component development are analogous to preliminary and 3-G surveys since these activities could be conducted either remotely (from the laboratory/office) or in the field in small-scale activities. Subsequently, system pilot testing is analogous to exploration drilling since pilot testing aims to significantly reduce the uncertainties of new technology by testing it in a relevant environment (in the field) (Barrera et al., 2011), just like exploration drilling that reduces resource uncertainties by confirming the surface 3-G data interpretation using direct subsurface data interpretation. Afterwards, demonstration testing is analogous to development drilling since demonstration testing further confirms the technology in an large-scale operational field environment (DOE, 2020), just like development drilling that provides production and reinjection wells to support power plant operation by considering the proven resource areas based on the exploration drilling results. Furthermore, technology commercialization is analogous to conventional GPP operation and maintenance phase, in which the technology (or GPP) is commercially available.

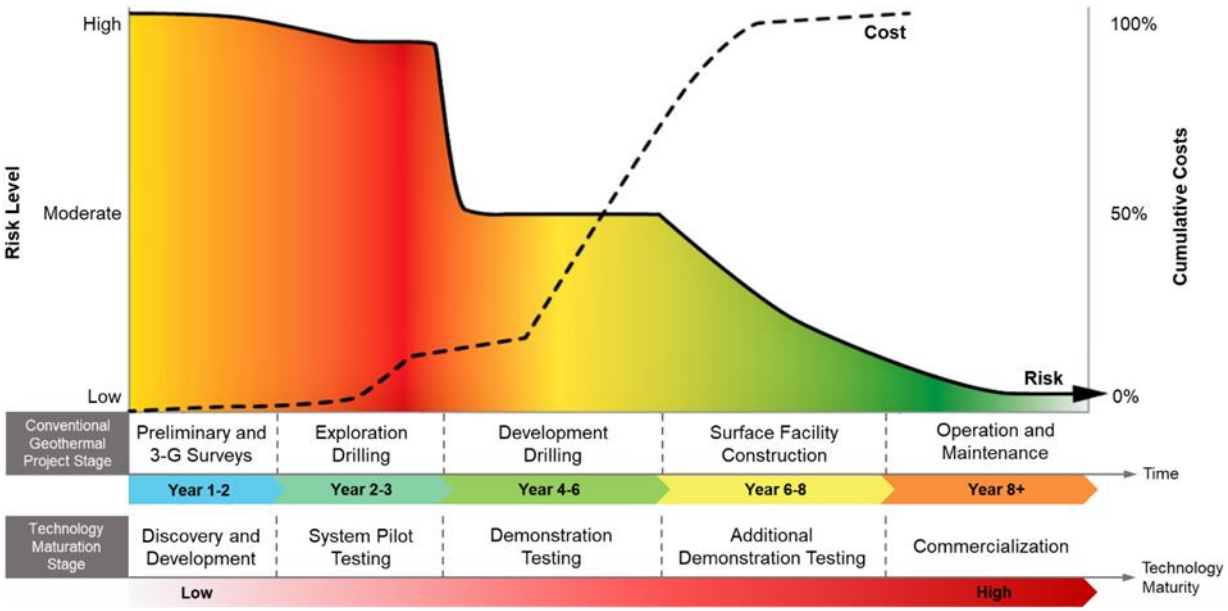


Figure 8: The analogy between conventional geothermal project stages and technology maturation stages (modified from: ESMAP, 2012).

Based on the analogy between conventional project stages and geothermal technology maturation stages, the potential impact to society on every technology maturation stage could be mapped, as shown in Table 2. Exploration drilling triggers most social unrest events since exploration drilling involves

large-scale field activities for the first time in a geothermal project compared to the previous preliminary and 3-G surveys with relatively limited field activities. These field activities include land clearing, infrastructure construction, equipment mobilization, and drilling process, which could cause cultural, economics, and environmental concerns from the society. Similar issues could happen to the pilot testing of new geothermal technology, which typically required to done in the field after the technology has been tested in laboratory. Therefore, pilot testing may require field activities similar to exploration drilling, which could raise cultural, economics, and environmental concerns from the society. However, regardless of the project stage, society could be involved in the project with various roles despite the arising concerns.

Table 2: Conventional geothermal project stages, impact to society, and analogy to technology maturation stages (modified from: Fadhillah et al., 2023).

Conventional Geothermal Project Stage	Potential Impact	Society Involvement	Society Concern	Analogous Technology Maturation Stage
Preliminary and 3-G surveys: Desk-study; infrastructure readiness survey; collection and analysis of 3-G data to assess the presence and characteristics of the geothermal resource	• Emerging of community curiosity • Area disturbance • Trespassing community-owned land area • Small-scale land clearing	• Local guide and survey helper • Provide accommodation for survey team	• Neutral perception • Assumed geothermal as a renewable and clean energy source. • Disturbed local activities, tourism, and sacred places	**Discovery:** Theoretical concept identified/proven at laboratory-scale. **Development:** Technology component validated/integrated
Exploration drilling: Drilling infrastructure survey and construction; exploration drilling to confirm the resource	• Area disturbance • Community acculturation with foreign workers • Soil, water, and air pollution • Deforestation	• Sell or rent community-owned land area for drilling infrastructure construction. • Assist the project as non-skilled workers (e.g., security, driver)	• Disturbed local activities, tourism, and sacred places. • Disrupted local cultures. • Unfair land acquisition process • Loss of occupation • Environmental pollution • Threatened water sources. • Fear of H_2S and blowout	**System Testing:** System performance confirmed at pilot-scale
Development drilling: Drilling infrastructure survey and construction; production and reinjection well drilling to support power plant generation	• Area disturbance • Community acculturation with foreign workers • Soil, water, and air pollution • Deforestation	• Sell or rent community-owned land area for drilling infrastructure construction. • Assist the project as non-skilled workers (e.g., security, driver)	• Disturbed local activities, tourism, and sacred places. • Disrupted local cultures. • Unfair land acquisition process • Loss of occupation • Environmental pollution • Threatened water sources. • Fear of H_2S and blowout	**Demonstration:** System demonstrated in operational environment
Surface facility construction: Construction of power plant and steamfield equipment	• Area disturbance • Community acculturation with foreign workers • Soil, water, and air pollution • Deforestation	• Sell or rent community-owned land area for power plant and steamfield construction. • Assist the project as non-skilled workers (e.g., security, driver)	• Loss of occupation • Environmental pollution	

Conventional Geothermal Project Stage	Potential Impact	Society Involvement	Society Concern	Analogous Technology Maturation Stage
Operation and maintenance: Sustaining electricity generation through resource management, make-up drilling, and equipment maintenance	• Community acculturation with foreign workers • Changed community occupations. • Soil, water, and air pollution	• Direct geothermal use for local society • Provide accommodations for workers. • Assist the project both as non-skilled and skilled workers	• Disrupted local cultures. • Loss of occupation • Human-induced disasters (e.g., landslide, flood, earthquake)	**Commercialization:** Technology available for market use

Each innovative geothermal technology may have unique impact to society and society involvement conditions. However, there are commonalities of typical impact to society and society involvement on each technology maturation stage, as shown in Table 3, based on the conditions in conventional geothermal power generation projects. In the discovery and development stages, there are negligible impacts to society, limited society involvement, and negligible society concerns, since these activities are mostly performed in the laboratory environment. However, once the technology maturation enters the pilot testing stage, it becomes vulnerable to social issues since it involves a significant on-the-field activities for the first time across the whole technology maturation stages. However, the level of impact of the society concerns to the project could be reduced if the pilot testing is conducted in existing operational geothermal fields. The effect of the society concerns on the project remains present throughout the demonstration testing and even when the technology has been used commercially. One of the society concerns from the cultural perspective on new geothermal technologies is the "not in my backyard" (NIMBY) mindset, which plagues other energy technologies that most community have not been familiar with, such as nuclear energy. A person or a group of people might accept nuclear energy as a low emission energy source and should be implemented to replace fossil fuels. However, some do not want nuclear power plants to be installed near to their houses due to safety concerns raised by past nuclear disasters in Fukushima and Chernobyl despite today's nuclear power plants have high safety standards (Uji et al., 2021). New geothermal technologies could possibly endure similar issues due to unfamiliarity of the society with the new technology. For example, EGS that requires fracturing may raise society concerns that it could cause human-induced seismicity.

Table 3: Comparison between conducting geothermal captive use development during mining exploration and production.

Geothermal Technology Maturation Stage	Potential Impact	Society Involvement	Potential Society Concern	Impact Level of Society Concern to the Project
Discovery: Concept identified/proven at laboratory-scale	Negligible impact	Limited society involvement	Negligible society concerns	Low
Development: Technology component validated/integrated	• Limited growth of community curiosity	Limited society involvement	**Cultural:** • Speculations regarding negative impacts from the technology	Low
System Testing: System performance confirmed at pilot-scale	• Rapid growth of community curiosity • Early community exposure to foreign workers • Small-scale land clearing • Area disturbance • Human-induced disasters (e.g., landslide, micro-earthquake)	• Sell or rent community-owned land area for pilot test infrastructure construction. • Assist the project as non-skilled workers (e.g., security, driver) • Provide accommodation for the pilot test team	**Cultural:** • "Not in my backyard" (NIMBY) mindset • Disturbed daily activity due to equipment mobilization. • Disturbed sacred places. **Economics:** • Unfair land acquisition process • Disturbed tourism areas	High

Geothermal Technology Maturation Stage	Potential Impact	Society Involvement	Potential Society Concern	Impact Level of Society Concern to the Project
			Environmental: • Threatened water resources • Fear of human-induced disasters (e.g., landslide, micro-earthquake)	
Demonstration: System demonstrated in operational environment	• Early community exposure to foreign workers • Deforestation • Area disturbance • Human-induced disasters (e.g., landslide, micro-earthquake)	• Sell or rent community-owned land area for demonstration test infrastructure construction • Assist the project as non-skilled workers (e.g., security, driver) • Provide accommodation for the demonstration test team	**Cultural:** • "Not in my backyard" (NIMBY) mindset • Disturbed daily activity due to equipment mobilization • Disturbed sacred places **Economics:** • Fearing that skilled workers will replace local workers • Disturbed tourism areas **Environmental:** • Threatened water resources, • Fear of human-induced disasters (e.g., landslide, micro-earthquake)	Medium
Commercialization: Technology available for market use	• Employment opportunity • Community acculturation with foreign workers • Access to geothermal electricity in more regions with & without volcanic geothermal systems • Operational pollution (e.g., solid waste, sewage, noise)	• Direct geothermal use for local society • Provide accommodation for workers • Assist the project both as non-skilled and skilled workers (e.g., field engineers, operators)	**Economics:** • Fearing that skilled workers will replace local workers **Environmental:** • Fear of human-induced disasters (e.g., landslide, micro-earthquake)	Medium

The past experiences of social issues in conventional geothermal power generation projects prompt the acquisition of Social License to Operate (SLO) in a geothermal project, including new geothermal technology R&D projects. SLO is a multiscale, multilayer, intangible agreement that reflects the implicit consent of affected parties for projects created by business entities, which is not explicitly required by legal statutes (Barich, et al., 2022). In the geothermal industry, the aspects that needed to be addressed to gain SLO are permission/legality, environmental and financial risks management, responsibility of land and water resources usage, mutual benefits provision, and industry acceptance, as shown in Figure 9.

Figure 9: Aspects of SLO for geothermal projects (Barich, et al., 2022).

SLO is constructed on the foundation of legitimacy, credibility, and trust from the community to the project (Taylor & Mahlangu, 2017). When communities accept a project, it indicates they have no objections or disapprovals to the project's operations and believe the geothermal developer is qualified to complete the project. Due to the trustworthiness of the developer, community support the project during the approval acceptance phase and are glad to participate in achievement. The greatest stage is stakeholder co-ownership of projects with fewer social boundaries, where the developer has adopted membership in the society by earning total stakeholder confidence (Barich, et al., 2022). The short-term goal for geothermal developers should be to obtain societal acceptance, while the medium- and long-term goals should be acquiring society approval and co-ownership (Fadhillah et al., 2023). Figure 10 depicts the framework of the SLO evolution in a geothermal project. The core stakeholders include the local communities, local governments (such as municipalities), direct users, scientists, local universities, local non-governmental organizations (NGOs), and any other stakeholders who the project will directly impact. Meanwhile, the governance bodies and broader stakeholders are the communities and authorities of bigger sizes (national and worldwide), international funding organizations, wider communities of practice/universities, and NGOs (Barich, et al., 2022).

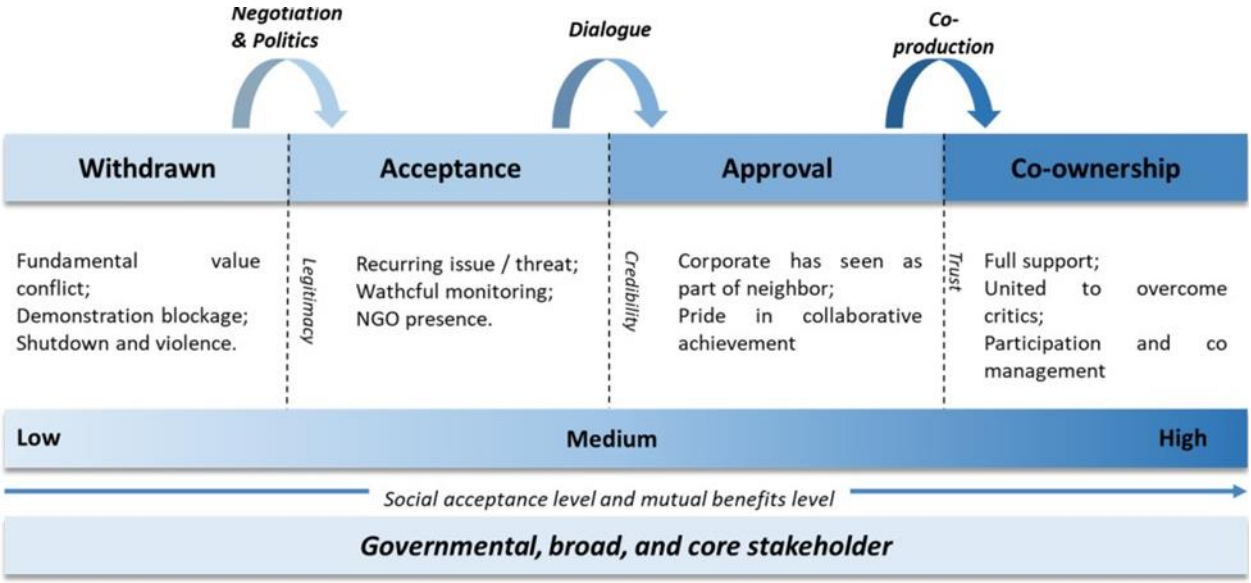


Figure 10: SLO framework in the geothermal industry (Fadhillah et al., 2023).

Fadhillah et al. (2023) summarized several strategies that might be taken into account to achieve SLO in conventional geothermal power generation projects that could be adopted to geothermal technology R&D projects as follows:

- **Community development program:** The degree of public comprehension appears to have a crucial role in how the public views geothermal projects, including new geothermal technology R&D projects, and how the local community will react to the project. Through frequent interaction and hearing sessions, a good community development program might offer a more thorough education and explanation of the community-related geothermal energy and R&D project consequences in the area where they live. In order to acquire authentic viewpoints from the stakeholder without putting them under pressure to approve the project, the geothermal technology developer must openly address stakeholder concerns and questions during the socialization and counseling process. Programs for community development prepare the local society for changes in occupations. Purba et al. (2021) underlines the possibility of creating an educational and training facility to provide the community's people resources with the fundamental geothermal sector knowledge and abilities (civil construction, machinery, health and safety, and project management). Both the local community and the developer would gain from the availability of a trained local workforce. Since the local workers are experienced with the project, it allows for more local involvement in the pilot testing and demonstration testing of geothermal technology R&D projects. There are a number of action plans that could be taken into account to carry out a good community development program, including:

    - Conduct multi-level discussions and reconciliation between the technology developer and stakeholders to provide a consensus for all major stakeholders in order to avoid opposition on the lower level.
    - Create the primary curriculum guidelines for Indonesia's community development program in accordance with international standards.
    - Create a comprehensive map of the positions, interests, and concerns of local community stakeholders on the geothermal technology R&D project.

- **Good project commitment and implementation:** Early commitment and implementing the geothermal technology developer's strategy connected to the project and community benefit are vital to closely supervise new geothermal technology R&D projects. The stakeholder's unfavorable reaction and the technology developer's credibility might both be affected by the implementation's deviation or cancellation of the agreement. To prevent a bad reputation for the technology developer, the operational issues with the project that have an impact on the neighborhood should also be appropriately handled. Additionally, the developer should respect local beliefs and cultural norms when carrying out the R&D project since there are various regions where project activities may cause disruption. Geothermal technology developers need to be aware that successful project execution not only impacts the current time but will also be noted as past performance that influences the geothermal technology developer and vice versa. Building a solid reputation in the geothermal industry requires professional social issue handling and resolution. Several action plans might be considered to carry out effective commitment and execution of the geothermal technology R&D project, including:

    - Set clear and realistic expectations for the community to prevent disappointment and unfavorable reactions from them.
    - Adopt rigorous HSE guidelines for all geothermal technology R&D activities, especially pilot testing and demonstration testing, to prevent harm to people and the environment from poor project execution.

- **Clear communication to stakeholders:** By presenting relevant issues relating to on-the-field activities, stakeholder communication is essential to shaping the community's image. Purba et al. (2021) claim that certified teams of skilled employees and the local communities may help geothermal developers and local government acquire community participation. Thanks to the efforts of this team, the geothermal technology developer and the local communities are anticipated to engage positively and communicate openly. Gaining the trust of all stakeholders also requires effective communication. There are a number of action plans that may be taken into account in order to conduct clear communication to stakeholders, including:

- Identify important stakeholders and group distribution on the project in order to understand the efficient communication routes.
- Establish a trustworthy, long-lasting, and transparent communication channel to facilitate fruitful discussions to local people with project-related information.

3.2 The Importance of Media Involvement

Public perception of emerging low-carbon energy technologies like geothermal energy technology affects how quickly these technologies are developed in a country. Those perceptions are significantly influenced by how the media portrays such technology (Trisiah et al., 2022) and those will affect the society's familiarity and, most importantly, acceptance to geothermal energy (Yogandari & Ibrahim, 2019). Moreover, the lack of risk of community engagement by the geothermal technology developer could lead to rejection of the project as well as public distrust to developer's information given to the community. Consequently, local communities could use social and local media instead to gather information regarding geothermal energy technologies (Syvarulli, 2020). This raises more concern on how crucial the media framing regarding geothermal energy technology to the public perception is. Positive framing regarding geothermal energy technology as a low emission and renewable energy source that can replace fossil fuel is important to increase public acceptance on geothermal energy technology. However, a balanced framing should still be enforced by the media since a boomerang effect may happen if readers believe the information is unbalanced. People may eventually regard the promotion of renewable energy sources as an effort to sway their opinions (Trisiah et al., 2022).

4. CONCLUSION

The Triple Helix framework, introduced in 1995, focuses on the dynamic interaction between government, businesses, and universities, fostering innovation and entrepreneurship. This framework is particularly relevant in geothermal technology R&D, where businesses aim for commercialization through pilot and field-scale testing and market use. The US geothermal technology R&D framework could be applied to Indonesia, where the government, business entities, and universities adopt similar mechanisms. However, Indonesia's unique social landscape and media influence can cause social rejections and delays in geothermal power generation projects. Therefore, the Penta Helix framework that incorporates the community and media components are vital for geothermal technology R&D in Indonesia. Addressing social issues is crucial for successful geothermal technology innovations, especially during technology maturation stages. Geothermal developers should acquire a Social License to Operate (SLO), which reflects the implicit consent of affected parties. SLO is built on legitimacy, credibility, and trust from the community, with short-term goals focusing on societal acceptance and long-term goals on society approval and co-ownership. Balancing media framing and community engagement is crucial for public acceptance of low-carbon energy technologies like geothermal energy, as unbalanced information may lead to swaying opinions.

REFERENCES

Abudu, K., Igie, U., Minervino, O. & Hamilton, R., 2020. Gas turbine Efficiency and Ramp Rate Improvement Through Compressed Air Injection. *Proceedings of the Institution of Mechanical Engineers, Part A: Journal of Power and Energy*, 235(4), pp. 866-884.

Adityatama, D., Umam, M., Purba, D. & Muhammad, F., 2019. *Review on Geothermal Direct Use Application as an Alternative Approach in Community Engagement at Early Exploration Phase in Indonesia*. Stanford, Stanford University, pp. 1-12.

Anggreta, D. K., Somantri, G. R. & Purwanto, S. A., 2022. Study of Student Community Movements Against the Development of a Geothermal. *Journal of Society and Media*, 6(1), pp. 62-83.

Barich, A. et al., 2022. Social License to Operate in Geothermal Energy. *Energies*, 15(1), p. 139.

Barrera, S., Becerra, M., Chacón, P. & Quelopana, H., 2011. Challenges in the Design of Pilot Tests. Perth, *Proceedings, 14th International Seminar on Paste and Thickened Tailings*.

Cunliff, C. & Nguyen, L., 2021. *Federal Energy RD&D: Geothermal Technologies*, Washington, D.C.: Information Technology & Innovation Foundation.

Directorate General of Electricity, 2021. *Statistik Ketenagalistrikan Tahun 2020*, Jakarta: Directorate General of Electricity.

Djankov, S. & Zhang, E., 2021. *Startups Boom in the United States During COVID-19*. [Online] Available at: https://www.piie.com/blogs/realtime-economics/startups-boom-united-states-during-covid-19 [Accessed 25 June 2023].

DOE, 2020. *The State of the DOE National Laboratories: 2020 Edition*, Washington, D.C.: U.S. Department of Energy.

EBTKE, 2017. *Buku Potensi Panas Bumi Jilid I*, Jakarta: Direktorat Jenderal Energi Baru Terbarukan dan Konservasi Energi.

ESMAP, 2012. *Geothermal Handbook: Planning and Financing Power Generation,* Washington, D.C.: Energy Sector Management Assistance Program.

ETF, 2021. *Policies for Human Capital Development: Southern and Eastern Mediterranean Region*, Torino: European Training Foundation.

Etzkowitz, H. & Leydesdorff, L., 1995. The Triple Helix -- University-Industry-Government Relations: A Laboratory for Knowledge Based Economic Development. *EASST Review*, 14(1), pp. 14-19.

Fadhillah, F. R. et al., 2023. Challenges in Getting Public Acceptance on Geothermal Project in Indonesia. Stanford, *Proceedings, 48th Workshop on Geothermal Reservoir Engineering*.

Harding, A., 2020. *Argonaut Gold to Run Florida Canyon*. [Online] Available at: https://elkodaily.com/mining/argonaut-gold-to-run-florida-canyon/article_e17f6642-1acb-5834-b8bc-f8c31f302bf0.html [Accessed 16 July 2023].

Huttrer, G. W., 2021. *Geothermal Power Generation in the World 2015-2020 Update Report*. Reykjavik, International Geothermal Association, pp. 1-17.

Ibrohim, A., Prasetyo, R. M. & Rekinagara, I. H., 2019. Understanding Social Acceptance of Geothermal Energy: A Case Study from Mt. Lawu, Indonesia. *IOP Conference Series: Earth and Environmental Science*, Volume 254, p. 012009.

IESR, 2023. *Making Energy Transition Succeed: A 2023's Update on The Levelized Cost of Electricity and Levelized Cost of Storage in Indonesia*, Jakarta: Institute for Essential Services Reform (IESR).

IMF, 2019. *What is Carbon Taxation?*, Washington, D.C.: International Monetary Fund.

Indonesian Ministry of Energy and Mineral Resources, 2023. *Geoportal Energi Baru Terbarukan*. [Online] Available at: https://geoportal.esdm.go.id/ebtke/ [Accessed 16 July 2023].

Indonesian Ministry of Energy and Mineral Resources, 2023. *Geoportal Ketenagalistrikan*. [Online] Available at: https://geoportal.esdm.go.id/ketenagalistrikan/ [Accessed 17 July 2023].

IRENA, 2019. *Flexibility of Conventional Power Plants: Innovation Landscape Brief*, Abu Dhabi: International Renewable Energy Agency.

ITIF, 2018. *Industry Funding of University Research: Which States Lead?*, Washington, D.C.: Information Technology & Innovation Foundation.

MakassarChannel, 2021. *Warga Tana Toraja Tolak Eksplorasi Geotermal Bittuang*. [Online] Available at: https://makassarchannel.com/index.php/2021/02/11/warga-tana-toraja-tolak-eksplorasi-geotermal-bittuang/2/ [Accessed 5 July 2023].

MDO Data Online Inc., 2023. *Florida Canyon Mine*. [Online] Available at: https://miningdataonline.com/property/332/Florida-Canyon-Mine.aspx [Accessed 16 July 2023].

Meijaard, E. et al., 2019. *Rapid Environmental and Social Assessment of Geothermal Power Development in Conservation Forest Areas of Indonesia*, Washington, D.C.: PROFOR.

Melaku, M., 2005. Geothermal Development at Lihir – An Overview. Antalya, *Proceedings, World Geothermal Congress 2005*.

NBMG, 2014. *Site Description: Rye Patch Reservoir*, Reno: Nevada Bureau of Mines and Geology.

NREL, 2021. *Life Cycle Greenhouse Gas Emissions from Electricity Generation: Update*, Golden: National Renewable Energy Laboratory.

NREL, 2022. *Mining G.O.L.D. (Geothermal Opportunities Leveraged Through Data): Exploring Synergies Between the Geothermal and Mining Industries*, Golden: National Renewable Energy Laboratory.

OpiniJateng.com, 2022. *Demo Warga Dataran Tinggi Dieng Menolak Pengeboran Pembangkit Listrik Tenaga Panas Bumi* (PLTPB). [Online] Available at: https://opinijateng.com/2022/01/25/5269/demo-warga-dataran-tinggi-dieng-menolak-pengeboran-pembangkit-listrik-tenaga-panas-bumi-pltpb/ [Accessed 5 July 2023].

Pambudi, N. A. et al., 2023. Renewable Energy in Indonesia: Current Status, Potential, and Future Development. *Sustainability*, 15(3), p. 2342.

Pew Charitable Trusts, 2015. *Federal and State Funding of Higher Education: A Changing Landscape*. [Online] Available at: https://www.pewtrusts.org/en/research-and-analysis/issue-briefs/2015/06/federal-and-state-funding-of-higher-education [Accessed 28 June 2023].

PT PLN (Persero), 2021. *Rencana Usaha Penyediaan Tenaga Listrik (RUPTL) 2021-2030*, Jakarta: PT PLN (Persero).

Qorizki, D., Permadi, D. B., Yuwono, T. & Rohman, R., 2021. Should Drill or Shouldn't Drill? Urban and Rural Dwellers' Acceptance of Geothermal Power Plant in Mount Slamet Protection Forest, Indonesia. *Forest and Society*, 5(2), pp. 575-590.

Richter, A., 2010. *U.S. Based GreenFire Energy Announces the Award of a US$2million Grant from the U.S. Department of Energy for the Development of Its Low-Temperature CO2-Based Geothermal Power Production Technologies*. [Online] Available at: https://www.thinkgeoenergy.com/greenfire-energy-announces-award-of-us2m-grant-from-the-u-s-doe/ [Accessed 25 June 2023].

Sage Geosystems, 2023. *SAGE – META: Unlocking the Potential of Geothermal for Clean, Compact, Renewable Baseload Power*. [Online] Available at: https://www.sagegeosystems.com/sage-meta-unlocking-the-potential-of-geothermal-for-clean-compact-renewable-baseload-power/ [Accessed 26 June 2023].

Stanford University, 2021. *Inflow Measurement in Geothermal Wells Based on Chloride Concentration (2021-2024)*. [Online] Available at: https://geothermal.stanford.edu/research/inflow-measurement-geothermal-wells-based-chloride-concentration-2021-2024 [Accessed 28 June 2023].

Statista, 2023. *Forecast Capital Expenditure of a Conventional Natural Gas Combustion Turbine Power Plant in the United States from 2022 to 2050*. [Online] Available at: https://www.statista.com/statistics/243704/capital-costs-of-a-typical-us-gas-turbine-power-plant/ [Accessed 17 July 2023].

Strata Policy, 2017. *The Footprint of Energy: Land Use of U.S. Electricity Production*, Logan: Strata Policy.

SuaraNTB.com, 2023. *Ditemukan Potensi Panas Bumi 150 Derajat Celcius di Hu'u Dompu*. [Online] Available at: https://www.suarantb.com/2023/03/14/ditemukan-potensi-panas-bumi-150-derajat-celcius-di-huu-dompu/ [Accessed 16 July 2023].

Su, Z. et al., 2021. Opportunities and strategies for multigrade waste heat utilization in various industries: A recent review. *Energy Conversion and Management*, Volume 229, p. 113769.

Syvarulli, R., 2020. Public Acceptance in Geothermal Energy. *Journal of Mechanical Engineering and Vocational Education*, 3(2), pp. 1-9.

Taylor, D. F. P. & Mahlangu, S., 2017. Earning the Social License to Operate: A Case Study About Culture. Johannesburg, *Proceedings, 5th International Conference on Management, Leadership and Governance*.

THERG, 2021. About TH | *University – Industry – Government*. Rio de Janiero, Federal Fluminese University's Triple Helix Research Group.

Trisiah, A., de Vries, G. & de Bruijn, H., 2022. Framing Geothermal Energy in Indonesia: A Media Analysis in A Country with Huge Potential. *Environmental Communication*, 16(7), pp. 992-1001.

U.S. DOE, 2020. *Capacity Factor by Energy Source in 2020*, Washington, D.C.: The United States Department of Energy.

Uji, A., Prakash, A. & Song, J., 2021. Does the "NIMBY Syndrome" Undermine Public Support for Nuclear Power in Japan? *Energy Policy*, 148(A), p. 111944.

UT Austin, 2021. *Texas Engineers Awarded DOE Grant to Study Engineered Geothermal Systems*. [Online] Available at: https://cockrell.utexas.edu/news/archive/9219-texas-engineers-awarded-doe-grant-to-study-engineered-geothermal-systems [Accessed 28 June 2023].

VoxNtt.com, 2022. *Aksi Tolak Geothermal Ricuh, Massa Robohkan Gerbang Kantor Bupati Manggarai Barat*. [Online] Available at: https://voxntt.com/2022/02/02/aksi-tolak-geothermal-ricuh-massa-robohkan-gerbang-kantor-bupati-manggarai-barat/85003/ [Accessed 5 July 2023].

Wallquist, L. & Holenstein, M., 2015. Engaging the Public on Geothermal Energy. Melbourne, *Proceedings, World Geothermal Congress 2015*.

Ward, J. D., Pisacreta, E. D., Weintraut, B. & Kurzweil, M., 2020. *An Overview of State Higher Education Funding Approaches: Lessons and Recommendations*, New York: ITHAKA S+R.

Yao, Y., Xu, J.-H. & Sun, D.-Q., 2021. Untangling Global Levelised Cost of Electricity Based on Multi-Factor Learning Curve for Renewable Energy: Wind, Solar, Geothermal, Hydropower and Bioenergy. *Journal of Cleaner Production*, p. 123827.

Yogandari, A. P. & Ibrahim, R. F., 2019. Media Framing on Social Acceptance of Geothermal Development. Auckland, *Proceedings, New Zealand Geothermal Workshop*.

Optimization Strategies for Well Design and Drilling Operations in Low-Medium Temperature Geothermal Systems in Indonesia

Brian Christiantoro[1], M. Rizqi Al Asyari[1], Daniel W. Adityatama[1],
Dorman P. Purba[1,2], and Nadya Erichatama[1,2]

[1]PT Geoenergi Solusi Indonesia (GEOENERGIS), Cibis Nine 11th Floor, Jakarta, Indonesia
[2]PT Enerka Bhumi Pratama (ENERKA), Cibis Park, Jakarta, Indonesia

brian.c@geoenergis.com

Keywords: geothermal, low-medium temperature, well design, drilling, rig, Indonesia

ABSTRACT

Indonesia's low-medium temperature geothermal potential, specifically in the 160°C to 200°C temperature range, presents an attractive opportunity for geothermal energy development. Several geothermal sites, like Ulubelu, Kotamobagu, Cisolok-Cisukarame, and Rantau Dedap, exhibit diverse characteristics such as outflow systems and fault-controlled systems, highlighting the variability of geothermal resources in the region.

The study emphasizes the significance of proper well design, which evolves through exploration, development, and operational phases. "Big Hole" well design is proposed as an optimal approach for low-medium temperature geothermal wells due to its ability to accommodate downhole pumps, crucial for artificially lifting fluids to the surface. The paper details various factors impacting well design including temperature-induced stresses, steel strength reduction, and material competence.

The analysis incorporates casing design, exploring the impact of temperature and setting depth on casing grades. Different casing grades are evaluated using sensitivity analysis based on depth and temperature variations. Results indicate that casing design factors are influenced by well depth and temperature but remain within acceptable safety margins for most scenarios.

Furthermore, the paper delves into wellhead design, accounting for fluid temperature, pressure, corrosiveness, and scale deposition potential. The wellhead components are designed to withstand thermal and mechanical stresses, with specific focus on saturated steam conditions.

Rig sizing is another crucial aspect addressed in the study. The analysis evaluates hoisting and setback capacities, as well as drawwork ratings, to determine suitable rig specifications. Rig sizing is vital to ensure efficient drilling operations, meet safety requirements, and manage costs. The research concludes that rig size requirements are influenced by both well depth and the use of "Big Hole" well design. An exploration of rig capacities ranging from 750 HP to 1500 HP reveals that a 1000 HP rig is recommended for the considered well designs.

Overall, the paper provides a comprehensive investigation into optimizing well design and drilling practices for low-to-medium temperature geothermal systems in Indonesia. By considering a range of factors including temperature effects, casing strength, wellhead design, and rig capabilities, the research offers valuable insights to enhance geothermal energy production in the region's diverse geothermal fields.

1. INTRODUCTION

Indonesia has significant potential for the development of low-to-medium geothermal systems. According to Fauzi (2015), the country has identified reserves of at least 2000 MWe (megawatts electrical) in the low-to-medium temperature range. This indicates a substantial resource that can contribute to the country's energy mix and reduce reliance on fossil fuels.

In a study by Febrianto et al. (2019), it is argued that reservoir temperatures ranging from 160° to 200° C are financially viable for geothermal development in Indonesia. This temperature range aligns with

the low-to-medium geothermal systems, making them attractive options for exploration and exploitation.

Indonesia showcases several lower temperature geothermal systems. These include Ulubelu in South Sumatra, Kotamobagu in North Sulawesi, Cisolok-Cisukarame in Java, and Rantau Dedap in Sumatra (Febrianto et al., 2019). These systems are characterized as outflow systems, where the geothermal fluid flows naturally to the surface due to pressure differences. Additionally, the Great Sumatran Fault represents a structural controlled system, where fractures and faults create pathways for the geothermal fluids to migrate. These geothermal sites demonstrate the diversity of low-to-medium temperature resources in Indonesia and provide opportunities for geothermal energy development.

Herdianita and Natasha (2017) add some geothermal fields in Eastern Banda Arc (Atedai and Lesugolo) as low-to-medium temperature geothermal system with 160^{o} – 240^{o} C reservoir temperature at 500 to 800 m depth. The EBTKE report from 2012 indicated that the geothermal potential for Atedai has a potential of 40 MW, and Lesugolo possesses a potential of 45 MW.

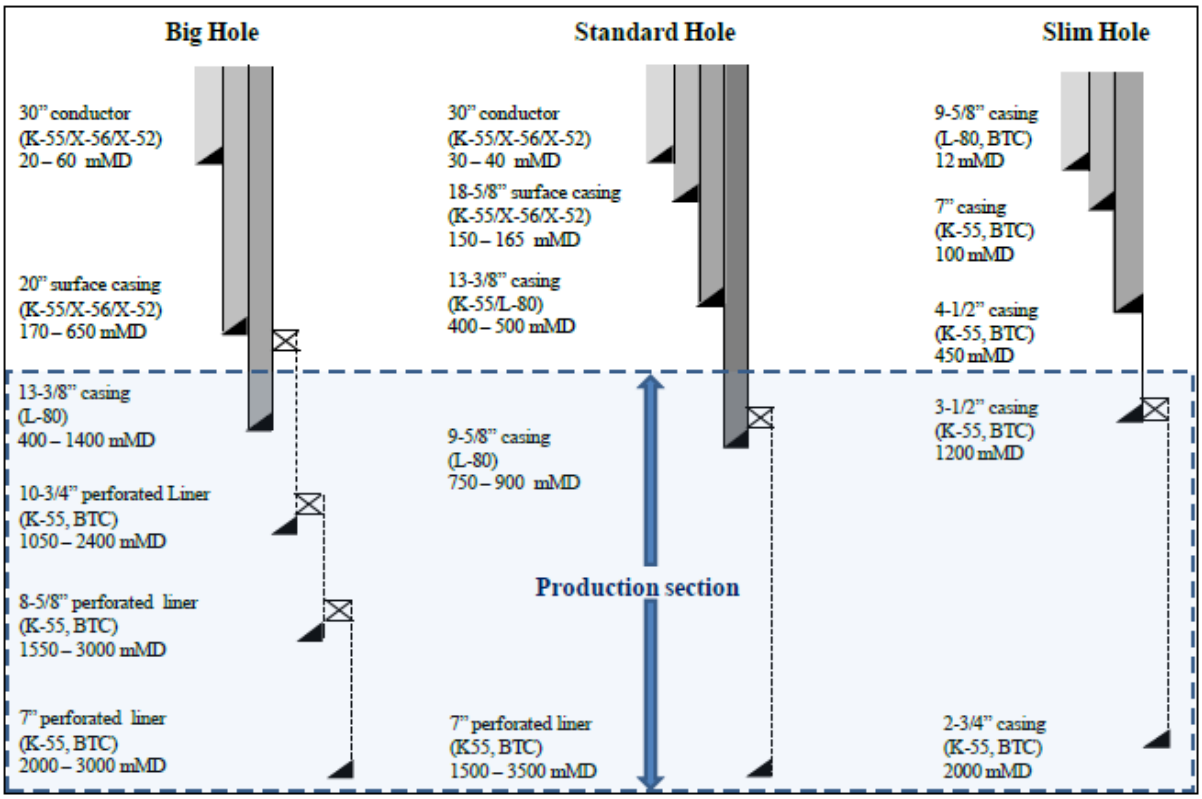


Figure 1: Typical well design and interval depth of 60 geothermal wells in Indonesia (Purwanto, et al, 2020).

2. TYPICAL GEOTHERMAL WELL DESIGN IN INDONESIA

Geothermal well designs undergo variations throughout the exploration and development stages. In the exploration phase, standard hole wells are commonly employed, while slim hole wells are used to confirm geothermal systems. In cases where developers have confidence in existing resources, they may opt for big hole wells during exploration, which can later be converted into production wells. In the development and operational phases, big hole wells are frequently utilized for the collection of geothermal fluids. According to data from 60 geothermal wells in Indonesia, approximately 83% were drilled using the big hole configuration (Purwanto, et al, 2020). The preference for big hole wells is attributed to several advantages, including the need for less surface casing, enabling deeper drilling, and offering more production hole sections. Notably, big hole wells yield 30-40% greater output compared to standard wells (Sveinbjornsson and Thorhallsson, 2014).

In the exploration stage, slimhole drilling is encouraged as it helps reduce risk and enhances exploration success, especially for companies facing resource uncertainty and budget constraints. However, it is essential to be cautious with deep slim hole drilling, as technical difficulties can lead to cost overruns. During the development phase, big hole wells prove to be more effective and efficient, providing higher steam gain and greater drilling depth. Additionally, they can utilize contingency perforated liners to address complications that may arise during drilling operations.

3. GEOTHERMAL WELL DESIGN

In geothermal applications (Hole, 2008), the most critical factor in designing a well is the high temperature loadings, affecting on the well components as follow:

- Unrestrained pipe experiences expansion, such as a 1.8 m expansion over a 1000 m length with a 150°C temperature change.
- Restrained (cemented) pipe faces compressive stress due to temperature rise, reaching 52,000 psi for a 150°C increase.
- Steel strength decreases, with casing tensile strength tests showing a reduction of 5% or more at 300°C, and wellhead equipment pressure ratings dropping by 17% at the same temperature based on ANSI Standards.
- Material competence is affected, particularly in flexible seals, leading to potential failures.

According to NZS 2403:2015, the well design follows the process as Figure 2.

4. WELL DESIGN CONSIDERATION FOR LOW-MEDIUM TEMPERATURE GEOTHERMAL SYSTEM

The other consideration beside temperature is that low-medium temperature geothermal system requires downhole pump to lift the fluid to the surface as the fluid does not naturally flow. In the scenario of production wells, each well is equipped with a downhole pump, typically lineshaft vertical turbine pump (LSP) or electrical submersible pumps (ESP), that remains positioned below the water level during production operations. Through the tubing within the production casing, the pump raises the fluid. The pumps are usually placed in the upper vertical section of the well, regardless of any deviation in the deeper section that accesses the reservoir. Therefore, it is important for production wells to possess an adequate diameter to accommodate pump installation, typically featuring production casing diameters of 13 3/8 inches or more (Febrianto et al., 2019).

5. OPTIMIZATION STRATEGY

For the purpose of this study, we have chosen the "Big Hole" well design (as depicted in Figure 4) as the foundational approach. This decision stems from the suitability of a 13-3/8” production casing for effectively accommodating downhole pumps in low-medium temperature geothermal systems. The study places its emphasis on three key aspects of well design, namely casing design, wellhead design, and rig sizing. Each of these aspects will be elaborated upon in the subsequent sections, providing an understanding of their respective roles and significance in optimizing geothermal well operations.

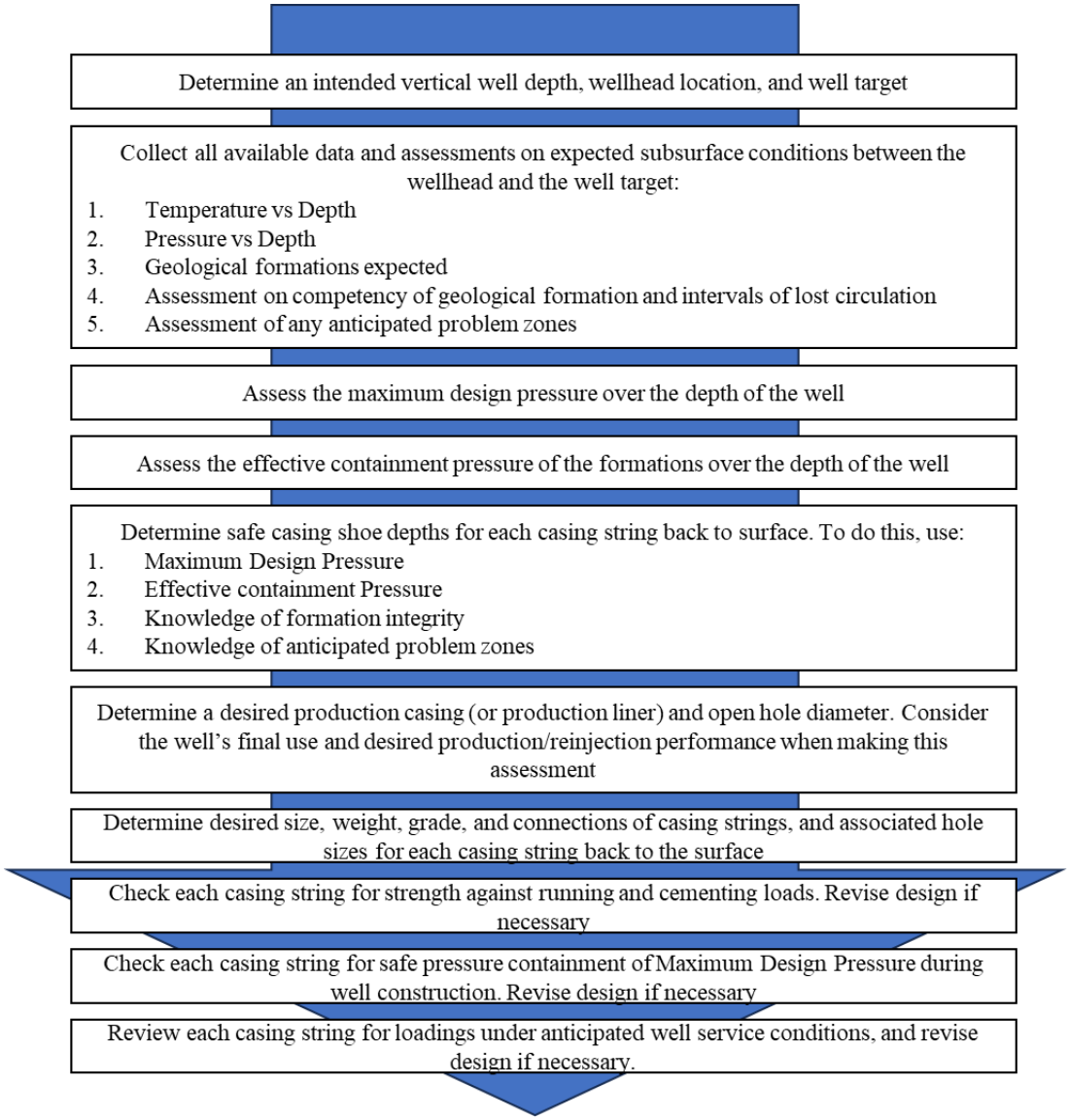


Figure 2: Geothermal well design process (NZS2403:2015).

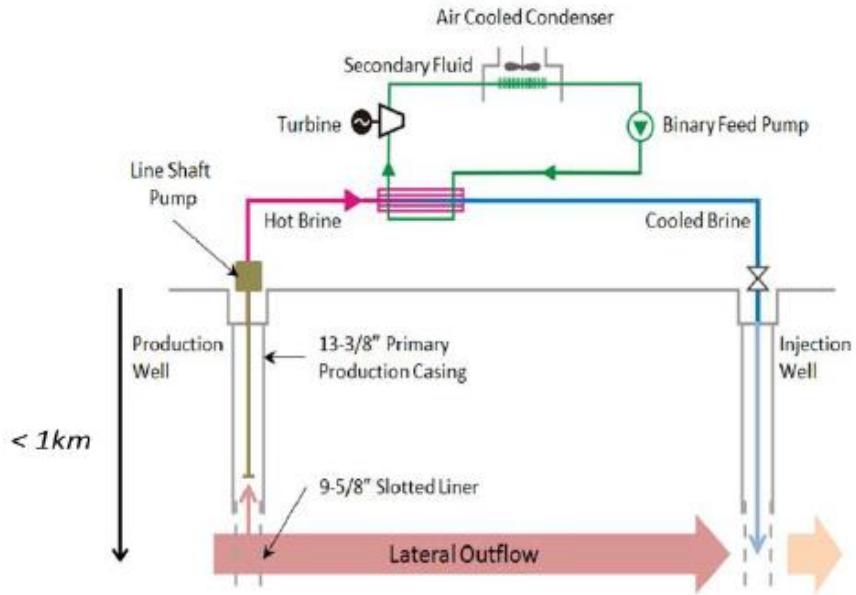


Figure 3: Schematic diagram of a typical pumped geothermal system (Febrianto et al., 2019).

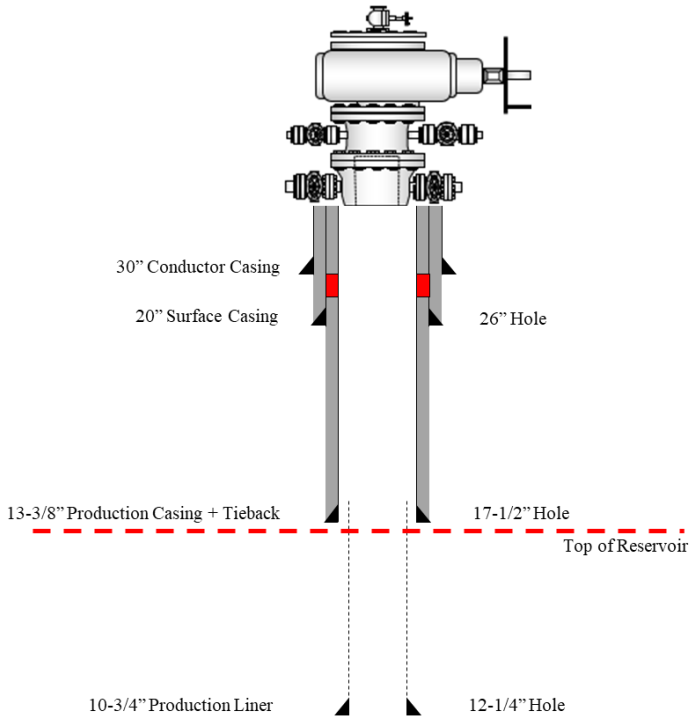


Figure 4: "Big Hole" well schematic used for low-medium temperature geothermal well study.

5.1 Casing Design

The main goal of this analysis is to assess how temperature and setting depth affect the performance of casing within the drilling and production stages of a low-medium temperature geothermal system. This study will specifically investigate two commonly used casing grade options in the Indonesian geothermal industry, namely K-55 and L-80, under varying conditions of setting depth and temperature. The primary focus will be on the production casing, including its tieback. The evaluation excludes the surface casing and production perforated liner, as their designs don't significantly differ between high-temperature geothermal systems and low-medium temperature geothermal systems. To present the findings concisely, the outcomes of these sensitivity analyses are compiled in Table 2 and Table 3.

Table 1: Sensitivity analysis cases based on depth.

		Case #1	Case #2	Case #3
Well TD		1000 m	1200 m	1500 m
Production Casing & Tieback	**Setting Depth**	600 m	800 m	1000 m
	Size	13-3/8"	13-3/8"	13-3/8"
	Weight	68 ppf	68 ppf	68 ppf
	Grade	K-55 & L-80	K-55 & L-80	K-55 & L-80
Max. Reservoir Temperature		200°C/392°F	200°C/392°F	200°C/392°F

Table 2: Sensitivity analysis based on temperature.

		Case #4	Case #5	Case #6
Well TD		1500 m	1500 m	1500 m
Production Casing & Tieback	**Setting Depth**	1000 m	1000 m	1000 m
	Size	13-3/8"	13-3/8"	13-3/8"
	Weight	68 ppf	68 ppf	68 ppf
	Grade	K-55 & L-80	K-55 & L-80	K-55 & L-80
Max. Reservoir Temperature		160°C/320°F	180°C/356°F	200°C//392°F

These cases are examined using load case scenarios (Table 3) where all the load case scenarios considered during the life of the well. The production casing and tieback are designed for burst, collapse, and tension, while the production perforated liner is designed for tension. Post yield (plastic deformation) tensile loading will be evaluated on casing string that goes beyond the derated yield strength of the casing when subjected to thermal induced stresses. The minimum safety factors applied to this study is summarized in Table 4.

Table 3: Casing load scenario for production casing, production casing tieback, and production perforated liner.

Casing String	Load	Scenario 1	Scenario 2	Scenario 3
Production casing & tieback	**Axial**	Tensile stress during running casing (weight of casing)	Tensile stress during cementing (weight of casing + pressure)	
	Burst	Burst during cementing (casing full of cement)	Burst during pressure test (hydrostatic + pressure test)	Burst due to internal pressure (pressure from reservoir)
	Collapse	Collapse during cementing (annulus full of cement, internal casing void)	Collapse during cementing (annulus full of cement, casing full mud/water)	
	Thermal Induced Stress	Compressive strength when casing is heated to the maximum system condition		
	Thermal cycle	Thermal cycle during lifetime (plastic deformation)		

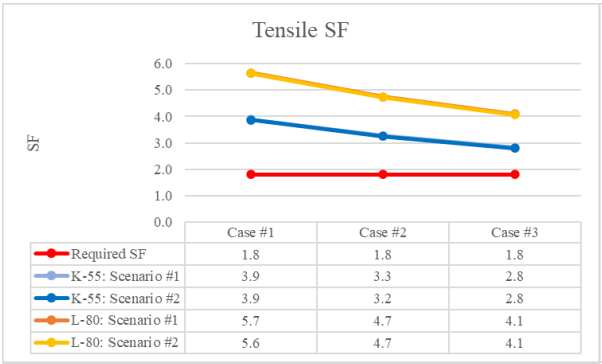
Table 4: Minimum safety factor used for casing design assessment (NZS 2403:2015; Unocal, 2001).

Minimum Safety Factor	
Minimum Tensile	1.8*
Minimum Burst	1.5*
Minimum Collapse	1.2*
Minimum Thermal Induced Stress	1.2**
Minimum Plastic Deformation Design (Thermal Cycle)	2**
Note: ***NZS 2403:2015** ****Unocal Well Design Guideline**	

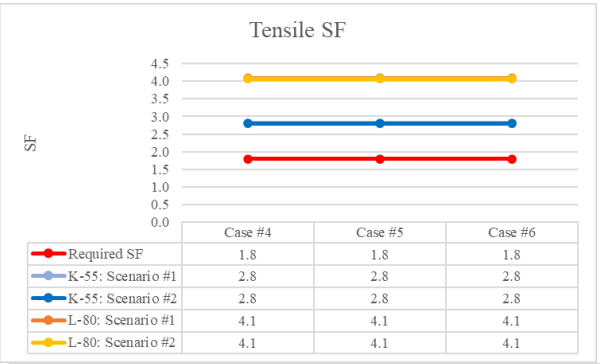
Figure 5 presents the outcomes of design factor calculations for the production casing across a range of load scenarios. It reveals that the tensile strength, burst resistance, and collapse resistance of the casing are significantly influenced by well depth, with limited impact from temperature variations. As well depth increases, the resulting design factor decreases proportionally. However, it is important to note that thermal induced stress and thermal cycle do not exhibit any substantial correlation with well depth.

The graphs also demonstrate a clear trend where the design factor influenced by thermal induced stress gradually decreases as wellbore temperatures rise. In terms of thermal cycle, the design factor for K-55 casing follows a decreasing pattern as temperatures increase, while L-80 casing displays an inverse behavior. Current hypothesis suggests that there might be a critical temperature threshold above 200°C, beyond which the design factor of casing grade L-80 is expected to decrease.

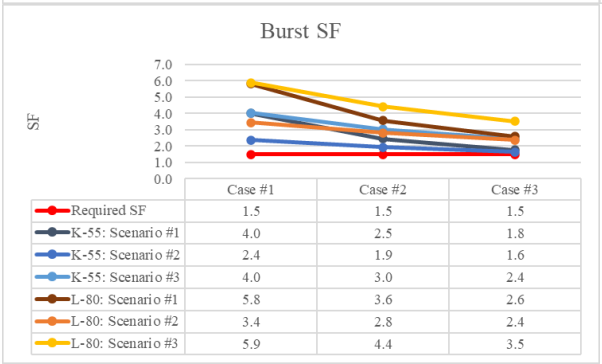
From the findings of this analysis, it can also be inferred that the K-55 casing could be a favorable choice for optimizing the production casing in low to medium temperature geothermal systems, as compared to the L-80 casing, in several scenarios simulated within this study. The K-55 casing is not deemed suitable as the production casing for Cases #4, #5, and #6, where the design factor for collapse resistance in Scenario #1 falls below the minimum safety threshold. Nonetheless, the consideration of K-55 casing remains viable given that the collapse resistance in Scenario #1, where the annulus is filled with cement and casing void, is less likely to occur.



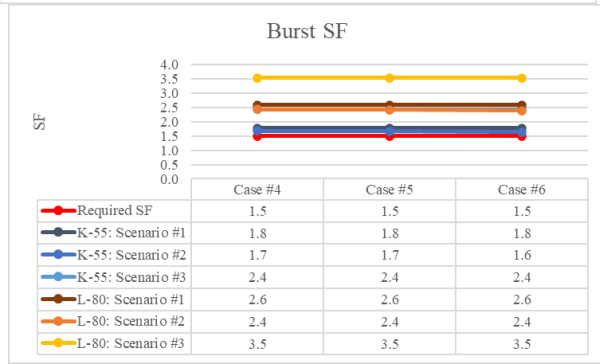
	Case #1	Case #2	Case #3
Required SF	1.8	1.8	1.8
K-55: Scenario #1	3.9	3.3	2.8
K-55: Scenario #2	3.9	3.2	2.8
L-80: Scenario #1	5.7	4.7	4.1
L-80: Scenario #2	5.6	4.7	4.1



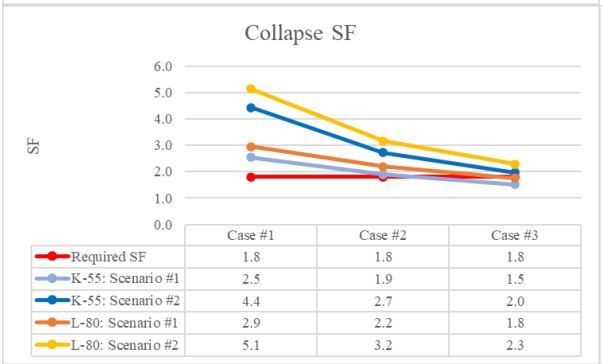
	Case #4	Case #5	Case #6
Required SF	1.8	1.8	1.8
K-55: Scenario #1	2.8	2.8	2.8
K-55: Scenario #2	2.8	2.8	2.8
L-80: Scenario #1	4.1	4.1	4.1
L-80: Scenario #2	4.1	4.1	4.1



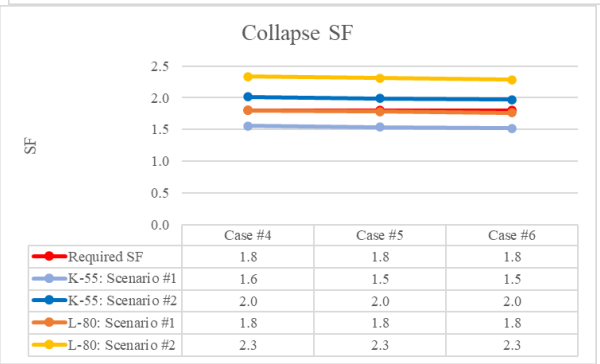
	Case #1	Case #2	Case #3
Required SF	1.5	1.5	1.5
K-55: Scenario #1	4.0	2.5	1.8
K-55: Scenario #2	2.4	1.9	1.6
K-55: Scenario #3	4.0	3.0	2.4
L-80: Scenario #1	5.8	3.6	2.6
L-80: Scenario #2	3.4	2.8	2.4
L-80: Scenario #3	5.9	4.4	3.5



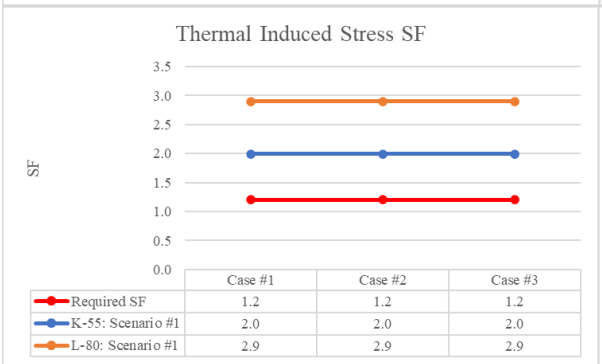
	Case #4	Case #5	Case #6
Required SF	1.5	1.5	1.5
K-55: Scenario #1	1.8	1.8	1.8
K-55: Scenario #2	1.7	1.7	1.6
K-55: Scenario #3	2.4	2.4	2.4
L-80: Scenario #1	2.6	2.6	2.6
L-80: Scenario #2	2.4	2.4	2.4
L-80: Scenario #3	3.5	3.5	3.5



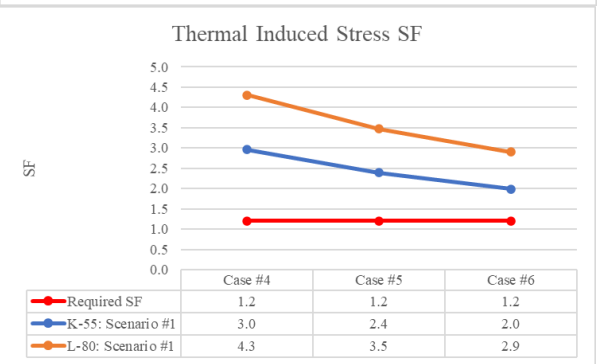
	Case #1	Case #2	Case #3
Required SF	1.8	1.8	1.8
K-55: Scenario #1	2.5	1.9	1.5
K-55: Scenario #2	4.4	2.7	2.0
L-80: Scenario #1	2.9	2.2	1.8
L-80: Scenario #2	5.1	3.2	2.3



	Case #4	Case #5	Case #6
Required SF	1.8	1.8	1.8
K-55: Scenario #1	1.6	1.5	1.5
K-55: Scenario #2	2.0	2.0	2.0
L-80: Scenario #1	1.8	1.8	1.8
L-80: Scenario #2	2.3	2.3	2.3



	Case #1	Case #2	Case #3
Required SF	1.2	1.2	1.2
K-55: Scenario #1	2.0	2.0	2.0
L-80: Scenario #1	2.9	2.9	2.9



	Case #4	Case #5	Case #6
Required SF	1.2	1.2	1.2
K-55: Scenario #1	3.0	2.4	2.0
L-80: Scenario #1	4.3	3.5	2.9

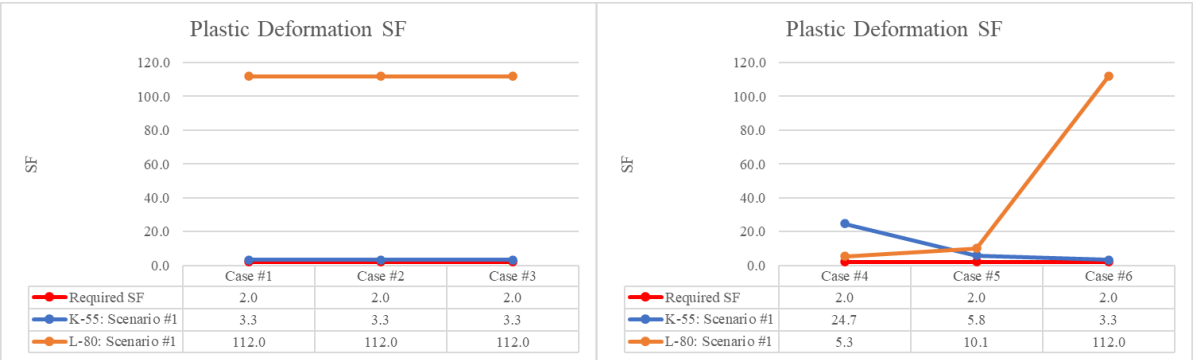


Figure 5: Design factor calculation results from six cases compared to minimum safety factor according to NZS 2403 (2015) and Unocal Well Design Guideline (2001).

When designing casings for geothermal wells, it's essential to account for thermally induced stress due to the cyclic temperature changes experienced throughout various phases, such as drilling, production, and well killing activities. According to Unocal Well Design Guideline (2001), the axial compression stress within the casing follows a linear rise with temperature until it reaches the yield point. Subsequently, while the stress remains constant, the temperature continues to increase. Upon cooling, the compression stress gradually decreases with decreasing temperature, reaching 0 psi. Beyond this point, a tensile stress emerges as the casing cools further.

To comprehensively analyze the thermally induced stress that manifest over the operational cycle of a geothermal well, it's imperative to establish a minimum operational temperature. In Indonesia, the typical initial well temperature during drilling and cementing averages around 72°C or 161°F, while the water used for post-drilling well kill operations is around 27°C or 80°F. These temperature benchmarks serve as the foundation for the subsequent assessment of thermal stress, which will be elaborated upon in the subsequent section. The thermal stress analysis for K-55 and L-80 casing under reservoir temperature range of 160°C to 200°C is summarized in Table 5. The outcomes demonstrate that within the reservoir temperature range of 160°C to 200°C, both K-55 and L-80 casings are unlikely to undergo any plastic deformation.

Table 5: Thermal stress analysis for K-55 and L-80 casing under several reservoir temperature.

Casing	Yield Temperature	Yield Stress	Temperature Cycle	Thermal Stress from 1st to 2nd Cycle	Thermal Stress at 3rd Cycle	Plastic Deform?
K-55	200°C	-45,775 psi (compression)	72°C ➔ 160°C ➔ 27°C	-31,680 psi (compression)	2,224 psi (tension)	No
			72°C ➔ 180°C ➔ 27°C	-38,880 psi (compression)	9,424 psi (tension)	No
			72°C ➔ 200°C ➔ 27°C	-46,080 psi (compression)	16,624 psi (tension)	No
L-80	247°C	-63,113 psi (compression)	72°C ➔ 160°C ➔ 27°C	-31,680 psi (compression)	15,115 psi (tension)	No
			72°C ➔ 180°C ➔ 27°C	-38,880 psi (compression)	7,915 psi (tension)	No
			72°C ➔ 200°C ➔ 27°C	-46,080 psi (compression)	715 psi (tension)	No

It should be noted that this casing design optimization study has exclusively focused on casing strength and temperature effects. The casing material assessment also warrants consideration due to the common presence of CO_2 and H_2S in geothermal fluids. Nevertheless, up to the point of this study, sufficient data regarding the specific CO_2 and H_2S content in the low to medium geothermal field is currently lacking for comprehensive evaluation.

5.2 Wellhead Design

The main goal of this section is to establish an initial wellhead design tailored to the specific temperature scope of a low-medium temperature geothermal system, which spans from 160°C to 200°C. The overarching purpose of wellhead design and analysis is to guarantee that the wellhead equipment is conceived and installed to proficiently handle production or injection fluids, while also preserving the integrity of the wellbore.

One commonly used standard in geothermal industry for wellhead design is NZS 2403:2015. Following NZS:2403 (2015) guidelines, the design of the wellhead system must account for anticipated fluid temperature and pressure, alongside the corrosive attributes of the fluids, potential scale buildup, and the capacity of the wellhead to support casing loads affected by thermal exposure. However, for this study, comprehensive information concerning the corrosive nature of geothermal fluids and the likelihood of scale deposition in low-medium temperature geothermal systems remains considerably limited, necessitating further investigation.

In this study, the assumption of saturated steam conditions is utilized to underpin the design of pressure ratings for wellheads and master valves. The wellhead components are engineered to surpass the projected pressure and temperature conditions as outlined by NZS 2403:2015. The wellhead rating can be ascertained through the use of the Temperature to Pressure de-rating plot depicted in Figure 6.

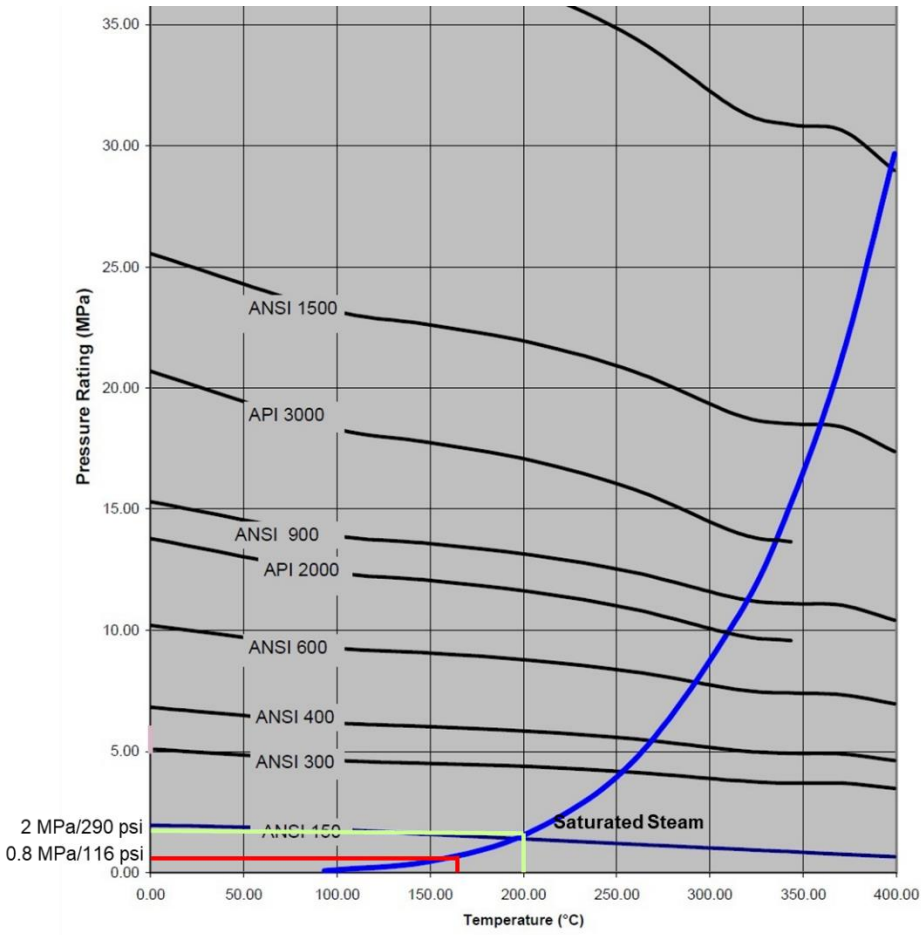


Figure 6: Wellhead working pressure de-rating conforming ANSI/ASME B16.5 and API 6A (NZS:2403, 2015).

Figure 6 illustrates that a steam temperature of 160°C corresponds to a wellhead pressure of 116 psi, indicating that the wellhead with ANSI 150 rating is suitable for this condition. Conversely, a steam temperature of 200°C results in a wellhead pressure of 290 psi, necessitating the utilization of a wellhead with ANSI 300 rating. This wellhead design operates below the designs commonly applied in high-

temperature systems, where wellheads with ANSI 400 and ANSI 600 ratings are employed for temperatures exceeding 250°C.

5.3 Rig Sizing

The significance of rig sizing lies in the realization that the size and capabilities of the rig exert substantial influence over the overall cost and timeline of the drilling endeavor. A rig falling short of the minimum prerequisites for the drilling campaign might prove incapable of executing essential tasks, consequently leading to project delays, escalated expenditures, and potential safety risks. Conversely, an excessively large rig (overcapacity) for the job might prove redundant and lead to unnecessary additional costs.

Appropriate rig sizing also profoundly impacts the safety and efficacy of the drilling operation. A rig of insufficient dimensions might lack the essential equipment and capacity necessary to handle unforeseen situations or emergencies that may crop up during drilling operations. Establishing the minimum rig criteria aids in the evaluation and selection of the fitting rig for the drilling undertaking. With a clear understanding of these criteria, drilling engineers can assess the array of available rigs and opt for the most economically viable choice that aligns with the requirements of the drilling program.

5.3.1 Hoisting & Setback Capacity

The derrick/mast capacity refers to the ability of the derrick/mast to endure the load of the BHA/drillstring while it is being lowered into the well. The hoisting capacity of the derrick or mast holds a pivotal role in the evaluation of rig size for geothermal drilling campaign. This factor establishes the upper limit for the weight of the drill string and related equipment that can be raised during drilling procedures.

In this study, the hoisting capacity is determined by calculating the combined load of the BHA and casing for the well designs in Case #1, Case #2, and Case #3, each with varying Total Depths (TD) of 1000 m, 1200 m, and 1500 m. This assessment also accounts for a Margin of Overpull (MOP) set at 100 klbs and a safety factor of 1.25. This assessment considers not only the static hook load but also the dynamic hook load, which is the combined result of the static hook load, fast line tension, and dead line tension.

The computed hoisting capacity results are summarized in Table 6. It's important to note that these BHA and casing load calculations are based on weight in air, although it's unlikely to occur in practice due to the drillstring and casing typically being filled with drilling fluid, which adds buoyancy. Therefore, the hoisting capacity values derived represent the worst-case scenario.

Table 6: Hoisting capacity calculation based on BHA and Casing load.

		Case #1	Case #2	Case #3
BHA Load (lbs)	**BHA 26"**	74,385	74,385	74,385
	BHA 17-1/2"	145,600	161,854	178,107
	BHA 12-1/4"	184,182	200,436	225,203
Casing Load (lbs)	**Casing 20"**	198,203	198,203	198,203
	Casing 13-3/8"	162,110	214,565	275,389
	Tie-Back 13-3/4"	168,408	184,661	217,159
	Liner 10-3/4"	168,408	184,661	217,159
MOP (lbs)			100,000	
Hoisting Safety Factor			1.25	
Setback Capacity Safety Factor			1.15	
Minimum Rig Hoisting Capacity (lbs)		372,754	393,206	469,236
Minimum Rig Setback Capacity (lbs)		211,809	230,501	258,983

5.3.2 Drawwork Rating

The rig's capacity or drawwork rating is indicative of the power the rig possesses while executing specific activities at particular depths, often measured in horsepower (HP). The drawworks functions as a lifting mechanism, responsible for the vertical movement of the drill string during drilling procedures. In evaluating rig size for geothermal drilling, the drawworks rating holds paramount significance as it determines the maximum feasible depth and borehole size.

This subsection encompasses the outcomes of drawwork capacity (HP) calculations necessary for executing drilling operations based on the previous hoisting capacity calculation. The intention behind scrutinizing the drawworks rating is to ensure that the chosen drilling rig for the project possesses adequate power to hoist and lower the drill string, along with associated equipment, throughout the drilling procedures.

Table 7: Drawwork rating calculation summary.

	Case #1	Case #2	Case #3
Heaviest String (lbs)	198,203	214,565	275,389
Heaviest String (lbs) with bouyancy 0.87	172,996	187,277	240,366
Desired Minimum Hookload Speed (fpm)		110	
Hook HP = Total Hoist Load x Hoist Speed / 33000	577	624	801
Drawworks HP = Hook HP / Eff^no. lines (assume 8 lines)	736	797	1,022

5.3.3 Summary of Minimum Rig Specification Requirements

Table 8 provides a summarized overview of the minimum rig requirements computed for Case #1, Case #2, and Case #3, subsequently compared against typical rig specifications found in Indonesia. In Indonesia, the prevailing land drilling rigs commonly utilized in both the oil and gas and geothermal industries are of 750 HP, 1000 HP, and 1500 HP capacities. As such, these three categories of land drilling rigs are being considered for rig selection in this study.

From Table 8, we can deduce that for the same well design type, the minimum rig requirement escalates with increasing well depth. The initial hypothesis was that drilling geothermal wells for low-medium temperature systems, which tend to be shallower, would demand smaller capacity rigs compared to those needed for high-temperature systems with greater depths. However, this assessment highlights that while a 750 HP rig could satisfy the drawwork rating and setback capacity requirements of Case #1, it falls short in accommodating the hoisting capacity requirement of up to 372 klbs. This is comprehensible as, despite the shallower well depth, the demand for hoisting capacity is significantly driven by the Big Hole well design necessitating a 13-3/8” production casing. As a result, a 1000 HP rig is a more suitable choice for Case #1.

Table 8: Comparison of Minimum Requirement with Typical Rig Specification in Indonesia.

	Case #1	Case #2	Case #3	750 HP Spec	1,000 HP Spec	1,500 HP Spec
Drawwork Rating	736	797	1,022	750	1,000	1,500
Rig Hoisting Capacity	372,754	393,206	469,236	250,000	400,000	680,400
Rig Setback Capacity	211,809	230,501	258,983	250,000	412000	500,000
Preferred Rig Adequacy	1,000 HP Rig	1,000 HP Rig	1,500 HP rig			

6. CONCLUSION

The optimization strategies discussed in this technical paper provide valuable insights into the design and drilling operations of low-medium temperature geothermal wells in Indonesia. The study primarily focused on three key aspects: casing design, wellhead design, and rig sizing. Through comprehensive analyses and simulations, the paper has shed light on the considerations required for each of these elements to ensure efficient and safe geothermal drilling operations.

In terms of casing design, the study explored the impacts of temperature and setting depth on casing and liner materials, particularly focusing on K-55 and L-80 grades. The findings indicated that the design factors of these casing materials are significantly influenced by well depth, while temperature variations have relatively less impact. The study suggests that K-55 casing could be a favorable choice for optimizing production casing in low-medium temperature geothermal systems. However, careful consideration should be given to safety factors and specific operational conditions.

The wellhead design section emphasized the importance of selecting appropriate wellhead equipment to handle the anticipated fluid temperature and pressure conditions. The study utilized NZS 2403:2015 guidelines to establish pressure ratings based on saturated steam conditions. The wellhead design aimed to ensure the integrity of the wellbore and equipment, although more research is needed to address potential corrosion and scale buildup issues.

Rig sizing was thoroughly analyzed, considering hoisting and setback capacities, as well as drawworks rating. Contrary to the initial hypothesis, the study demonstrated that even for low-medium temperature geothermal systems with shallower well depths, the demand for hoisting capacity is still significant, especially when employing Big Hole well designs. The study recommended a 1,000 HP rig as a suitable choice for these conditions.

7. RECOMMENDATIONS FOR FURTHER RESEARCH

While this paper has provided valuable insights into optimization strategies for low-medium temperature geothermal well design and drilling operations in Indonesia, there are several areas where further research can enhance the understanding and efficiency of these processes:

Corrosion and Scale Buildup: The paper briefly mentioned the potential corrosive nature of geothermal fluids and the possibility of scale deposition. Further research is needed to characterize the specific corrosive attributes and scale-forming tendencies of low-medium temperature geothermal fluids in Indonesia. This information would significantly influence wellhead and casing material selection.

Geothermal Fluid Characterization: Gather more comprehensive data on the chemical composition of geothermal fluids in low-medium temperature systems. This information would aid in material selection, wellbore design, and equipment durability.

Cost-Benefit Analysis: Conduct a comprehensive cost-benefit analysis of different well designs, casing materials, and drilling technologies for low-medium temperature geothermal systems. This would help developers make informed decisions based on economic feasibility.

REFERENCES

Fauzi, A. (2015). Geothermal resources and reserves in Indonesia: an updated revision. *Geothermal Energy Science*, *3*(1), 1–6. https://doi.org/10.5194/gtes-3-1-2015

Febrianto, R., Bydder, J., Hochwimmer, A., Ussher, G., & Libbey, R. (2019). Developing low temperature Geothermal projects in Indonesia using pumped well technology. *IOP Conference Series: Earth and Environmental Science*, *254*, 012021. https://doi.org/10.1088/1755-1315/254/1/012021

Hole, H. (2008). *Geothermal Well Design – Casing and Wellhead,* Petroleum Engineering Summer School, Dubrovnik, Croatia.

Herdianita, N., Natasha, N. (2017). *Geothermal Potency (Greenfield) of the Eastern Banda Arc Island, Indonesia*. Joint Convention Malang. Malang, Indonesia.

Purwanto, E. H., Suwarno, E., Hakama, C., Pratama, A. R., & Herdiyanto, B. (2020). *An Updated Statistic Evaluation of Drilling Performance, Drilling Cost and Well Capacity of Geothermal Fields in Indonesia*. In Proceedings World Geothermal Congress (p. 1).

New Zealand Standard, 2015: *Code of practice for deep geothermal wells*. Standards New Zealand, Wellington, NZ, 102 pp.

Sveinbjörnsson, B.M. and Thórhallsson, S. (2014). *Drilling Performance, Injectivity and Productivity of Geothermal Wells*. Geothermics, 50.

Operation and Maintenance of Dual Flash Binary Combined Cycle Geothermal Power Plant

Adethia Lufti, Richard Alexander, Dedy Setiawan, and Terry Satria Indra

KSORKA

adethia.nasution@ksorka.com, richard.alexander@ksorka.com,
dedy.setiawan@ksorka.com, terry.indra@ksorka.com

Keywords: Modular Power Plant, Organic Rankine Cycle, Binary Geothermal, Sorik Marapi

ABSTRACT

Sorik Marapi Geothermal Power is a geothermal company owned by KS Orka Renewables Pte. Ltd. that recently operated Sorik Marapi Unit 1 until Unit 4. The development of Unit 1 began after successfully exploration drilling Pad A and it was completed within 1.5 years. It took around a total 3 years, from 1st drilling of exploration A 101 well until unit 1 Commercially Operated in October 2019. Unit 1 consists of 6 steam expander and 12 steam ORC modules with various types and capacity depending on resource availability. In parallel, the company continued with exploration and exploitation drilling while operating Unit 1 and started with Unit 2 development activities.

In July 2021, Unit 2 was successfully having a commercial operation date (COD) and later followed it with COD for Unit 3 in October 2022. Currently, the company continues with exploration and exploitation drilling and construction Unit 4. It is expected unit 4 will commercially operate by the end of 2023. Currently, there are 12 modular steam expanders and 28 modular Organic Rankine Cycles (ORC) which consist of 23 steam ORC and 5 brine ORC plants with the total capacity 122 MW of net power output with average capacity and availability factors 89 % and 90 % respectively. By using Kaishan technology and combined development in each phase, the company can develop and expand the plant with greater flexibility while maximizing the utilization of resources efficiently. Compared with the conventional plant, this technology provides double the power output.

Additional benefit of development in a phase, COD can be achieved in a short period and consequently generating the revenue earlier, even though the wellhead pressure is not high enough the company still can utilize the resources as an initial revenue.

1. INTRODUCTION

The potential of geothermal energy in Indonesia is up to 30 to 40% of total geothermal energy available in the world. Sorik Marapi Geothermal Power Plant is the first geothermal that uses dual flash binary combined cycle technology in Indonesia, 122 Mwe has produced the electricity which consists of unit 1, unit 2 and unit 3. Sorik Marapi geothermal is implementing a well pad modular power plant, by using an integrated geothermal system, it is a more complicated heat resources interconnection line between one well pad and another well pad.

The small to medium scale can be expanded by adding more units with greater flexibility. In terms of opportunity, we may see how much we can get; modular units (small- to medium-scale) can also reduce the downtime period in each maintenance outage. The geothermal power station will have a good opportunity to partially shut down for maintenance, and a total shutdown can be avoided if any equipment malfunctions. Revenue maintainability will always exist by using binary systems, and with medium to low enthalpy, it may also be possible to generate electric power.

In order to maintain this power plant, 122 MW has been generated to support the SUMBAGUT (Sumatera Bagian Utara) grid. All the equipment that supported dual flash binary combined cycle units, the equipment should be reliable through the best operation and maintenance strategy and continuous improvement.

Sorik Marapi Geothermal Power (SMGP) main resources have two sections High Pressure (HP) steam and brine and Low Pressure (LP) steam and brine, HP resources is delivered 185 degC temperature of the steam and brine to HP steam expander module and the brine transferred to the LP separator for secondary flash. LP steam is combined with LP steam expander module, the steam waste becomes wet steam (steam with condensate) can be transferred to steam ORC. LP brine with 165°C temperature is the last stage of the SMGP production. Using brine ORC modules will add more net power output of electricity.

Revenue stability is the best way to prove it; it is not only how we can build the geothermal power plant faster but also how to maintain all those components of the power plant. The fastest geothermal project has brought many challenges due to the operation and maintenance phases paralleling the project expansion continuously until Sorik Marapi unit 4 and possibly unit 5. Operation and maintenance program development must be planned earlier.

Dual Flash Binary Combined Cycle Geothermal is the most advanced geothermal system in Indonesia. Recently, Steam Expander and ORC steam and brine are energy sources that support Sorik Marapi Geothermal Power (SMGP) production. The technology of the ORC unit was originally owned by Kaishan Company, and we are using an environmentally friendly motive fluid to generate electricity in ORC, refrigerant R-245Fa (PentafluoroPropane) colorless gas, which is a non-flammable liquid with a boiling point of 15.3 degrees Celsius. It is the strong point of our ORC technology, and other than that, complicated fire protection is not necessary.

Nevertheless, the balance of plant (BOP) facility in Sorik Marapi is quite different from other conventional geothermal facilities; the brine fluids need to be transferred by increasing the pressure brine transfer pump and several brine booster pumps. It has become an integrated process to generate electricity through steam and brine heat source conversion. The operation and maintenance strategy that has recently been implemented has been supported by our production process, and to overcome serious equipment problems, especially the critical source transfer equipment, Sorik Marapi conducted the BOP monitoring and analysis and mapped the critical parts by following the maintenance geothermal best practices.

Sorik Marapi Geothermal Power facilities are different from conventional geothermal fields. We have 15 brine transfer pumps and 5 brine booster pumps, those pumps transferring all the brine fluid through the ORC units. Stability of the reinjection system and the injection capacity also can maintain the production.

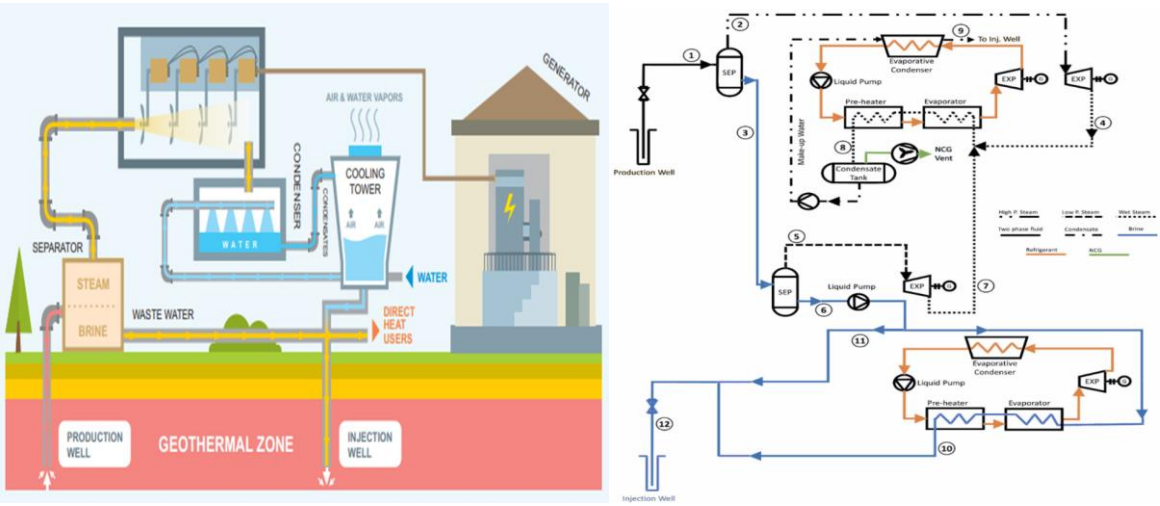


Figure 1: Conventional Geothermal vs Dual Flash Binary Geothermal Plant Overview.

2. SCREW EXPANDER TECHNOLOGY

Steam expander is the first heat expansion level of SMGP, in every unit consisting of several steam expander that are converting the heat steam to electricity. The steam expander technology is using a screw expander model as primary mover with generator set unit as an electricity producer.

High pressure steam 180°C from the separator system is transferred into the several steam expanders through in one gathering pipeline, the steam is distributed to steam expander unit 1-2-3 in the first HP steam section. Isentropic efficiency of steam expander is above 90%, it is the higher expansion machine have, the steam expander that SMGP using is screw expander. Typically, the screw expander works if the two parts are rotated together with a very small gap between the screw parts.

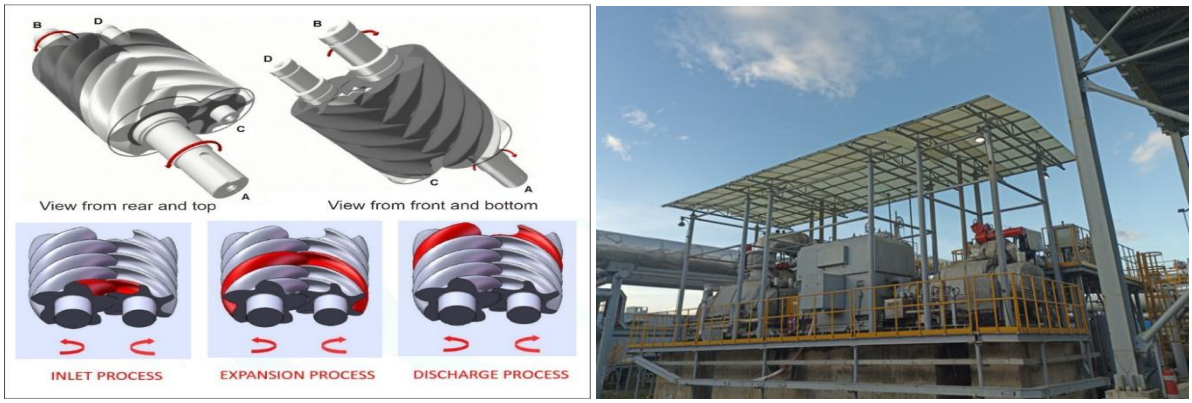


Figure 2: Screw Expander.

Screw expander rotation in 3000 rpm that is coupled by the electric generator, electricity produced by the magnetic induction and producing 11 kV electric voltage. The medium voltage (MV) is stepped up to 66 kV and 150 kV to high voltage (HV) level by using a step up transformer.

Generator voltage output and load (MW) is controlled by an electronic hydraulic control valve as a screw expander controls the following 50 Hz frequency of the PLN grid. The advantages of the screw expander are high isentropic efficiency, steam quality is not quite critical and silica scale by the wet steam would be very thin, it's like filming or coated and there is no room for deposition because of the thin gap between two parts of the screw expander.

3. BINARY POWER PLANT

Binary power plant is the new concept of geothermal power plant in Indonesia. Medium to low geothermal resources have the potential to produce high amounts of electricity with high flexibility and it's possible to develop even in the small area. Binary power plants are a relatively new technology, but they are becoming increasingly popular. This is because they are an extremely efficient and environmentally friendly way to generate electricity from geothermal resources. Binary power plants utilize waste energy: wet steam (condensate) and brine fluid (hot water). In conventional geothermal, usually the waste of steam and brine will go directly to the reinjection system; the waste heat cannot be converted to electricity because the plant technology is not sufficient to accept the low temperature level.

Binary power plant development is significantly interesting to have flexibility for maintenance programs; the plant does not need to be totally shut down during its maintenance activity. The secondary working fluid that binary plants use is typically an organic component with a low boiling point, such as isobutane or propane and also refrigerant. These characteristics have lower boiling point than freshwater, so they can be vaporized at lower temperatures (Aditya et al, 2022). This makes binary power plants a good option for geothermal resources that are too hot for direct steam generation but not hot enough for conventional flash steam power plants. Binary power plants are also more efficient than direct steam generation power plants. This is because the secondary working fluid is not heated to the

same temperature as the primary working fluid. The lower temperature of the secondary working fluid means that less energy is lost as heat; we call it the waste energy conversion by the exergy calculations.

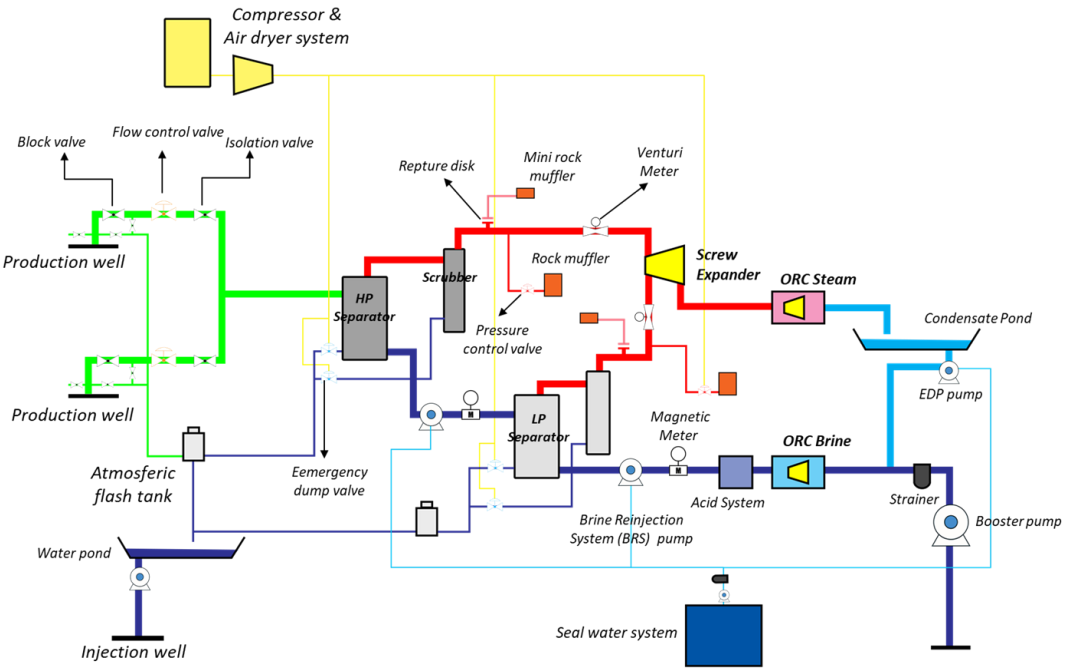


Figure 3: Sorik Marapi Binary Geothermal Plant Technology.

3.1. Organic Rankine Cycle (ORC)

The Kaishan Technologies was exist in Indonesia, the company prove the ORC technology to continue with reliable operation and low energy production costs, the company generate a percentage of energy from the thermal waste of the engine (Steam Expander), applying the ORC technology which is advantageous given the type of experience of the plant and the generation experience by implementing heat waste conversion. Figure 4 shows the simple Rankine Cycle of the ORC unit and the process flow diagram of how the ORC's works.

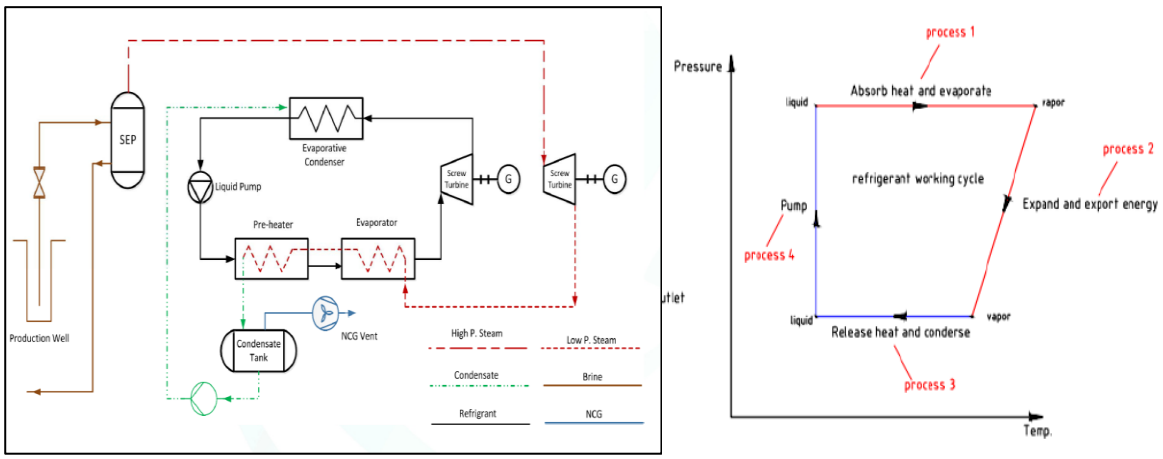


Figure 4: Steam Organic Rankine Cycle (ORC) Unit.

An Organic Rankine Cycle (ORC) is a type of geothermal plant that uses a secondary working fluid to generate electricity. The waste steam or wet steam is re-use for heating the secondary working fluid that has a boiling point at the lower temperature 15 degC. Organic vapor will directly go to the screw expander to rotate the generator as an electricity producer. The exergy loss can be reduced and converted to multiple generation, it is the best way to have high availability of the geothermal power plants.

3.2. Operation and Maintenance Method

Operability and maintainability of a Binary Geothermal Power Plant are the critical point, how to handle the integrated geothermal power plant. Some scenarios are applicable to implementing are:

- **Operator and maintenance training:** The operation and maintenance personnel should understand the operating and maintenance system. Even if modern power stations are remotely controlled, the ability and knowledge of the operators determine the smooth operation of the power plant machinery. If the operators are not well trained in the machine they operate and also do not know how to maintain the machine, the use of modern technology has no meaning.
- **Developing asset register:** Binary geothermal power plant equipment is more complicated than conventional geothermal plants due to being fully integrated and sequential and cascading. Developing asset registration is a must and that is the way we are able to categorize critical equipment.
- **Operation big data:** Despite power stations having a Distributed Control System (DCS), sorik marapi geothermal is implementing and recording all those operation parameters data in one system. Operation dashboard is developed to see power plant overview and deep analysis by using comprehensive data.
- **Developing standard procedure of binary power plant:** Plant procedure starts from the balance of plant (BOP) consisting of production well, separation system, gathering system, auxiliary system, binary modular plant and re-injection well operations.
- **First line maintenance (FLM):** The way to improve and keep operability and maintainability is on the top performance, to avoid system failure becomes urgent and emergency by doing FLM. Major problems start from minor problems, FLM activity can fix minor problems as soon as possible without any maintenance crew interference, it is being a hybrid strategy.
- **Reliability centered maintenance (RCM):** is a concept of maintenance planning to ensure that systems continue to do what their users require in their present operating context. Successful implementation of RCM will lead to increase in cost effectiveness, reliability, machine uptime, and a greater understanding of the level of risk that the organization is managing. Operators have gained good experience in handling any breakdown.
- **Brine treatment:** Binary geothermal plants significantly absorb the heat source two and three times, it will produce low brine temperature. What is the problem with low brine temperature? Silica Saturation Index (SSI) of the brine fluid becomes higher, mineral deposition possibility occurs in heat exchangers and injection lines. Brine treatment in low temperatures must be considered.
- **Cooling water treatment:** Condensate treatment in an evaporative condenser is mandatory because condensate water contaminated with oxygen (oxidation) will be affected to change the condensate PH into an acidic condensate. Corrosion effect may occur and disturb binary plant operation. Condensate treatment in low temperatures must be considered.
- **Spare Parts management:** Binary geothermal plants have critical parts that need to be maintained, integrated systems and many sequential systems have to be maintained. Balance of plant consists of brine transfer, separation system, steam gathering system including pressure and liquid control facility and auxiliary equipment are very critical. The last or waste fluid such as condensate and excess brine are released to the pond, there is a critical part also needed to have a transfer pump with good performance.

The operability and maintainability assurance of a binary geothermal power plant is confident to have the highest performance with several things to do. The important things are construction and O&M phase handover, some documents of development, completion test and everything supposed to be good handed over.

4. CONCLUSION

The success story of the Kaishan Technology combined with development strategy (partial development, depending on the readiness of resources) is important for Indonesia's geothermal development in the future. This technology is one the alternative solutions for low to medium temperatures reservoirs.

By combining rigorous people, plant, process (good operation and maintenance strategy) and following with continuous evaluation and improvement, it proves to have higher and sustain both capacity and availability. With those strategies, Sorik Marapi Plant is able to continue supporting the Sumatera Grid System with a green and reliable energy.

REFERENCES

Aditya Negara: Construction Of The Fastest Geothermal Power Plant, Sorik Marapi, *IIGCE* (p. 8). Jakarta. (2022)

Alexandra Kjeld, Helga Johanna Bjarnadottir, Ragnheiður Ólafsdóttir: Life cycle assessment of the Theistareykir geothermal power plant in Iceland, *Geothermics*. (2022)

Jose C. Jimenez-Garcia, Alexis Ruiz, Alejandro Pacheco-Reyes and Wilfrido Rivera: *A Comprehensive Review of Organic Rankine Cycles*, Mexico. (2023)

Muluken Tessema Abisa: *Geothermal Binary Plant Operation and Maintenance with Svartsengi Power Plant As a Case Study, Reykjavík*. Iceland. (2002)

Richard Alexander: Focus Improvement: Measuring Level of Condensate Pump to increase unit reliability up to 98%, Sarulla, *IIGCE* (2019)

Successful Sidetrack for Fishbone Well in Geothermal Case Study Sorik Merapi Field, Indonesia

Sarwono[1], Paulina Saraswati[1], Bambang Sigit[1], Yessica Fransisca[1], David Munoz[1], Ashadi[2], and Kiki Yustendi[2]

[1]Halliburton
[2]KSORKA

Nfn.Sarwono@halliburton.com, Paulina.Saraswati@halliburton.com, BambangSigit.Ariyanto@halliburton.com, YessicaFransisca.Sthepani@halliburton.com, David.Munoz@halliburton.com, Ashadi@ksorka.com, Kiki.Yustendi@ksorka.com

Keywords: Fishbone Well, Directional Drilling, Geothermal, Sidetrack

ABSTRACT

Fishbone well design is usually used to increase well productivity and increase accessibility to difficult geological formations, the design offers an alternative solution that is safe and more cost-effective (Dutta et al. n.d.; Farhi et al. n.d.). This design will be beneficial when drilling geothermal wells since geothermal drilling have different geological difficulties and drilling hazard compared to oil & gas wells. A sidetrack is required when starting the secondary wellbore, this sidetrack process is critical for the completion of the fishbone wells. A thorough and detailed procedure is needed to ensure a successful sidetrack.

Sidetracking is a common process in drilling operation, however sidetracking to make a fishbone well is relatively new for geothermal operations in Indonesia. Since geothermal operation have different hazard and difficulties compared to oil & gas operation, a different procedure needs to be developed and a full risk assessment is required to ensure that sidetracking process is completed in a safely manner and as required by the Geothermal company. The open hole sidetrack must be done without any additional support such a cement plug that facilitates the operation.

Well AS-339 is one of the wells in Sorik Merapi Geothermal Power (SMGP) field that was designed with a fishbone approach (consisting of 2 legs). Thorough preparation and detail review were done in the planning stage of this well to ensure the sidetrack process of the second leg in this well. Detailed discussions and adjustments were also done during the planning to accommodate the actual well position and ensure delivering a safe sidetrack process.

The implemented procedure has proven to be effective in successfully sidetracking the leg 2 safely and according to the company needs.

1. INTRODUCTION

1.1 Well Background and Purpose

Well AS-339 consisting of boreholes AS-339OH and AS-339L2 was design as multi-leg injection well from Pad AS, both wells targeted the permeability zone in the reservoir that was seen by two offset production wells. The first borehole leg (AS-339OH) is targeted closer to the existing Pad AS wells than the second borehole leg (AS-339L2) because it provides a higher probability of success while still accommodating the option of a future sidetrack. Success in this first leg will also expand the area of proven permeability, AS-339L2 is targeted to the south of AS-339OH.

The placement of the fishbone wells and the distance to the offset wells was set to less than 500m, this approach was done due to previous success with injector wells that was achieved in this same Pad AS. The multi-leg design aims to increase injection capacity and provide pressure support to the reservoir, while minimizing the cooling breakthrough and optimizing surface facilities.

As it can be inferred, the objective of the well is to maximize the geothermal power generation by effectively placing an injector well with high injection capacity by using a dual leg fishbone design.

1.2 Geothermal Well

Geothermal energy is one of the renewable energy sources, capable of generating electricity by using the stored energy coming from the hot steam/water geothermal reservoir that is pumped out through drilled wells. Geothermal drilling can be more expensive in cost per drilled foot than onshore oil and gas drilling for two principal reasons:

1. Technical challenge: Geothermal reservoirs may host highly corrosive fluids at high temperature, which means that special tools and techniques are required for the harsh downhole conditions.
2. Large diameter design: Because the produced fluid (hot steam/water) is of intrinsically low value, large flow rates and thus large holes and casing sizes are required.

The geological conditions of geothermal wells are generally harsher compared to standard oil and gas wells and might be more similar to drilling for hydrocarbons in high-pressure high temperature (HPHT) environment. Geothermal wells are generally more challenging due to the drilling and production conditions, limited equipment availability (including measurements and logging while drilling tools – MWD and LWD) and well control issues which makes it difficult to handle since it is often characterized by either high or low pressures, and high temperatures (Blankenship et al., 2005). Another challenge is that targeted reservoir zones that are normally characterized by the presence of fractures and faults that frequently lead to drilling with total mud losses.

Casing and tubing design demands high maintenance, and a quantitative risk evaluation is necessary for more complex designs. This makes the drilling part one of the most high-risk phase in the geothermal development cycle (Anon, 2012).

1.3 Challenge

Challenges identified in planning stage for the AS-339 well:

1. Drill the 12-1/4" HS Sidetrack from main hole with loss circulation condition and no cuttings return (Nugroho, Hermawan, and Lazuardi n.d.).
2. Drilling in consolidated "hard rock" formation (felsic intrusion, mixed of some clastic sediment/limestones), that can cause high drilling vibration conditions.
3. Risk of stuck pipe and losing the hole due to hole cleaning issue and high friction factor which ranges between 0.8 to 0.90 based on the actual values seen in the main hole and other offset wells (Nugroho et al., n.d.).
4. Allocate MWD and LWD technology to be used in high static temperature environment requiring a detailed circulating temperature management in order to keep the circulation bottom hole temperature below 150 ºC

2. METHOD

2.1 Well Design

As described in the well background section, SMP AS-339OH/L2 targets the high permeability zone found by offset wells AS-338 and AS-341 east of the Sumatra Fault System (SFS), the majority of which are found deep and close to the SFS (Manurung et al. n.d.). The multi-leg design aims to increase injection capacity and provide pressure support to the reservoir, while minimizing cooling breakthrough and optimizing surface facilities.

The first leg (SMP AS-339OH) is targeted closer to the existing Pad AS wells and the success in this first leg will also expand the area of proven permeability to the south of AS-338- well. SMP AS-339L2 is targeted to the south of SMP AS-339OH.

Below are the details of well plan (see figure 1 and 2):

1. 26" hole section will start from 35 to 400m measured depth (MD) using a steerable bottom hole assembly (BHA) with ElectroMagnetic measurement while drilling tool (EM MWD). The

objective is to kick off according to well plan at 300m with 1.5°/30m dog leg severity (DLS) and build to 5° Inclination in the 230.03° Azimuth direction.

2. 17 1/2" hole section will be tangent for the first 30m until 430m where a building starts with a dogleg of 2.5°/30m to end of build (EOB) at 783.52m MD using a steerable BHA. Planned target inclination is 34.46° heading to 230.03° Azimuth with total depth (TD) for the section of 1350m MD.

3. 12 1/4" hole section will remain tangent from 1350 to 2400m MD using a steerable BHA. Target is assigned at well TD with a 50m radius circle.

4. 12 1/4" second leg section to be drilled from sidetrack point at 1390 and well TD at 2200m MD using a steerable BHA. Target is assigned at well TD with a 50m radius circle.

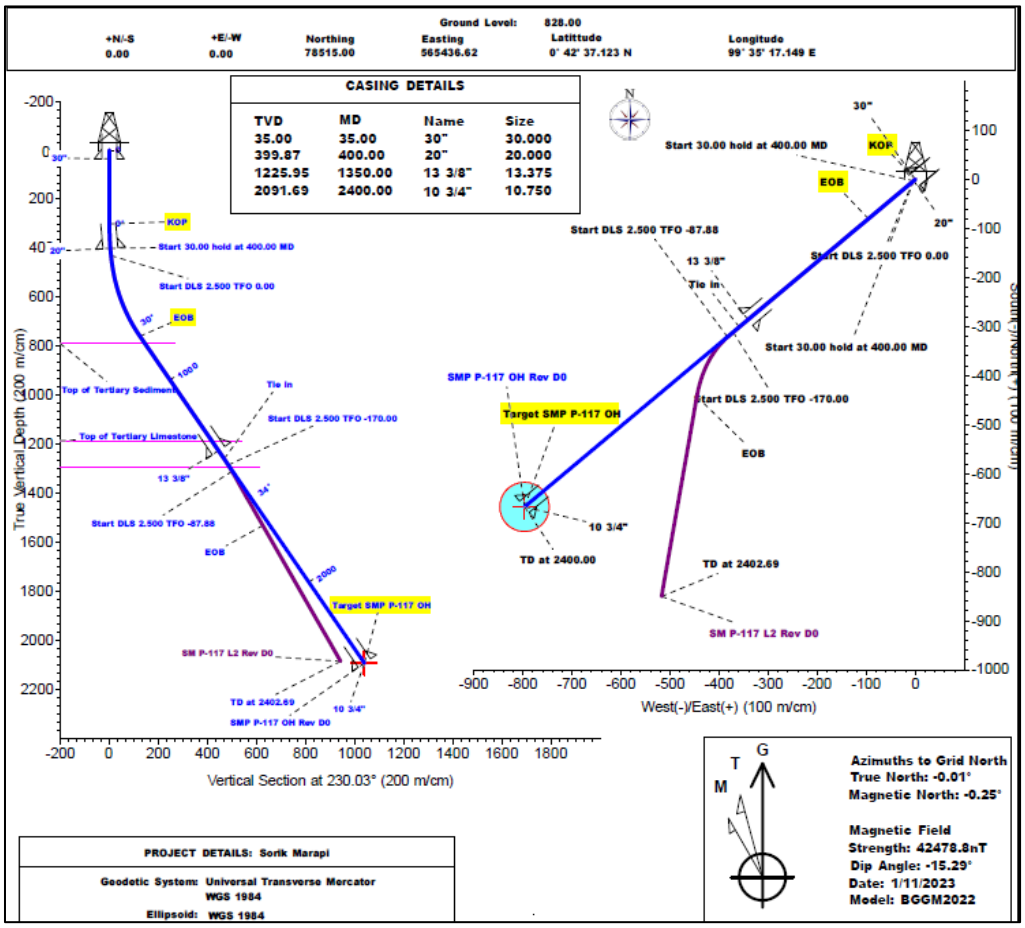


Figure 1: AS-339 Well Plot.

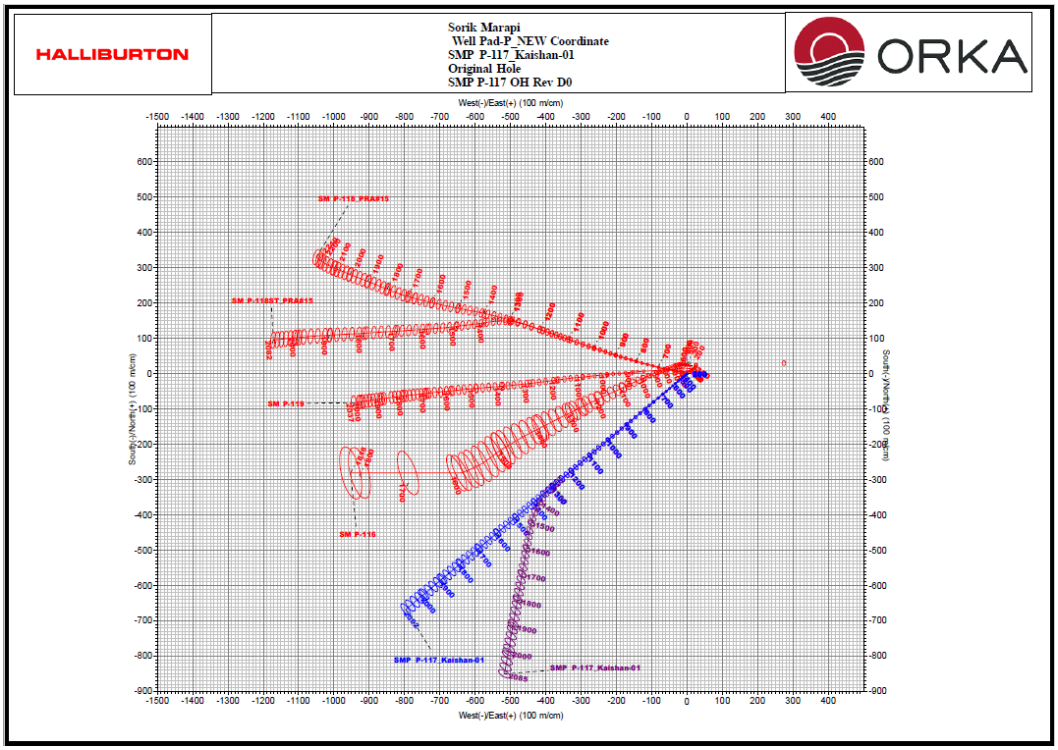


Figure 2: AS-339OH and L2 Spider Plot.

2.2 Days vs Depth

AS-339OH well Days vs Depth curve has been prepared based on the time spent during the drilling of adjacent offset wells at Sorik Marapi. A Perfect Well (P10) for the P-117OH well is shown by a blue line in Figure 3 with an estimated time of 32 days to complete the well at 2,400 m-MD, from spud to rig release. This includes 3 days of a 5-day flat time at TD to cover the time it takes to assess well success for drilling decisions (stage test) and the completed leg after the liner has been run (completion test). A borehole image log will be run prior to the stage test and before the liner is run. Additionally, estimated times based on P50 and P90 are 37 and 40 days respectively.

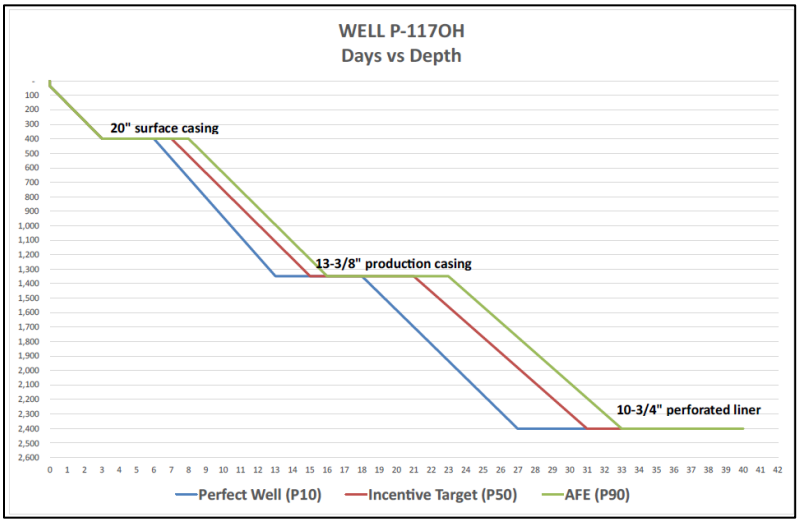


Figure 3: AS-339OH Planned Days vs Depth.

2.3 Open Hole Sidetrack Procedure

Before the execution of AS-339L2, a through planning and discussion were held between ORKA and Halliburton teams to develop a specific procedure to execute the sidetrack phase of AS-339L2 well. This procedure was generated as a guideline to assist the Directional Driller in effectively sidetracking in open hole without any support for the sidetrack (like cement). Extra precaution and relatively longer time would be needed to ensure bit is forming a ledge that will help the BHA to start separating from mother hole.

This procedure provides details in executing the sidetrack successfully, in summary the procedure outlines the following:

1. **Well planning preparation and sidetrack tie-in point:** select the point and of sidetrack that fulfill the trajectory objective of hitting the second leg target while staying within the dog leg specification for the tools to be run. Select the tool face that is normally recommended to be a low side exit (See figure 1 and 2), Sidetrack point was selected at 1390m MD.

2. **Steering tool selection:** there are multiple options, but the most common are motors, and followed by rotary steerable technology (where the preference would be a point the bit system). In this well, the motor BHA was selected as primary too due to its higher open hole sidetrack probabilities, it additionally allows to select the best approach when choosing the bend housing angle that accommodates better for the application and the dog leg requirements.

3. **Perform ledging and time drilling procedure:** it is key to make a ledge before start with a detailed time drilling procedure. For both process the time to be spend for the "ledge creation" and the pace of the "time drilling" can be selected based on the rock where the sidetrack would be performed (it is recommended to be patient as this operation is time consuming and trying to speed up the process can lead to lose what has been already achieved, requiring to start all over again)

4. **Confirming sidetrack:** this can be challenging if facing complete mud losses, therefore there won't be cuttings to be evaluated to confirm that new rock is being drilled. Therefore, it is required to wait for the surveys to confirm that the ST has been successful, it is recommended to place the surveying tool as close to the bit as possible (if an at bit inclination ABI tool is available, it can facilitate the process)

5. **Drill Pipe arrangement:** it is recommended to space out the drill pipe in order to perform the above process without interruption and connection make ups.

6. **Confirm free passage into new hole:** Confirming that it is ok to run in and out of the new hole is recommended but avoid any rotation or reaming that can compromise the sidetrack, instead use same tool face orientation that was used during the sidetrack. Then, continue drilling as per plan to TD or pull out of the hole (POOH) if the BHA for the sidetrack was a dedicated run and not aimed to drill to section TD.
   In this application a tricone bit and a motor with 1.83° bend angle was used for sidetracking the well, and then a kymera bit and a motor with 1.15º bend angle was used to drill the well to TD. This approach would increase the success probability of the open hole sidetrack (see figure 4).

7. Drilling with foam and additional chemical to reduce the friction factor and optimum hole cleaning.

COMPONENT DATA	
Item #	Description
1	12-1/4" Tricone Bit
2	8" TerraForce Lobe 6/7 - 4.0 stg, Bend angle 1.83deg
	Bottom Stabilizer
3	8" Float Sub /w Float Valve
4	12" String Stabilizer
5	8" NMDC
6	8" EM Index Sub
7	8" EM Antenna Sub
8	1 x 8" Spiral Drill Collar
9	X-Over
10	5 x 6-1/2" Spirall Drill Collar
11	4 x 5" HWDP
12	6-1/2" Drilling Jar
13	4 x 5" HWDP
14	Drill Pipe 5 in

COMPONENT DATA	
Item #	Description
1	12-1/4" Kymera Bit
2	8" TerraForce Lobe 6/7 - 4.0 stg, Bend angle 1.15deg
	Bottom Stabilizer
3	8" Float Sub /w Float Valve
4	11-1/2" String Stabilizer
5	8" NMDC
6	8" EM Index Sub
7	8" EM Antenna Sub
8	1 x 8" Spiral Drill Collar
9	X-Over
10	5 x 6-1/2" Spirall Drill Collar
11	10 x 5" HWDP
12	6-1/2" Drilling Jar
13	4 x 5" HWDP
14	1 x 5" Sacrificial Joint
15	3 x 5" HWDP
16	Drill Pipe 5 in

Figure 4: Sidetrack BHA.

3. RESULT AND DISCUSSION

Implementation of this procedure proved to be successful in assisting drilling operation during execution of the well. Sidetrack and second leg were executed smoothly (see Figures 5 and 6) and faster than planned days (see figure 7) 11.3 days planned but achieved in 9 days (Leg2 well TD was called earlier).

Measured Depth (m)	Inclination (°)	Azimuth (°)	Vertical Depth (m)	+N/-S (m)	+E/-W (m)	Vertical Section (m)	Dogleg Rate (°/30m)	Toolface Azimuth (°)	Build Rate (°/30m)	Turn Rate (°/30m)	Distance to Plan (m)	Y Offset to Plan (m)	X Offset to Plan (m)
1,323.60	31.94	232.44	1,201.32	-280.46	-345.36	434.91	0.000	0.00	0.000	0.000	0.00	0.00	0.00
1,350.00	30.94	231.70	1,223.85	-288.92	-356.22	448.31	1.221	-159.22	-1.140	-0.843	0.32	0.32	0.01
13 3/8"													
1,393.10	29.31	230.39	1,261.13	-302.52	-373.04	469.44	1.221	-158.59	-1.133	-0.911	2.22	2.21	0.08
1,409.40	26.47	224.93	1,275.53	-307.63	-378.68	476.96	7.025	-140.42	-5.227	-10.049	3.39	3.33	0.62
1,428.70	26.77	222.25	1,292.79	-313.90	-384.64	485.58	1.924	-77.17	0.466	-4.166	4.78	4.52	1.56
1,448.70	28.26	220.20	1,310.53	-320.85	-390.73	494.81	2.648	-33.35	2.235	-3.075	5.47	4.88	2.47
1,467.50	30.40	217.78	1,326.92	-328.01	-396.52	504.02	3.903	-30.04	3.415	-3.862	5.51	4.46	3.23
1,488.92	33.39	215.81	1,345.10	-337.07	-403.29	515.32	4.434	-20.03	4.188	-2.759	5.17	3.43	3.87
1,507.60	35.67	214.26	1,360.49	-345.75	-409.36	525.89	3.924	-21.72	3.662	-2.489	4.67	2.03	4.20
1,525.40	36.06	212.57	1,374.91	-354.45	-415.10	536.27	1.793	-69.19	0.657	-2.848	4.39	0.60	4.35
1,544.80	37.39	211.54	1,390.46	-364.28	-421.26	547.79	2.266	-25.26	2.057	-1.593	4.37	-0.81	4.29
1,564.40	38.17	209.77	1,405.95	-374.61	-427.38	559.68	2.044	-54.97	1.194	-2.709	4.58	-2.23	4.01
1,583.40	38.82	208.36	1,420.82	-384.95	-433.12	571.33	1.724	-54.03	1.026	-2.226	4.94	-3.39	3.59
1,601.30	39.58	205.58	1,434.70	-395.03	-438.25	582.41	3.208	-67.69	1.274	-4.659	5.36	-4.38	3.10
1,621.80	40.48	201.98	1,450.40	-407.09	-443.56	595.14	3.635	-70.14	1.317	-5.268	5.98	-5.32	2.74
1,641.50	40.69	199.56	1,465.36	-419.08	-448.11	607.33	2.419	-83.32	0.320	-3.685	6.46	-5.87	2.68
1,660.40	41.22	199.21	1,479.63	-430.76	-452.22	619.01	0.917	-23.54	0.841	-0.556	6.92	-6.28	2.91
1,679.70	40.68	199.21	1,494.21	-442.71	-456.38	630.93	0.839	180.00	-0.839	0.000	7.41	-6.68	3.22
1,698.70	40.90	199.98	1,508.59	-454.40	-460.54	642.66	0.867	66.67	0.347	1.216	7.81	-6.98	3.50
1,718.10	41.17	200.54	1,523.23	-466.35	-464.95	654.73	0.705	53.92	0.418	0.866	8.23	-7.39	3.64
1,737.30	41.29	199.89	1,537.67	-478.22	-469.33	666.73	0.695	-74.60	0.187	-1.016	8.71	-7.91	3.66
1,756.90	41.24	200.11	1,552.40	-490.37	-473.75	678.97	0.235	109.10	-0.077	0.337	9.23	-8.41	3.82
1,775.80	40.90	200.31	1,566.65	-502.02	-478.04	690.74	0.579	158.95	-0.540	0.317	9.66	-8.83	3.93
1,795.00	40.48	200.92	1,581.21	-513.74	-482.44	702.64	0.904	136.79	-0.656	0.953	9.94	-9.10	4.00
1,814.10	39.94	201.13	1,595.79	-525.25	-486.87	714.38	0.874	165.99	-0.848	0.330	10.04	-9.24	3.94
1,833.30	39.11	201.95	1,610.60	-536.61	-491.35	726.05	1.532	148.16	-1.297	1.281	9.89	-9.11	3.84
1,852.80	38.62	201.85	1,625.79	-547.97	-495.92	737.76	0.760	-172.74	-0.754	-0.154	9.50	-8.81	3.55
1,872.10	38.10	202.33	1,640.92	-559.07	-500.42	749.24	0.932	150.38	-0.808	0.746	8.95	-8.32	3.29
1,891.20	37.45	202.86	1,656.02	-569.87	-504.92	760.48	1.141	153.67	-1.021	0.832	8.18	-7.64	2.93
1,910.90	36.92	203.12	1,671.71	-580.83	-509.57	771.93	0.842	163.59	-0.807	0.396	7.17	-6.75	2.44
1,930.50	35.97	202.98	1,687.48	-591.54	-514.12	783.14	1.460	-175.05	-1.454	-0.214	5.93	-5.62	1.90
1,949.20	35.46	203.39	1,702.66	-601.58	-518.42	793.66	0.904	155.03	-0.818	0.658	4.52	-4.30	1.39
1,968.30	34.96	203.32	1,718.27	-611.69	-522.79	804.27	0.788	-175.41	-0.785	-0.110	2.91	-2.79	0.80
1,987.60	34.42	203.61	1,734.14	-621.76	-527.16	814.87	0.878	163.12	-0.839	0.451	1.11	-1.10	0.20
2,007.20	33.63	205.05	1,750.38	-631.76	-531.68	825.49	1.727	135.03	-1.209	2.204	1.04	0.84	-0.61
2,026.30	32.97	204.14	1,766.34	-641.29	-536.04	835.66	1.300	-143.25	-1.037	-1.429	3.31	2.98	-1.43

Figure 5: AS-339L2 Distance to Plan.

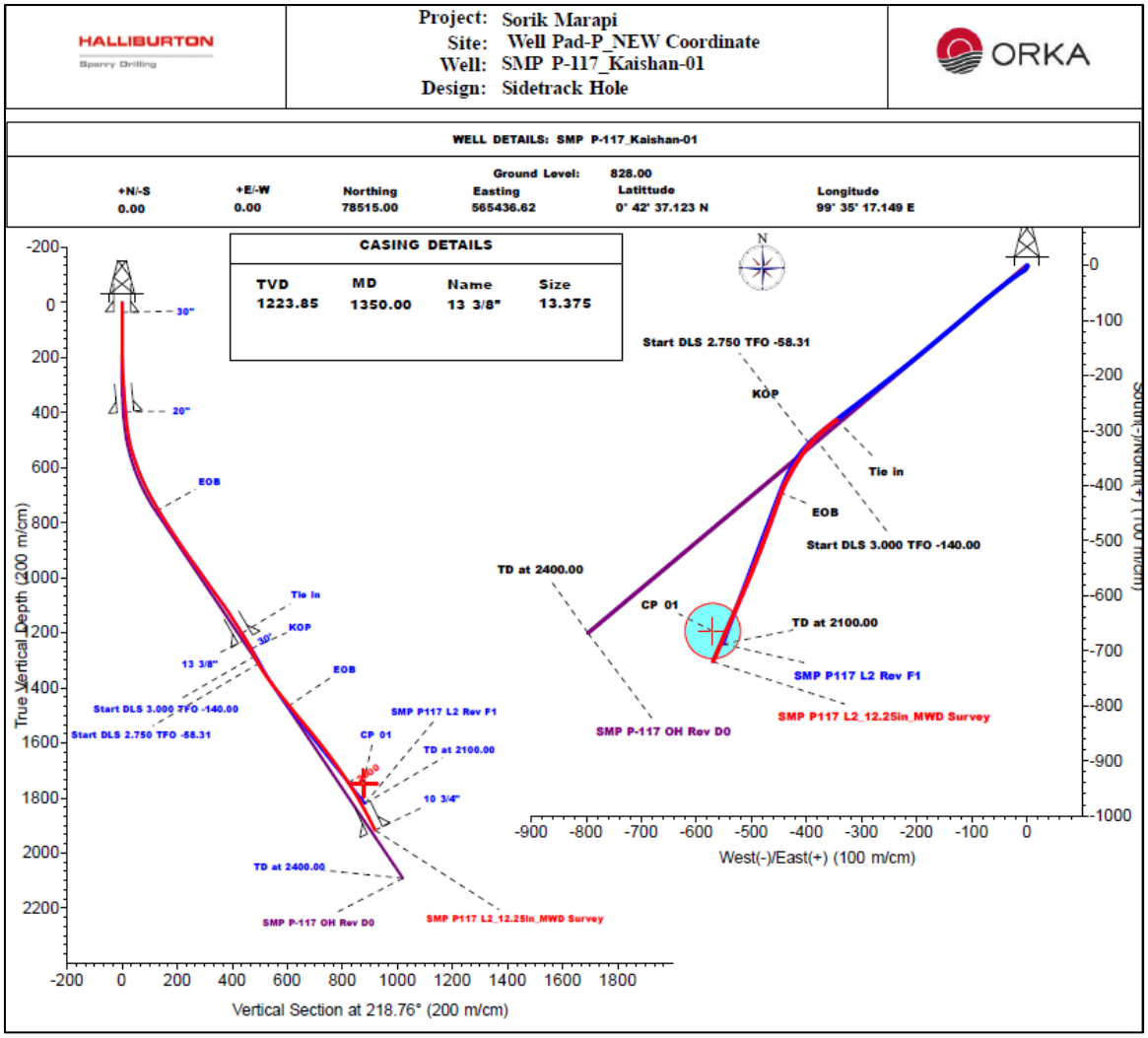


Figure 6: AS-339 Final Plot.

4. CONCLUSION

Implementing this selected procedure proved to be successful in assisting drilling operation during the well execution. AS-339 was considered successful well both in drilling and reservoir target for an injection well:

1. Successfully drilling open hole sidetrack in one run. While performing the ledge, no cutting return to confirm the hole sidetrack was being successful. Only used the EM MWD surveys to confirm separation from main hole.
2. Reduced friction factor and continue drilling to TD without any issue.
3. Save 2.3 drilling days during the sidetrack execution and drilling of the second leg.
4. Prove that fishbone drilling with open hole sidetrack is doable in geothermal wells and can represent an attractive option that could help to reduce overall well cost, while increasing the injection and production flows.

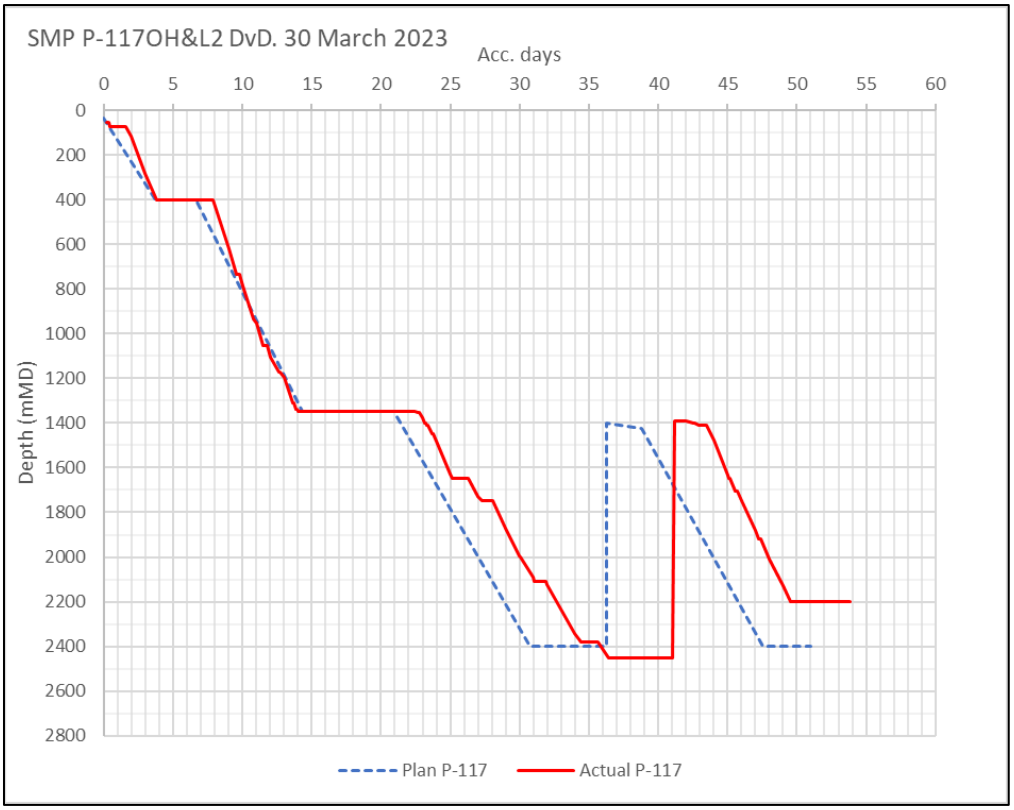


Figure 7: AS-339 Time vs Depth for Plan and Actual.

REFERENCES

Anon. 2012. Geothermal Energy Systems: Exploration, Development, and Utilization. 2nd reprint. Weinheim: Wiley-VCH.

Blankenship, D. A., J. L. Wise, S. J. Bauer, A. J. Mansure, R. A. Normann, D. W. Raymond, and R. J. LaSala. 2005. "Research Efforts to Reduce the Cost of Well Development for Geothermal Power Generation." OnePetro.

Dutta, Ashim, Mariam Ahmed Al Hosani, Jose Alejandro Aranda, Rashad Masoud, Abiodun Isiaka Jaiyeola, Mohamed Ahmed Baslaib, Ahmed Mohamed Al Bairaq, Adel Mohammed Al Hammadi, Mubashir Ahmad, and Ayman El Shahat. n.d. "Effective Multilateral Open Hole Sidetrack Strategy in Thin Reservoir Units for Maximum Reservoir Contact-A Case Study of Onshore Drilling in UAE."

Farhi, Nadir, Mohamed Ahmed Abdel Samie, Walid Saher Nouh, Hamdi Saber Ibrahim, Hadi Saad, Youcef Mohammed Khan, Abdullah Jaffar Merza, and Talal Abdulhameed Hussain. n.d. "Unconventional Drilling and Creative Solutions Delivered World Record a Multi-Laterals Fishbone All Legs Drilled, Accessed and Stimulated First Attempt - Case Study from Kuwait."

Manurung, Vinda Berlianta, Laila Warkhaida, David Jockey Hutabarat, Taufan Maulana, Christovik Simatupang, Dhani Sanjaya, Riza Pasikki, Redha Bhawika Putra, and Ks Orka. n.d. "LWD Acquisition of Caliper and Drilling Mechanics as a New Approach on Geothermal Drilling Operation, a Case Study in Sorik Marapi Field – Indonesia."

Nugroho, W. A., S. Hermawan, and B. H. Lazuardi. n.d. "Drilling Problems Mitigation in Geothermal Environment, Case Studies of Stuck Pipe and Lost Circulation."

The Impact of Tie Back Engineering on Geothermal Power Plant Production, Case Study: Change in Steam Production Phase WP-L Patuha Geothermal

Mochammad Fa'iq Khasmadin, R. Bayu Wibowo, and Huda Nugraha

PT Geo Dipa Energi Unit Patuha, Bandung, Indonesia

faiq@geodipa.co.id, r.bayu@geodipa.co.id, Huda@geodipa.co.id

Keywords: Geothermal Modification, Irreversibility, Energy Efficiency, Exergy Efficiency, Tie Back Engineering

ABSTRACT

The Indonesian government provides sources of fossil energy as well as new and renewable energy (EBT) in an effort to ensure national energy security, which is accompanied by an increase in electrical energy demand each year. Geothermal energy is one of Indonesia's renewable energy sources. There are several conditions in geothermal extraction that may reduce the efficacy of geothermal power plants. One example of this phenomena is a phase transition anomaly in one of the wells (WP-L) at PLTP Patuha in 2016. The phase shift was caused by the flow of surface water into the well as a result of a casing leak (WP-L). The producing system emerged as a result of a well's phase shift from an initial steam-dominated phase to a mixed phase of water. The switch of the generating system from Direct Dry Steam to a Separated Steam Cycle is expected to impair the plant's thermal and exergy efficiency. Meanwhile, PLTP Patuha is executing workovers in wells that had a phase change in 2020 in an effort to improve the producing system. The major steps taken were cementing the leaking casing in the well (WP-L) and employing technical procedures to tie back. Tie back engineering solutions may be used to alleviate the two-phase steam problem in WP-L. The true result of the approach may be observed in the demister's increased energy efficiency from 93% to 94%. Because of this program's ability to reduce wasted mass flow in the flow drain demister, the demister's irreversibility value was reduced from 18,369.41 kW to 12,271.87 kW after tie back engineering was completed, demonstrating a significant change in the amount of energy wasted from the flow demister drain. An increase in the exergetic efficiency rating of the demister has an effect on the quality of the steam entering the turbine intake. Turbines cannot fully use the exergy value of the steam collecting system of 273,202.33 kW to generate power. The generator is estimated to have a maximum energy efficiency rating of 37% and a maximum generating output of 61,968 kW. According to thermodynamic calculations, the tie back engineering technique has a substantial impact on the quality of the steam fraction entering the demister.

1. INTRODUCTION

Indonesia has a geothermal potential of 29.5 GW, which will expand when additional geothermal resources are identified (Agency for the Assessment and Application of Technology, 2020). Patuha Geothermal is a 60MW power production. Efforts to improve continually result in cost savings. According to PT Geo Dipa Energi - Patuha (2019), this facility has been in operation since 2014 and is supported by 9 operating wells with a dry phase. Patuha Geothermal has encountered an anomaly with a shift in phase conditions from one of its wells over time. The presence of a casing breach, which allows water to enter the pipeline in the well, has altered its phase from dry to mixed (water and steam). Patuha Geothermal has a policy of fixing an aberrant condition in one of its wells to preserve the condition of its producing equipment. The first kind of maintenance is the installation of a separator. The separator's role is to separate the mixed phase from the dry phase. (Saptaji, 2001).

Patuha Geothermal has been investigating the reasons of the pipe leak for four years. Patuha Geothermal investigated the WP-L anomaly by doing a workover in 2020 and discovered a surface water leak that had penetrated the pipe casing. Dealing with unusual circumstances in the WP-L well requires creativity. Tie Back engineering involves cementing and installing smaller pipe casings inside the Well-pad to alter the steam pipeline system and fix faulty pipes. Tie Back Engineering is the best technology, which is implemented by disconnecting the connection from the well head to the separator and altering

it by not operating the separator as a two-phase steam separator. The pipeline is then routed straight from the WP-L well head to the main steam line steam collecting system (SGS).

Engineering attempts to tie back are thought to have a significant influence on variations in the steam phase entering the intake demister header. Prior to the implementation of this invention, the fractional value of steam entering the demister tended to be wet, with a fractional value of 98% (Patuha Production Data - PT Geo Dipa Energi, 2020); this value is the consequence of separating the steam phase in the separator. Despite the use of a separator, the bulk flow of water continues to exit the drain demister outlet. Using computational and thermodynamic research, this study examines the influence of tie back engineering innovation on generation at Patuha Geothermal.

2. METHODS

2.1 Research Methods

Tie back engineering activities are thought to have a substantial influence on changes in the steam phase entering with dry steam production that occur within one year. The following stage is to identify equipment specifications, generating operational data, environmental observation data, and geochemist fraction observation data. The next stage is to develop a system modeling and energy balancing framework based on changes in the producing system. Data was observed for 12 weeks before and after the system modification. These data will be modeled into computations using Microsoft Excel. Data analysis comes after compiling, calculating, and comparing data. As a consequence, the empirical results gained from the analysis. Figure 1 depicts the study's flowchart.

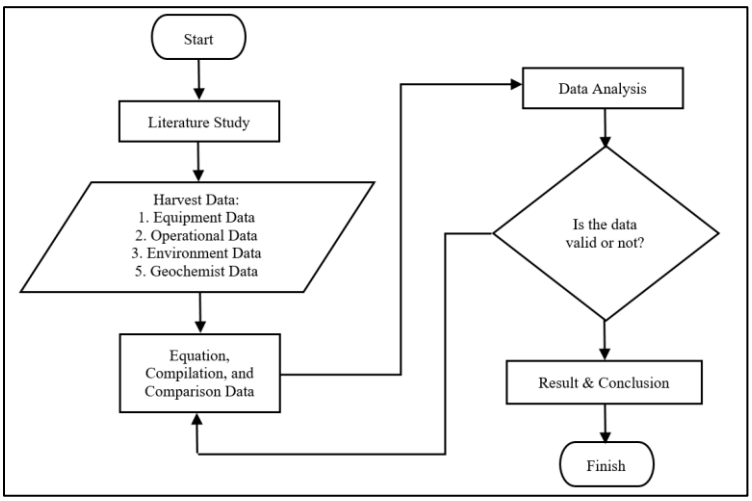


Figure 1: Flow Chart Method of Study.

2.2 Data Validation

Equations and data modeling are carried out using the MS Excel application. The enthalpy and entropy calculations of each were validated using the X Steam Tables Excel Macros IF-97 by Magnus Holmgren and Table A-4 in Standard International Units. Thermodynamic Properties of Water, Including Vapor, Liquid, and Solid Phases After validation, the energy and exergy values can be calculated and analyzed.

2.3 Energy Analysis

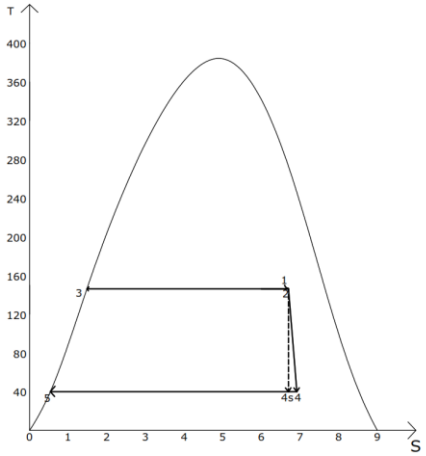


Figure 2: T-s Diagram for Patuha Geothermal.

Before carrying out an energy analysis, it is necessary to identify and calculate the energy balance and state of each piece of equipment to facilitate input and output parts in a system (Aziz, 2011). The energy balance is shown in Figure 5. The scope of this analysis will carry out calculations from downstream to upstream (state 0–state 4). Calculations to determine each state will be contained in Formula 1 (DiPippo, 2007).

$$E_{n\,state} = \dot{m_{state}}\, x\, (h_{state}) \tag{1}$$

The efficiency of the Plant (thermal) is the ratio between the output power and the input power using Formula 2 (DiPippo, 2007).

$$\text{ŋ Plant} = \frac{W_{output}}{Q_{input}}\, x\, 100\%, \tag{2}$$

2.3 Exergy Analysis

Exergy analysis is a form of the development of the second law of thermodynamics that is used to calculate the sum of the values of irreversibility and exergy efficiency in a thermal power plant (Cengel & Boles, 1998). This analysis will initiate from the dead state to state 4. The focus of this analysis is only on physical analysis and ignores kinetics and chemistry. In an exergy analysis, the enthalpy and entropy values of the dead state (environment) will affect the irreversibility and exergy efficiency of the generator (Rudiyanto, Bahtiyar, Pambudi, Widjonarko, & Hijriawan, 2021). The calculation of the exergy analysis of the power plant can be formulated in Formula 3 (DiPippo, 2007).

$$E_i = \dot{m}_i.[(h_i - h_0) - T_0(S_i - S_0)] \tag{3}$$

The exergy balance of geothermal compliance in each state is presented in Table 2. The exergy efficiency of each component is contained in formulas 4 and 5 (Pambudi, Jalilinasrabady, & Jaelani, 2014).

$$\eta_{Exsergy\,state} = \left[1 - \left(\frac{\dot{I}}{\dot{E}_{input}}\right)\right] x100\% \tag{4}$$

$$\eta_{Ex.Plant} = \frac{\dot{W}_{out}}{\dot{E}_{in}} x100\% \tag{5}$$

3. GEOTHERMAL ENERGY IN PATUHA

3.1 Description of Patuha Geothermal

Based on previous studies, the Patuha field geothermal has a potential energy of 400MWe. GPP Compliant (Geothermal Power Plant) run by a state-owned business under the Indonesian Minister of Finance, which operates the Patuha Unit 1 plant with a capacity of 60 MW (Khasmadin & Harmoko, 2021). There are 9 geothermal wells and 2 reinjection wells. The average steam flow production capacity for 60 MW is 373 ton/h at 7.1 bar pressure. It will respond to fluctuations in generator operation (PT Geo Dipa Energi - Patuha, 2019).

3.2 Description of Patuha Anomali and Tie Back Engineering

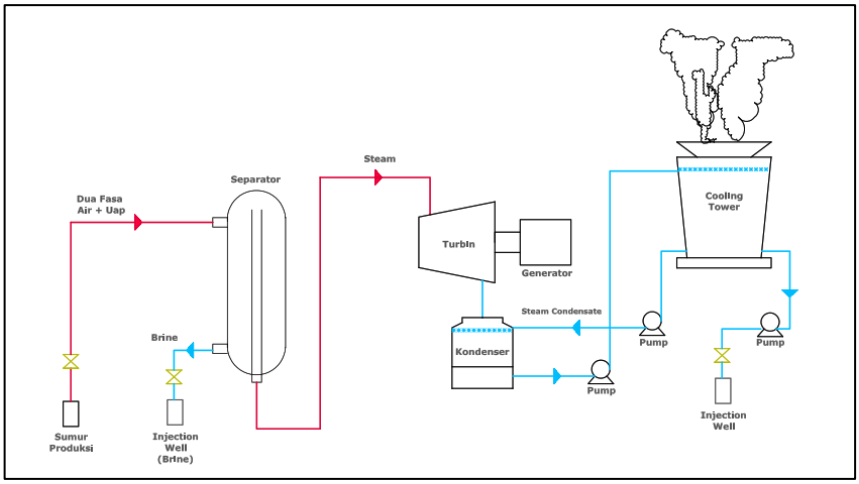


Figure 3: Illustration of WP-L before modified.

The Patuha Anomaly happened in 2016, when the geochemist team discovered that indications from one of the Patuha wells were suffering a phase transition condition. Repairs are being performed to the pipeline that enters the steam main line as a result of this anomaly. The well is WP-L, and the first line alteration is the installation of a separator to separate the mixed phase (steam and water) between the wellhead line and the main steam line. After analyzing this anomaly for four years, the business discovered that there was a leak of surface water that entered the well, allowing the phase in the WP-L well to mix with water. In 2020, the business completed a beneficial workover to boost the WP-L well's production efficiency. The workover was successful in correcting the pipe leak at WP-L by cementing it and installing a smaller-diameter pipe than the existing pipe. Because the pipe leak has been repaired, the Tie Back Engineering procedure is required. This technique involves altering or modifying the pipeline such that instead of the wellhead first sending steam to the separator, the wellhead now sends steam straight into the main steam line, as shown in Figure 3.

3.3 Description of State and Patuha Data System

The Patuha Geothermal has relatively the same main components before and after the tie back engineering activities, the only difference lies in the path and bypass separator at WP-L. The main components of the generation include separator, steam gathering system, demister, rock muffler, atmospheric flash tank, turbine, main condenser, inter-condenser, after-condenser, first stage ejector, cooling tower, ejector (1st and 2nd stage), Hot Well Pump, Liquid Ring Vacuum Pump, Auxiliary Cooling Water Pump. The wet phase well before the tie back engineering was carried out was WP-L. The function of the separator is to separate the mixture of water and steam in the well before it is channeled into the main steam line (Aziz, 2011). The steam produced is a combination of several wells (west and east wells). The western wells include WP-L, WP-L1 and WP-P. While the eastern wells include (WP-K, WP-K1, WP-K2, WP-M, WP-N, WP-O, WP-Q, WP R, and WP-S). The schematic of the gathering system is shown in the figure, as shown in Figure 4.

In this research, the schematic of the power plant will be shown in general as shown in Figure 5. The existence of tie back engineering does not affect the identification and analysis of the state of this

research. State 0 is an environmental condition which is defined as a dead state which will later be associated with irreversibility. State 1 is the inlet demister (steam gathering system) where in this state all steam from various wells will accumulate in this state. The range of steam fraction in this state is 98-99.8% dry steam dominated. The contribution of the WP-L mass flow steam is only 9% of the total steam gathering system, so the presence or absence of a separator does not have significant implications for the fraction that enters the demister. State 2 is the fluid that is at the output of the demister which will flow and enter the turbine inlet. The flowing fluid is the result of separating steam from pollutants. While state 3 is the output of a mixture of pollutants and water which is directly discharged into the environment. State 4 is located at the output of the turbine which will enter the condenser.

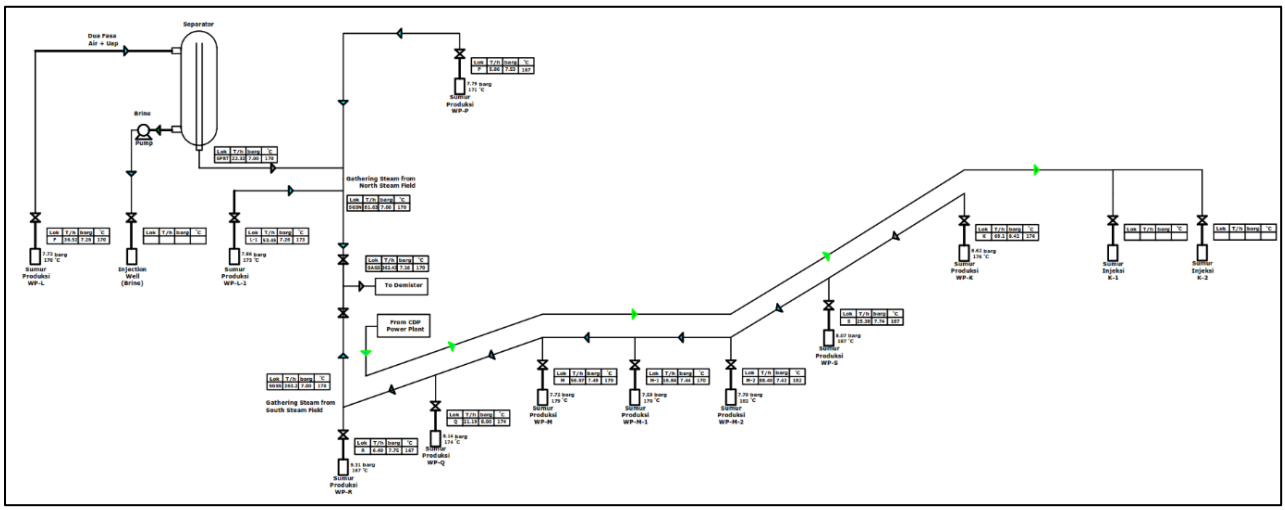


Figure 4: Patuha Steam Above Ground System before Implementation Tie Back Engineering PPL-2.

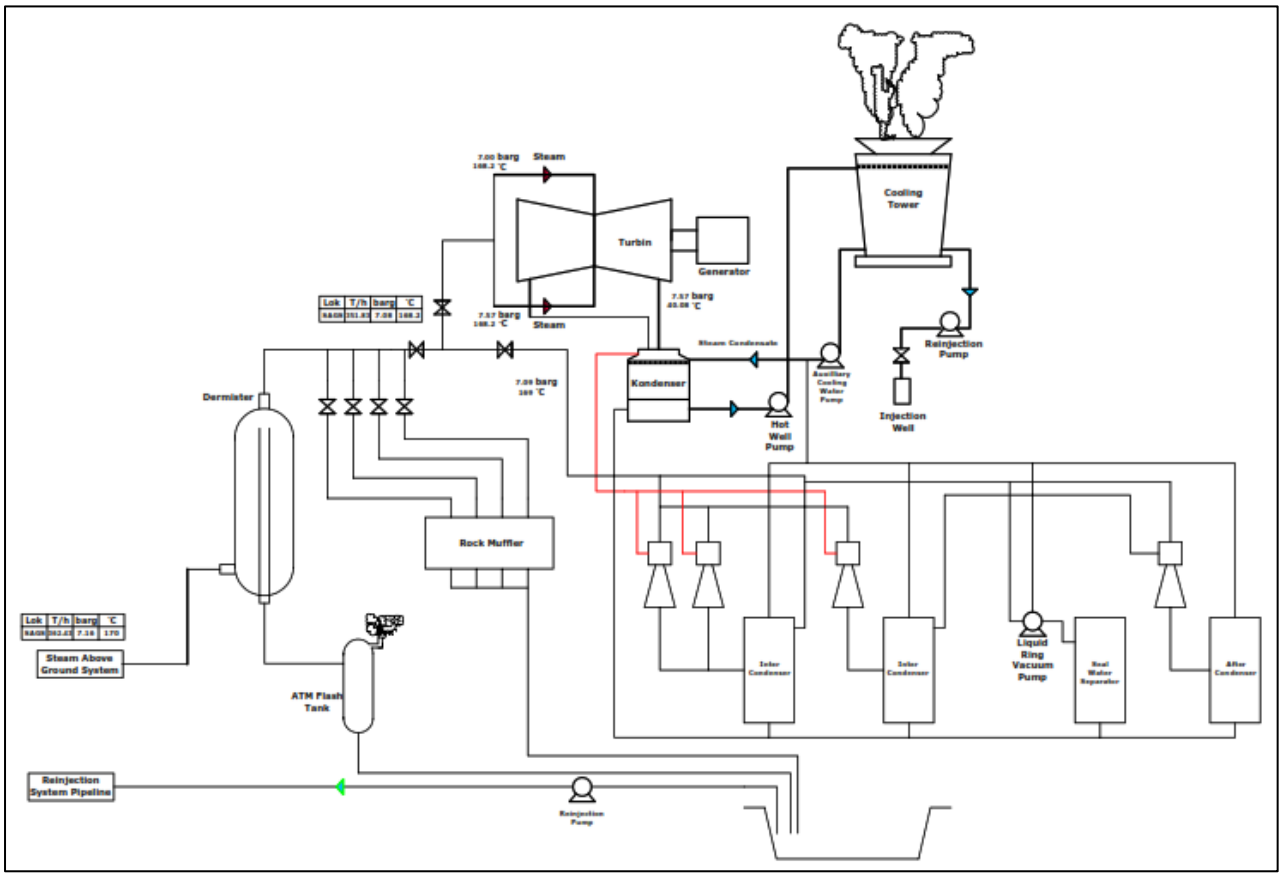


Figure 5: Power Plant Schematic Diagram.

Data values for temperature (T), pressure (P), and mass flow (m) in each state were obtained from operation data 12 weeks before and after tie back engineering work in 2020. The data is shown in Table 1. Values of enthalpy and entropy obtained from open source software X steam tables affiliated with Ms. excel. Data analysis in this study only reaches the turbine point, this is considering the large contribution of tie back engineering to generation efficiency.

4. RESULT AND DISCUSSION

4.1 Energy & Exergy Balance

Energy balance calculations are used to make it easier to identify inputs and outputs that work in the system (Amrita & Nugroho, 2018). In this study, the energy balance is loaded from the steam gathering system to the turbine. The energy balance of this research is published in Table 1. Based on Table 1, the mass flow value of the steam gathering system is obtained from the accumulated amount of steam that will enter the demister input, the enthalpy value at this point will be affected by the value of the steam fraction, pressure and temperature measured at the accumulation point. In the 1st law of thermodynamics, it has been explained that energy in a system cannot be created or destroyed. In the law of energy balance, the energy entering the system is equal to the energy leaving the system.

Table 1: Energy Balance.

Equipment	Energy Equation
Steam Gathering System	$\dot{E}n_{sgs} = \dot{m}_{sgs} . h_{sgs}$
Demister	$\dot{E}n_{dem} = \dot{E}n_{sgs} - \dot{E}n_{dem.drain} - \dot{E}n_{dem.turbin}$
Turbine	$\dot{E}n_{turbine} = \dot{E}n_{inlet.turbine} - \dot{E}n_{out.turbine}$

This also applies to the exergy equilibrium of this study, the exergy balance and irreversibility of the system are contained in Table 2. In this study the operation data displayed is the result of the average observation of data for 10 weeks before and after the implementation of Tie Back Engineering which is contained in Table 3 and Table 4.

Table 2: Exergy Balance.

Equipment	Irreversibility
Steam Gathering System	$\dot{E}_{sgs} = \dot{m}_{sgs} \left(h_{sgs} - h_0\right) - T_0(s_{sgs} - s_0)$
Demister	$\dot{E}_{dem} = \dot{E}_{sgs} - \dot{E}_{dem.drain} - \dot{E}_{dem.turbine}$
Turbine	$\dot{E}_{Turbine} = \dot{E}_{inlet.turbine} - \dot{E}_{outl.turbin}$

From an environmental perspective, the average enthalpy and entropy values of the environment at Patuha Geothermal have not increased significantly. The data is taken from observations every three months by a trusted third party company. The function of the Data environment will be used as a baseline dead state for exergy value calculations. Based on Table 3 and Table 4, the difference in ambient temperature is only 0.57OC. This difference does not significantly affect the enthalpy and entropy values of the environment. When viewed from the accumulated mass flow value in the steam gathering system, the average mass flow value after the Tie Back Engineering was carried out, decreased by 3.11kg/s. This value tends to decrease, influenced by many factors including decreased well production in several wells and the effect of workover on the PPL-7 well. The inoperability of one of the production wells affects the amount of steam production at SGS. This is also supported by the value of the pressure at the SGS which will enter the inlet demister, where there is a difference of 0.18 bar and a decrease in the temperature value of 1.11OC. However, when viewed from the steam fraction, even though there has been a change in the system at PPL-2 (no separator installed), in fact it does not affect the aggregate fraction of the steam entering SGS. By reducing the pressure and temperature values after the tie back engineering has been carried out, this affects the energy production of Patuha Geothermal. If viewed from the flow drain demister and outlet demister, the value of mass flow flowing into the turbine pipeline is better after tie back engineering, the difference in the percentage of mass flow drain demister before and after tie back engineering is 0.30% less than before the change is made,

with a comparison of the value of energy wasted into the flow drain of 471.06 kW before the change and 209.54 after the change. Meanwhile, if viewed from the fraction of steam that enters the turbine inlet both before and after tie back engineering is 100%.

Table 3: Data Operation Before Tie Back Engineering.

Equipment	State	ṁ (kg/s)	P (bar)	T (°C)	X (%)	h (kJ/kg)	s (kJ/kgK)	Ėn (kW)	Ė (kW)
Environment	0		0.84	14.04		2,526.67	0.21		
Steam Gathering System	1	99.56	7.18	169.25	98.94	2,742.05	6.65	273,002.32	270,236.58
Outlet Demister	2	97.36	7.13	168.71	99.47	2752.49	6.68	267,986.86	253,510.45
Flow Drain Demister	3	0.66		168.71	0.00	713.55	2.03	471.06	416.20
Inlet Turbine A	4’	47.82	6.64	168.18	100	2,737.89	6.75	130,910.03	123,460.56
Inlet Turbine B	4’’	47.82	6.64	168.18	100	2,773.71	6.75	132,635.42	124,531.92
Outlet Turbine	5	95.64	0.09	43.24	18.91	636.82	0.62	641.32	54,500.86

Table 4: Data Operation After Tie Back Engineering.

Equipment	State	ṁ (kg/s)	P (bar)	T (°C)	X (%)	h (kJ/kg)	s (kJ/kgK)	Ėn (kW)	Ė (kW)
Environment	0		0.83	14.61		2,527.52	0.22		
Steam Gathering System	1	96.45	7.00	168.14	98.85	2,738.87	6.65	264,168.60	261,401.91
Outlet Demister	2	94.72	6.91	167.77	99.37	2,749.15	6.68	260407.27	245,790.50
Flow Drain Demister	3	0.29		167.77	0.00	709.44	2.02	209.54	3551.79
Inlet Turbine A	4’	46.15	6.64	166.76	100	2,736.45	6.75	126293.41	118,964.53
Inlet Turbine B	4’’	46.15	6.64	166.76	100	2,770.25	6.75	126293.41	120,059.62
Outlet Turbine	5	92.30	0.09	43.81	18.90	639.12	0.62	619.70	52,694.36

4.2 Energy Analysis

Energy analysis from Patuha Geothermal refers to the energy balance contained in Table 1. This analysis is divided into two data, namely first data 10 weeks before and 10 weeks after tie back engineering. Table 5 contains the energy flow rate for each component before tie back, in terms of incoming and accumulated energy. Energy at SGS tends to fluctuate every week, but there is no significant difference. In June W1 and W2 the energy value in the flow demister drain is not measured in kg/s units because the value is very small. If seen from the lowest energy in the demister system it occurs in August W2 with a value of 533.80 kW with the energy flowing into the flow drain demister of 533.03 kW whereas the most energy in the demister point occurs in July W4 of 9,148.24 kW. Meanwhile, the highest energy that can be generated before the tie back engineering is carried out is in June W2 of 61,968.62 kW. Meanwhile, when compared with the energy flow rate data after the tie back is carried out in Table 6, the value of steam produced in October tends to decrease, this is influenced by the non-operation of one of the production wells (PPL-7) due to work-over work.

Judging from the energy flow drain demister from September to October, the drain energy value tends to decrease to zero. This affects the magnitude of the energy efficiency of the demister to further increase. The existence of tie back engineering work affects the energy losses that occur in the demister. In addition to the value of the fraction carried by the steam from the well to SGS, the level of dryness of the steam is close to dry, so no energy is wasted outside the system. However, in September W4 there were greater energy losses with a value of 10,075.10 kW in the demister, so that the power generated also decreased to 56,795.19 kW. The reduced mass flow value is affected by phishing in the Rock Muffler and Atmospheric Flash Tank. In the implementation that occurred at Patuha Geothermal, the value of the mass flow that enters the turbine inlet and what is considered is the reading of the mass flow after the rock muffler, so that there is a difference in mass flow at the outlet demister and after rock muffler. In addition, in terms of the energy aspect, the results of the tie back engineering on losses demister have reduced a lot as evidenced by the reduced energy in the flow drain demister.

Table 5: Energy Flow Rate of Each Component Before Tie Back.

Period	$\dot{E}_{sgs}$ (kW)	$\dot{E}_{dem.turbin}$ (kW)	$\dot{E}_{dem.drain}$ (kW)	$\dot{E}n_{dem}$ (kW)	$\dot{E}n_{turbine}$ (kW)
Jun W1	269,898.49	263,102.67	-	6,795.82	58,887.76
Jun W2	276,109.95	275,224.42	-	885.53	61,968.62
Jun W3	274,818.97	272,200.24	593.14	2,025.60	61,003.69
Jun W4	273,735.30	264,016.88	713.32	9,005.10	59,251.81
Jul W1	274,822.19	272,239.56	596.65	1,985.99	61,453.51
Jul W2	273,896.19	272,393.96	342.61	1,159.61	61,401.23
Jul W3	275,845.75	265,876.46	618.64	9,350.65	59,736.00
Jul W4	274,354.42	268,875.06	925.67	4,553.69	60,389.43
Agt W1	263,392.68	253,856.94	387.49	9,148.24	57,492.95
Agt W2	273,149.27	272,082.43	533.03	533.80	61,556.17

Table 6: Energy Flow Rate of Each Equipment After Tie Back.

Period	$\dot{E}_{sgs}$ (kW)	$\dot{E}_{dem.turbin}$ (kW)	$\dot{E}_{dem.drain}$ (kW)	$\dot{E}n_{dem}$ (kW)	$\dot{E}n_{turbine}$ (kW)
Agt W3	274,294.86	271,801.08	522.64	1,971.14	61,421.69
Agt W4	272,416.71	264,667.48	1,572.72	6,176.52	60,012.06
Sept W1	273,236.90	268,772.05	-	4,464.85	60,582.71
Sept W2	265,692.06	263,359.92	-	2,332.14	59,318.54
Sept W3	265,383.10	263,193.27	-	2,189.84	59,533.26
Sept W4	261,115.06	251,039.97	-	10,075.10	56,795.19
Okt W1	258,701.69	258,417.67	-	284.02	58,689.46
Okt W2	257,335.27	256,021.15	-	1,314.12	57,844.27
Okt W3	258,044.74	255,175.74	-	2,869.00	57,612.65
Okt W4	255,465.60	251,624.41	-	3,841.19	56,741.30

4.3 Exergy Analysis

Based on Table 7, the highest exergy value at SGS before tie back engineering was 273,202.33 kW in June W2. A total of 13,074.23 kW of exergy loss has occurred at the wasted demister point in the form of air condensate brine. While the total exergy value that goes into the inlet side of turbine A and B is 260,128.10 kW. The reduction in exergy by the turbine is 254,750.05 kW in the form of a water phase mixed with NCG (Non Condensable Gas). The exergy efficiency to the SGS Exergy with the Turbine is 20.45%. Meanwhile, when compared with the exergy efficiency of the turbine itself in Figure 3, it is 27.74%. Based on Figure 2, the irreversibility comparison between the demister and the turbine shows that the demister has a higher value, the form of irreversibility from steam can be in the form of NCG and condensate water. In this case the demister has a higher irreversibility before the occurrence of a greater Tie Back Engineering. The presence of tie back engineering has the potential to reduce the irreversibility of the demister. If viewed from the turbine equipment, the irreversibility value tends to be stable even though there is a difference between before and after tie back engineering, but it does not have a significant impact.

Compared to the results of the exergy calculation after the tie back is the same as the energy value, that after Sept W1 the exergy value of the demister drain starts to be absent, this can be seen in Table 8. If you look at the irreversibility value of the turbine in Figure 6, it is shown that after the tieback is carried out the irreversibility value increases, although not significant with a range of 9,676.77 kW to 11,684.89 kW. The increase in the value of exergy losses (irreversibility) flowing from the turbine to the condenser, most of the exergy is destroyed in the turbine outlet. Exergy losses in the turbine occur at different stages which affect the exergy efficiency of the turbine.

Table 7: Exergy of Each Equipment Before Tie Back.

Period	$\dot{E}_{sgs}$ (kW)	$\dot{E}_{dem.turbin}$ (kW)	$\dot{E}_{dem.drain}$ (kW)	$\dot{E}_{inlet\ turbin\ A}$ (kW)	$\dot{E}_{inlet\ turbine\ B}$ (kW)	$\dot{E}_{outlet\ turbine}$ (kW)	Eff. $\dot{E}_{Plant}$ (%)
Jun W1	266,996.65	248,627.25	-	124,108.64	127,855.43	242,351.03	19.46
Jun W2	273,202.33	260,128.10	-	129,356.04	133,733.68	254,750.05	20.45
Jun W3	271,919.80	257,254.19	522.38	127,731.55	132,270.09	251,543.33	20.08
Jun W4	270,816.66	249,469.53	627.47	123,975.21	128,304.64	242,767.17	19.15
Jul W1	272,064.37	257,894.11	528.37	128,378.38	132,635.93	252,236.99	20.12
Jul W2	271,145.69	258,053.64	303.46	128,532.83	132,711.05	252,379.30	20.16
Jul W3	273,039.26	251,850.68	547.47	125,787.06	129,544.22	245,409.90	19.14
Jul W4	271,585.06	254,705.44	819.65	126,950.90	130,961.26	248,094.36	19.46
Agt W1	260,930.79	239,926.04	342.13	119,528.23	123,464.54	231,534.89	18.59
Agt W2	270,665.16	257,195.53	471.07	127,392.89	132,190.18	247,898.20	19.19

Table 8: Exergy of Each Equipment After Tie Back.

Period	$\dot{E}_{sgs}$ (kW)	$\dot{E}_{dem.turbin}$ (kW)	$\dot{E}_{dem.drain}$ (kW)	$\dot{E}_{inlet\ turbin\ A}$ (kW)	$\dot{E}_{inlet\ turbine\ B}$ (kW)	$\dot{E}_{outlet\ turbine}$ (kW)	Eff. $\dot{E}_{Plant}$ (%)
Agt W3	271,787.11	256,949.50	462.00	127,561.63	132,174.38	250,059.24	19.83
Agt W4	269,892.11	250,184.45	1,389.78	124,588.35	128,714.84	242,752.71	19.26
Sept W1	270,237.89	253,715.32	-	126,038.06	130,641.45	246,949.41	19.57
Sept W2	262,740.02	248,592.59	-	124,079.66	128,015.74	241,499.99	19.53
Sept W3	262,450.21	248,433.08	-	123,542.31	127,935.79	240,865.42	19.46
Sept W4	258,204.81	236,942.06	-	118,109.32	122,035.47	229,059.23	18.61
Okt W1	256,000.10	243,728.23	-	121,181.83	125,722.99	237,845.42	20.19
Okt W2	254,627.53	241,444.68	-	120,146.90	124,566.72	234,763.18	19.65
Okt W3	255,320.99	240,640.12	-	119,815.06	124,158.54	233,609.50	19.37
Okt W4	252,758.32	237,274.94	-	118,113.99	122,437.07	229,455.67	18.92

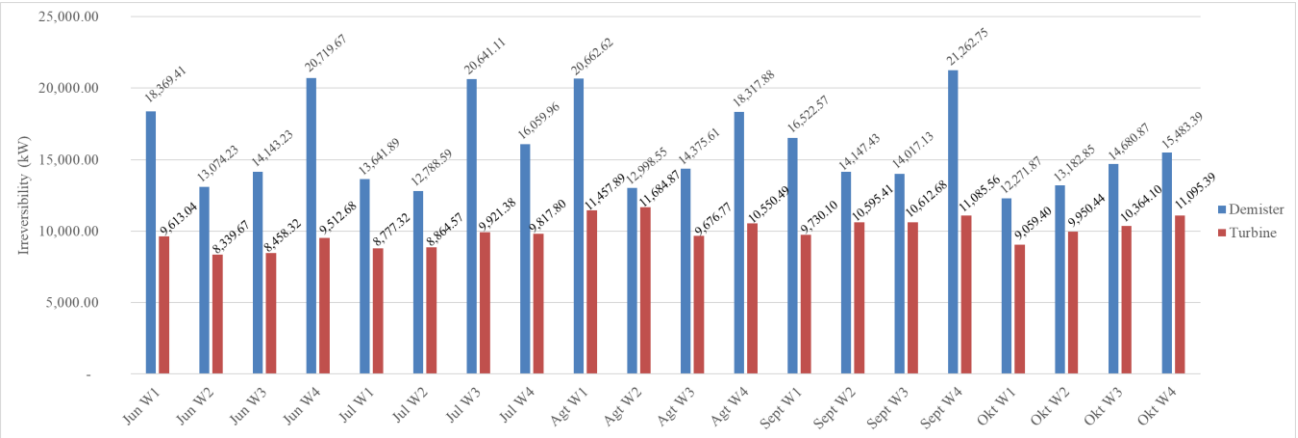


Figure 6: Irreversibility for Demister and Turbine.

4.4 Exergetic Analysis Review of Tie Back Engineering

If a sample is taken from one of the data, for example August W3 which is contained in Table 8, that the exergy value entering the inlet demister is 271,781.11 kW, the exergy value entering the turbine inlet is 256,373.86 kW. This shows that there has been an exergy loss of 15,407.25 kW. This value is suspected to be lost in the form of substantial material carried by steam in the form of sewage pollutants.

Not all of the exergy value that goes into the turbine inlet is converted into electricity as a whole, the exergy losses in the turbine are in the form of NCG and the water that comes out goes to the condenser.

Based on Figure 7, the value of the exergetic efficiency before and after tie back engineering, the plant efficiency value of the demister tends to increase by 1% compared to tie back engineering with a range of 93% to 94%. While the value of turbine efficiency tends to decrease by 1% when compared to before tie back engineering, the range of efficiency changes to 35-36%. However, this is different from the efficiency of the plant as a whole, which is only in the range of 19-20%. The impact of tie back engineering on demister efficiency is very significant when compared to turbines. The effect of dryness of SGS on demister efficiency is directly proportional. Meanwhile, tie back engineering innovation does not have a direct impact on increasing turbine efficiency. This can be influenced by the quality of the steam that enters the turbine, a pressure drop may occur. The main steam output line from the demister to the turbine has several branches which have the potential to reduce pressure and mass flow of steam. This condition requires further research on the potential for exergy losses in the main steam line demister outlet to the turbine inlet.

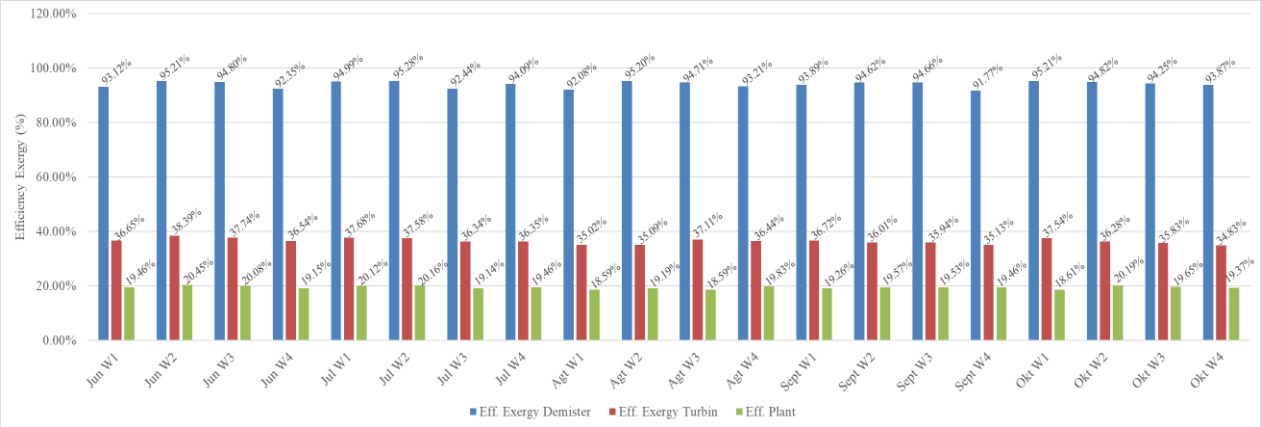


Figure 7: Efficiency Exergetic for Plant and Each Component.

5. CONCLUSSION

Based on the calculations and data analysis that has been carried out in the previous section, it can be concluded that the influence of tie back engineering from one of the wells in Patuha Geothermal has on generator efficiency. Judging from the energy analysis, this change does not really affect the energy produced by the turbine. However, these changes affect the energy released by the flow demister drain which tends to decrease. If viewed from exergy efficiency, the best efficiency value is demister which reaches 93-94%, then turbine exergy efficiency ranges from 34-37%. With exergy analysis it can be seen that the point that has the highest irreversibility is in the turbine because in the outline of the turbine the fraction, temperature and pressure of the steam change down to the liquid phase in the condenser. The higher the irreversibility value of each stage or equipment will affect the exergy efficiency, and vice versa. In future research it is necessary to evaluate the exergetic efficiency of each component, especially in the steam outlet demister line and the stage after the turbine. By carrying out this analysis, it is hoped that optimization will be carried out at the appropriate point.

REFERENCES

Amrita, K. C., & Nugroho, G. (2018). Analisis Thermal pada Pembangkit Listrik Tenaga Panas Bumi PT. Indonesia Power UPJP Kamojang. *Jurnal Teknik ITS* Vol. 7 No. 2, 2301-9271.

Aziz, A. (2011). *Analisa Eksergi PLTP Kamojang 68 Kapasitas 3 MW*. Jakarta: Peneliti Konversi dan Konservasi Energi dan Team Panas Bumi BPPT.

Badan Pengkajian dan Penerapan Teknologi. (2020). *Indonesian Outlook Energy 2020*. Jakarta: Pusat Pengkajian Industri Proses dan Energi (PPIPE).

Cengel, Y. A., & Boles, M. A. (1998). *Thermodynamics: an engineering approach*. New York: McGraw-Hill.

DiPippo, R. (2007). *Geothermal Power Plants: Principles, Applications, Case Studies and Environmental Impact*. Amsterdam: Elsevier Science & Technology Books.

Khasmadin, M. F., & Harmoko, U. (2021). Kajian Potensi dan Pemanfaatan Energi Panas Bumi di Wilayah Kerja Panas Bumi Patuha Ciwidey. *Jurnal Energi Baru dan Terbarukan*, https://doi.org/10.14710/jebt.2021.11187.

Pambudi, N. A., Jalilinasrabady, S., & Jaelani, K. (2014). Exergy Analysis and Optimization of Dieng Single-Flash Geothermal Power Plant. *Energy Conversion Management* 78, 405-411.

Patuha Production Data - PT Geo Dipa Energi. (2020). *PENGAMATAN PEMBANGKIT DAN EFFISIENSI COOLING TOWER 2020*. Bandung: PT Geo Dipa Energi - Patuha.

PT Geo Dipa Energi - Patuha. (2019). *INO: Geothermal Power Development Project*. Jakarta: Prepared by P. T. Geo Dipa Energi for the Asian Development Bank.

Rudiyanto, B., Bahtiyar, M. A., Pambudi, N. A., Widjonarko, & Hijriawan, M. (2021). An update of second law analysis and optimization of a single-flash Geothermal Power Plant in Dieng, Indonesia. *Geothermics* 96.

Saptaji, N. M. (2001). *Teknik Panas Bumi*. Bandung: Departemen Teknik Perminyakan, Institute Teknologi Bandung.

Nomenclature

$\dot{m}$	mass flow rate, kg/s
P	pressure, bar
T	temperature, ^{o}C
$\dot{E}$	exergy, kW
$\dot{E}n$	energy flow rate, kW
h	enthalpy, kJ/kg
s	entropy, kJ/kg.K
W	net work, kJ
X	fraction of fluids, %
ŋ	efficiency, %

Measurement Units

kW	kilowatts
MW	megawatts
MWe	megawatts electric
kPa	kilopascal
bar	bar

Abbreviations

GPP	Geothermal Power Plant
NCG	non condensable gas
HWP	hot well pump
ACWP	auxiliary cooling water pump
SGS	steam gathering system
W1	1st Week
W2	2nd Week
W3	3rd Week

W4	4th Week

Subscript	
State	condtititions being analyzed
Input	Input Condition
Output	Output Condition
i	Initiate state
0	dead state (environment)
Exergy State	Exergy State
Ex. Plant	Exergy Plant
sgs	steam gathering system
dem	demister
dem.drain	flow drain demister
dem.turbin	demister to turbin
turbine	
inlet.turbine	turbine inlet
out.turbine	turbine outlet

Prevention of the Silica Compounds at the Geothermal Power Plants with HYDRODIS® GE Products

Mustafa EROGLU, Ayhan ERTEN, Irfan AVCI, and A.Talha BILGIN

BOZZETTO

mustafa.eroglu@bozzetto.com.tr, ayhan.erten@bozzetto.com.tr,
irfan.avci@bozzetto.com.tr, talha.bilgin@bozzetto.com.tr

Keywords: Bozzetto, Hydrodıs®Ge, Silica, Differential Pressure

ABSTRACT

One of the most frequent geochemical events is the precipitation of silica scaling from brine at geothermal power plants. Precipitation in pipes and heat exchangers significantly reduces electricity production. Binary geothermal power plants in Turkey have experienced serious silica precipitation problems in their exchangers and separators which is one of the main issues. It is known that scale formation occurs in geothermal systems under various enthalpy and chemical conditions.

The silica-saturated geothermal water becomes supersaturated with silica after evaporation and silica begins to precipitate. Silica precipitation is mainly dependent on pH, temperature, silica concentration and the influence of other minerals and salts. Silica precipitation in brine pipes causes silica scaling, which directly affects electricity generation. In this study, silica scale deposition from geothermal fluids and in geothermal reservoirs was studied in the field and the laboratory. The distribution of silica in geothermal brine was investigated in a geothermal power plant in Turkey.

This study, which was presented as a case study from the field, demonstrated the effect of HYDRODIS® GE polymers' chemical inhibition techniques for silica prevention on sediment mineral deposition.

1. INTRODUCTION

The hot water and steam formed by the transfer of the heat energy accumulated in the rocks deep into the ground by the fluids and stored in the reservoirs are called geothermal resources. Geothermal energy is the name of the energy created by the enthalpy and heat of these fluids. This energy creates a renewable energy source by converting it to other different types of energy or by making use of direct heat energy. The brine that is extracted from the geothermal resource is commonly referred to as the geofluid. Geofluid is produced from a geothermal reservoir and directed into the power plant. Following the use of heat to produce electric power, some fraction of the geofluid is then reinjected into the rock formation (Finster et al., 2015). Geothermal wells are used to transfer the hot magma energy under the earth's crust to underground water (ERTEN & EROGLU, 2021). These wells transport the brine to geothermal systems. The characterization of transporting fluids is critical in determining appropriate management approaches, including the consideration of specialized handling and potential environmental implications (Finster et al., 2015). Scale and precipitation are currently major issues for Geothermal power plants. The decreasing production of electricity generation at geothermal power facilities is unacceptable given the energy demands. The formation of siliceous deposits (called "silica scales") from geothermal water has been a serious problem in the operation of geothermal power stations over a long period (Yokoyama et al., 2002). Silica scaling inhibits electricity generation and is also a common problem in geothermal power plants (Hayati et al., 2021). However, during the operation of geothermal power plants, the silica scale tends to adhere to the reinjection well and ground piping because of the pressure and temperature drop of the geothermal brine as it flows to the surface (Ikeda & Ueda, 2017). Formation of silica deposits are influenced by many factors such as pH, temperature, solubility degree, ionic strength, the presence of nucleating species and the turbulence of fluid flow and the presence of organic and inorganic matter (Setiawan et al., 2018). The polymorphs of this compound,

both crystalline and amorphous, have essentially constant solubility between pH 2 and 8.5 but increase rapidly from 9 onwards (Hayati et al., 2021). The solubility of quartz often regulates the quantity of silica in reservoir fluids. As the fluid separates into water and steam at the surface due to a decrease in pressure and temperature, silica is concentrated in the fluid. Pipelines and reinjection wells will start to accumulate silica scale if the fluid reaches an excessive silica saturation level. However, the kinetic behavior of silica is much less predictable because of slow nucleation behavior. When the brines are extracted from deep, hot reservoirs, the silica content corresponds to the solubility of a-quartz in the brine at the reservoir temperature (Bohlmann, n.d.). Because of the very slow kinetics of quartz crystallization below 300°C, silica is deposited in the more soluble amorphous form during the heat extraction process. Considerable supersaturation (often several times the equilibrium solubility) occurs (Bohlmann, n.d.). At temperatures of 250–300°C, silicon occurs in a solution predominantly in the form of individual molecules of silicic acid H_4SiO_4. The total content (Ct) of silica SiO_2 in water under these conditions can be estimated from the solubility of quartz at 250–300°C: Ct = 500–700 mg/kg (Potapov et al., 2002). Nucleation and polymerization bring about the formation of hydrated silica (mSiO2 · nH2O) particles of colloid sizes (305 nm and greater) in the solution. Part of the SiOH silanol groups on the particle surface dissociate with the detachment of H+ protons, and the particle surface acquires a negative electric charge, which prevents coagulation of the particles due to electrostatic repulsive forces and ensures the stability of colloidal silica in the solution. The instability of colloidal silica near the surface of carrying channels leads to the formation of amorphous silica deposits from a flow of hydrothermal solution in fissured porous rocks and on the inner surface of thermal equipment and wells of geothermal electric power stations (Potapov et al., 2002).

2. EXPERIMENTAL

This study was carried out in a power plant in Saraykoy, Denizli, Turkey. In this study, there were two different vaporizers and three different preheaters in the geothermal power plant designed by Exergy Energy Converter units. HYDRODIS® GE injected into system at the entrance of the LP preheater. In this study, initial dose was set at 50 ppm for first week Then, we decreased our dosage step by step, second week we set dosage to 30 ppm and then last dosage set at 30 ppm entrance of HP vaporizer and entrance of LP vaporizer together and it was monitored for 1 month. Our aim is to decrease system pressure without any maintenance operation to prevent precipitation and disperse the scales those which with had already formed. During the trial, the scale coupon controls, and chemistry of the brine was carried out. The scale coupon checks were supported by both physical observation and XRF measurements. The chemistry of brine analyses has also shown us whether there is any change in the chemistry of the brine depending on the dosage made.

The average temperature of the inlet brine is 175.4^{o}C and the average temperature of the outlet brine is 55^{o}C. The flow rates of the brine were on average 450 tones/hour. The figure given Figure 1. Design of Geothermal Power Plant.

3. RESULTS

The coupons and brine chemistry experiments were followed up over one month. Throughout one month period, the following information was acquired by physically inspecting the coupons and carrying out XRF analysis. The scale coupon was subjected to a XRF examination using the X-MET8000 Expert XRF equipment. Various graphs show how the chemistry of brine is affected by HYDRODIS® GE products.

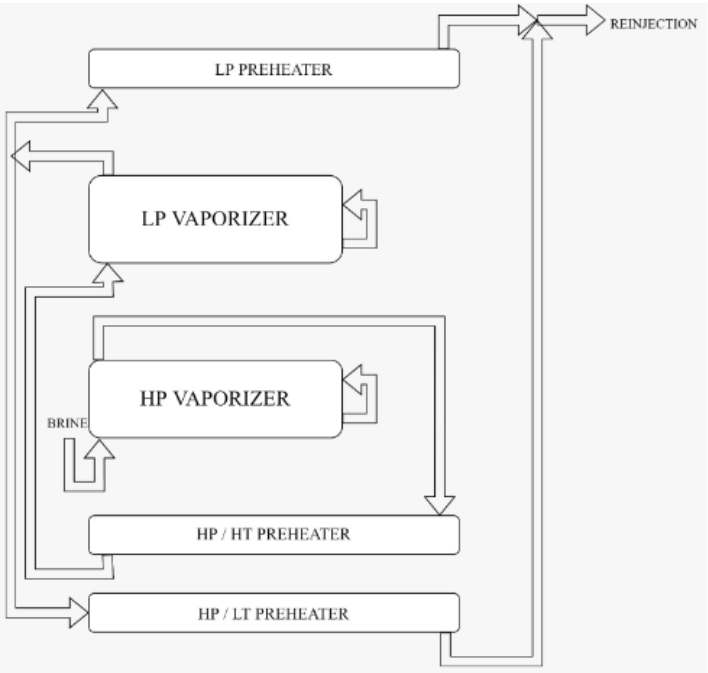


Figure 1: The design of the geothermal power plant is designed by Exergy Energy.

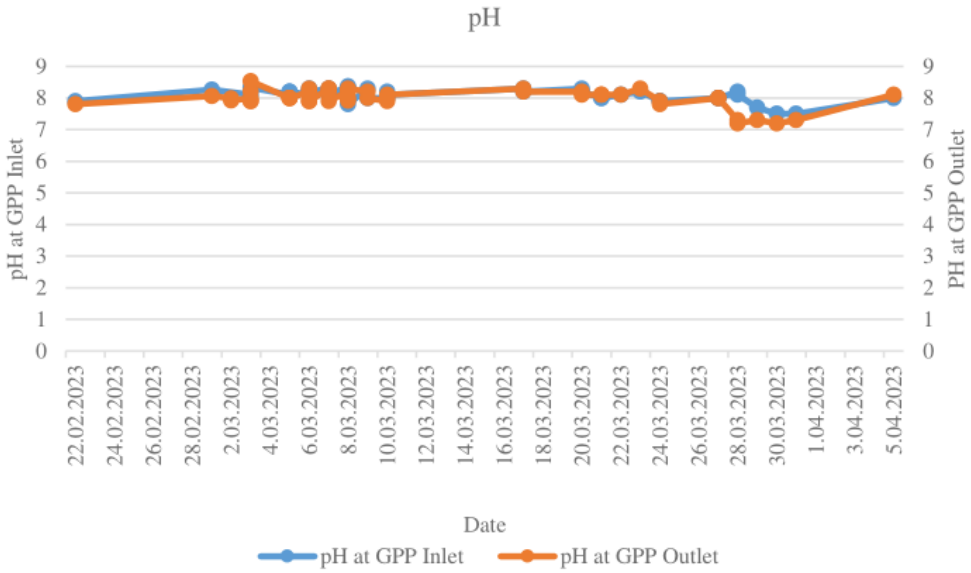


Figure 2: The effect of HYDRODIS® GE on pH of plant inlet and outlet of brine chemistry.

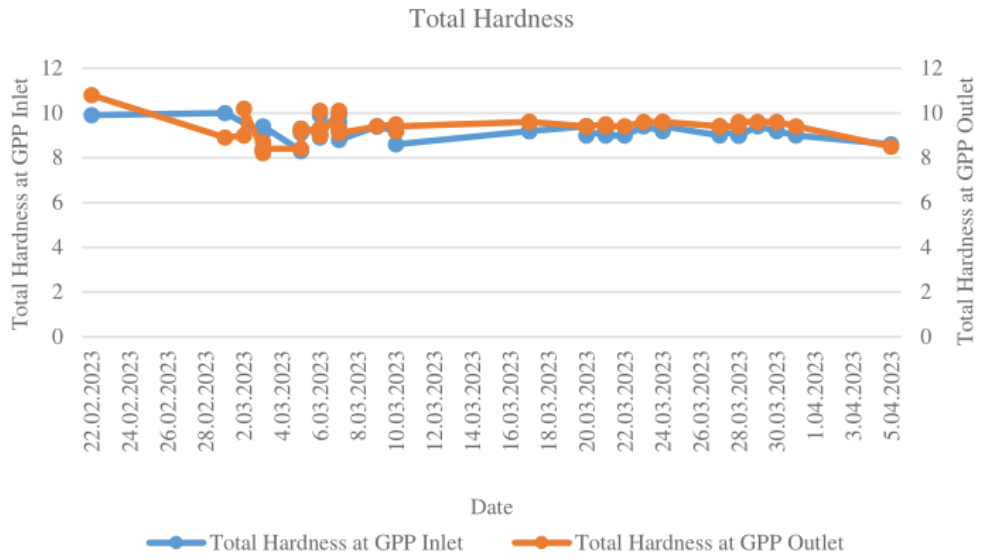


Figure 3: The effect of HYDRODIS® GE on Total Hardness of plant inlet and outlet of brine chemistry.

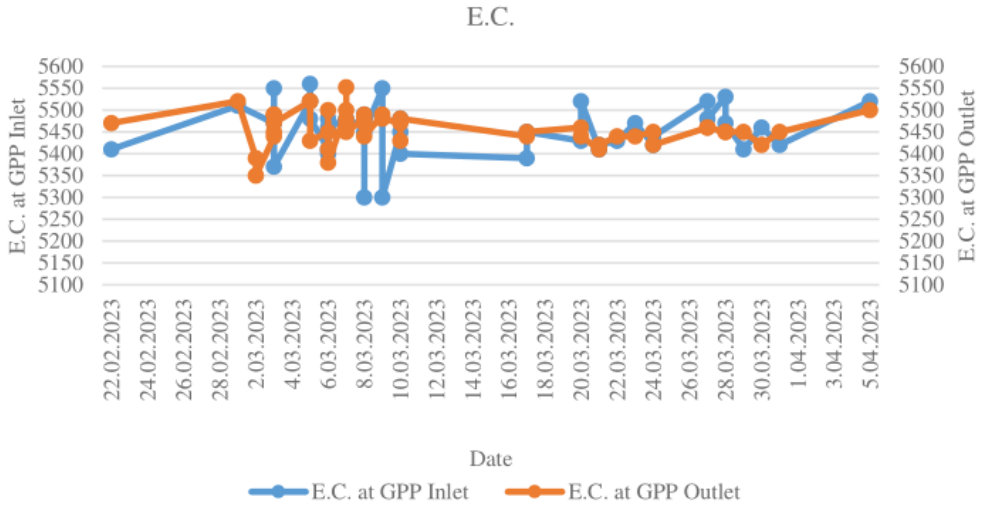


Figure 4: The effect of HYDRODIS® GE on E.C. of plant inlet and outlet of brine chemistry.

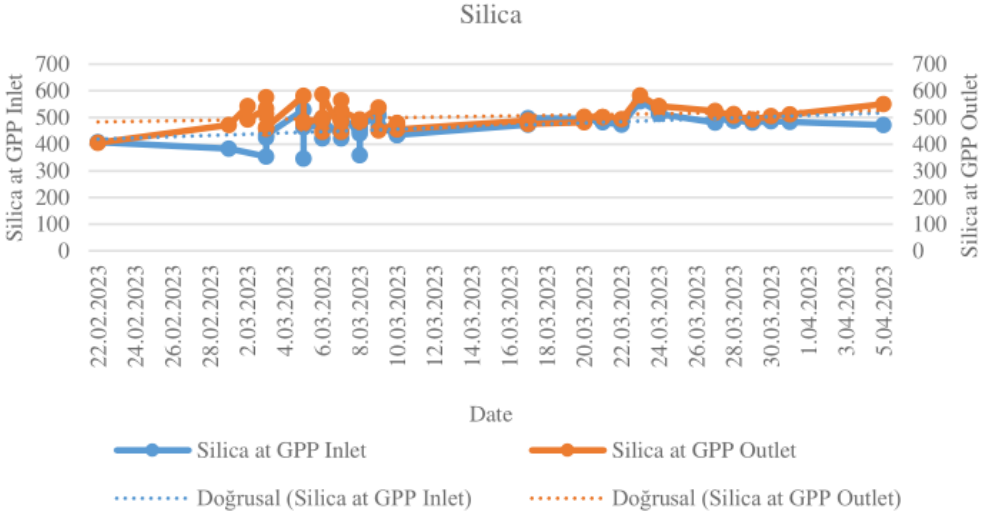


Figure 5: The effect of HYDRODIS® GE on silica plant inlet and outlet of brine chemistry.

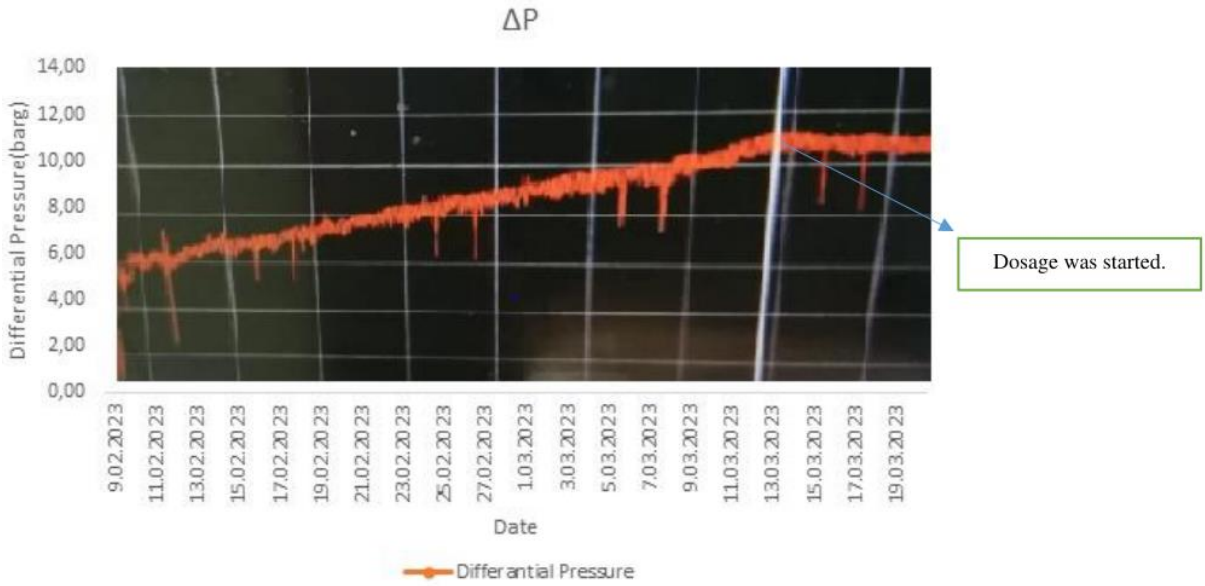
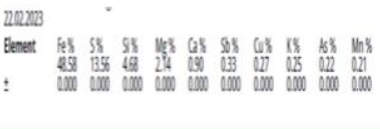
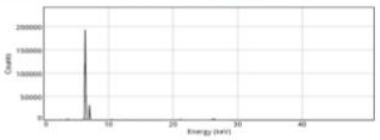
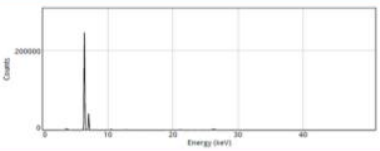
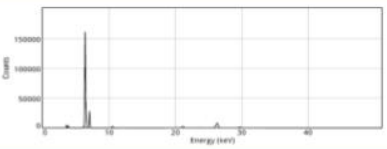
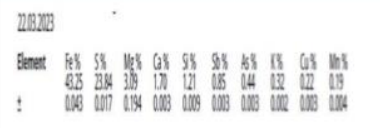
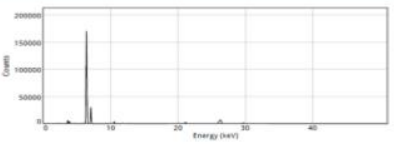


Figure 6: The effect of HYDRODIS® GE products to differential pressure at the electricity power plants.

Table 1: The evaluation scale coupons with HYDRODIS®GE products at the geothermal power plant.

Date	Coupon Images	XRF Measurement	XRF Measurement Counts
22.02.2023			
1.03.2023			
15.03.2023			
22.03.2023			

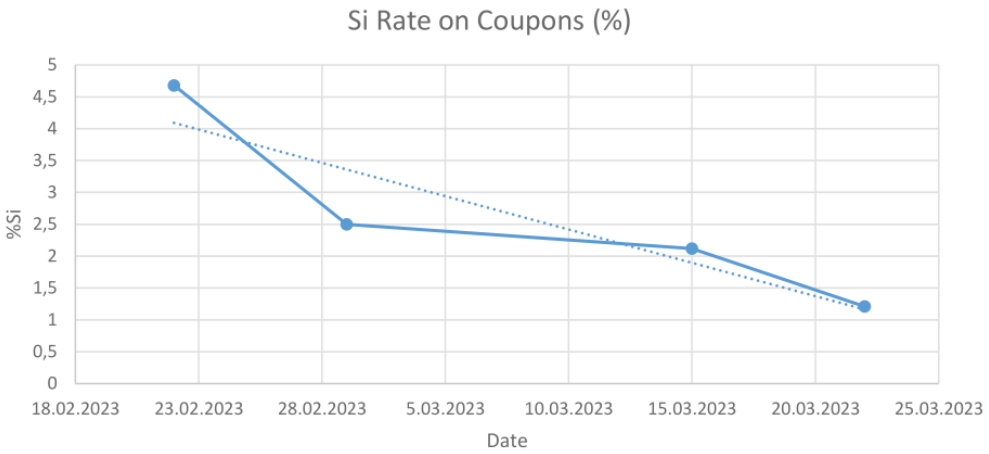


Figure 7: The effect of HYDRODIS® GE to the rate of the Si on the scales coupon.

Table 2: SSI value before the trial.

Phase	SI	Log IAP	Log K	
Chalcedony	3.08	-0.47	-3.55	SIO_2
Quartz	3.51	-0.47	-3.98	SIO_2
SIO_2	2.24	-0.47	-2.71	SIO_2

Table 3: SSI value after the trial.

Phase	SI	Log IAP	Log K	
Chalcedony	3.32	-0.23	-3.55	SIO_2
Quartz	3.75	-0.23	-3.98	SIO_2
SIO_2	2.48	-0.23	-2.71	SIO_2

4. CONCLUSION

As shown in the Tables 2 and 3, the chalcedony value increased from 3.08 to 3.32, the quartz value increased from 3.51 to 3.75, and SiO_2 value increased from 2.24 to 2.48. These results indicate an increase in silica saturation index (SSI). Based on the results of this study, Phreeqc İnteractive 3.7.3-15968 was successfully implemented.

The system in the plant inside the Exergy Energy Converter was successfully protected and stabilized using HYDRODIS®GE products, according to the results. The study was successful because the overall system pressure was kept constant and under control. The product's success was recognised in stibnite literature research with an article released in 2021, albeit this study revealed that the product protects even at adequate dosage for silica compounds as of brief periods. According to brine chemistry analyses, the measurements of silica were increased, while total hardness were stable and unchanged parallel results at the plant's inlet and outlet demonstrate that our technology, HYDRODIS®GE, offers stability even with different dosage.

REFERENCES

Bohlmann, E. G. (n.d.). *Kinetics of Silica Deposition From Simulated Geothermal Brines*.

ERTEN, A., & EROGLU, M. (2021). Prevention of the Antimony Compounds at the Geothermal Power Plants with HYDRODIS®GE Products. *Bilge International Journal of Science and Technology Research*. https://doi.org/10.30516/bilgesci.952134

Finster, M., Clark, C., Schroeder, J., & Martino, L. (2015). Geothermal produced fluids: Characteristics, treatment technologies, and management options. In *Renewable and Sustainable Energy Reviews* (Vol. 50, pp. 952–966). Elsevier Ltd. https://doi.org/10.1016/j.rser.2015.05.059

Hayati, N., Humaida, H., & Siswanta, D. (2021). Adsorption of silicate anions from geothermal brine using chitosan-polyethylene glycol composite to prevent silica scaling on the dieng geo dipa geothermal energy system. *Indonesian Journal of Chemistry*, 21(5), 1063–1071. https://doi.org/10.22146/IJC.49248

Ikeda, R., & Ueda, A. (2017). Experimental field investigations of inhibitors for controlling silica scale in geothermal brine at the Sumikawa geothermal plant, Akita Prefecture, Japan. *Geothermics*, 70, 305–313. https://doi.org/10.1016/j.geothermics.2017.06.017

Potapov, V. V., Karpov, G. A., & Podverbnyi, V. M. (2002). Removal of silica from geothermal brine. *Theoretical Foundations of Chemical Engineering*, 36(6), 589–595. https://doi.org/10.1023/A:1021269918804

Setiawan, F. A., Alfredo, D., Panthron, H., & Perdana, I. (2018). *Mitigation of Silica Scaling from Dieng's Geothermal Brines using Ca(OH)2 Mitigation of Silica Scaling from Dieng's Geothermal Brines using Ca(OH)2 View project Geothermal Sludge View project Mitigation of Silica Scaling from Dieng's Geothermal Brines using Ca(OH)2*. https://www.researchgate.net/publication/324599586

Yokoyama, T., Ueda, A., Kato, K., Mogi, K., & Matsuo, S. (2002). A study of the alumina-silica gel adsorbent for the removal of silicic acid from geothermal water: Increase in adsorption capacity of the adsorbent due to formation of amorphous aluminosilicate by adsorption of silicic acid. *Journal of Colloid and Interface Science*, 252(1), 1–5. https://doi.org/10.1006/jcis.2002.8382

This page is intentionally left blank

Part 3:
Resource Management

Geothermal Institute's Modelling Framework Application For Geothermal Resource Assessment of An Exploration Field

Rony P. Nugraha[1,2], Michael Gravatt[2], Theo Renaud[2],
Ken Dekkers[2], Ryan Tonkin[2], John O'Sullivan[2], and Michael J. O'Sullivan[2]

[1]Geoenergi Solusi Indonesia (Geoenergis), Cibis Nine 11th Floor, Jakarta, Indonesia
[2]Department of Engineering Science, The University of Auckland, Private Bag 90210, Auckland, New Zealand

rony@geoenergis.com, rnug441@aucklanduni.ac.nz

Keywords: Exploration, Geothermal Reservoir, Natural State, Resource Assessment, Uncertainty Quantification

ABSTRACT

The common practice of building a numerical model is usually undertaken after the exploration drilling phase. Ideally, numerical model generation should commence during the early stages of geothermal field development as it can be highly beneficial in supporting the process. The model aids in conducting a preliminary study of fluid flow behavior and temperature distribution beneath the explored area, both of which are crucial in identifying structures with potentially high permeability values and elevated temperatures. Furthermore, numerical simulation represents the most robust method for conducting resource assessment, which can then be used to substantiate the potential resources of those fields and serve as the foundation for generating the Plan of Development (POD). Presently, numerous geothermal fields in Indonesia are in the exploration stage, equipped with ample 3G survey data and, in some cases, drilling data. This presents a significant opportunity for developers to initiate the construction of numerical models, including 3D conceptual models.

This paper presents the application of Geothermal Institute's modelling framework in developing a dynamic model at the exploration phase. The benefits of 3G survey integration data into a 3D geological model using LEAPFROG geothermal software will be presented. The natural state model is simulated using Waiwera and calibrated with the field data. The simulation results describe the fluid flow behaviour and temperature distribution in the subsurface formation are then incorporated with the 3D model and used as the basis for developing well targets. The application of the uncertainty quantification for resource assessment using the developed well targets will be explained.

1. INTRODUCTION

Geothermal reservoir modeling plays a vital role in the effective development of geothermal fields, aiding geothermal companies in strategic decision-making and resource Plan of Development (POD). The process involves collecting and analyzing field data, constructing a 3D conceptual model, creating a numerical model for natural state simulation, and calibrating it using existing field data. Additionally, a production model is generated using the calibrated natural state model, validated against production history data (if the field is operational), and used to simulate future scenarios. Geothermal models serve various purposes, such as estimating the economic viability of exploiting the geothermal system, determining optimal scheduling for make-up well drilling, selecting the most suitable reinjection method, and forecasting how environmental factors might impact production (O'Sullivan & O'Sullivan, 2021).

Recently, the Geothermal Institute and PT Geoenergis Solusi Indonesia (Geoenergis) are carrying out detailed resource assessments for two geothermal exploration fields in Indonesia. The primary objectives of these commercial projects are to verify potential resources and formulate comprehensive future scenarios for the field's Plan of Development (POD) through reservoir simulation. To accomplish these resource assessment projects, a novel integrated geothermal modeling framework (O'Sullivan et al., 2023c) is employed, for constructing both 3D conceptual and numerical models. This geothermal modeling framework (GMF) has undergone rigorous testing across various geothermal fields globally, encompassing both commercial and academic initiatives. This paper focuses on the application of GMF

in the creation of 3D conceptual and numerical models for an exploration field, presenting the workflow of the integrated resource assessment process. The paper will also highlight the role of Waiwera (Croucher et al., 2020) and PyTOUGH (Croucher, 2011;2015) library in streamlining the modeling process. Subsequently, the natural state simulation results depicting fluid flow behavior and temperature distribution in the subsurface formation are merged into the 3D model and serve as the foundation for identifying well targets. Furthermore, the paper will delve into the application of uncertainty quantification in resource assessment, utilizing the developed well targets.

2. GEOTHERMAL INSTITUTE'S MODELLING FRAMEWORK

Over the last decade, the development of GMF has transpired (O'Sullivan et al., 2023c). During this time, the central idea of combining a digital conceptual model with a numerical reservoir model has consistently persisted, with a key emphasis on standardizing the collection of Python scripts used to implement GMF and ensure consistency in data storage approaches. However, the GMF has not always existed, as it was created to fill the gap from previous frameworks that lacked several requirements. In their journal, O'Sullivan et al. (2023c) highlights several important aspects for a comprehensive and integrated geothermal modeling framework to work, which includes:

- All data, including the digital conceptual model, should be universally applicable and adhere to a consistent format for all reservoir models.
- User-friendly and reusable tools, like scripts, should be accessible to seamlessly integrate different modeling steps, simplifying the setup and execution of modified or new reservoir models.
- Intuitive and reusable visualization tools should be available to aid in calibration and create informative plots for both modelers and end-users.
- The framework should offer flexibility, allowing easy incorporation of additional tools, such as generating new types of future scenarios, creating different plots, or including advanced features like uncertainty assessment or inverse modeling.

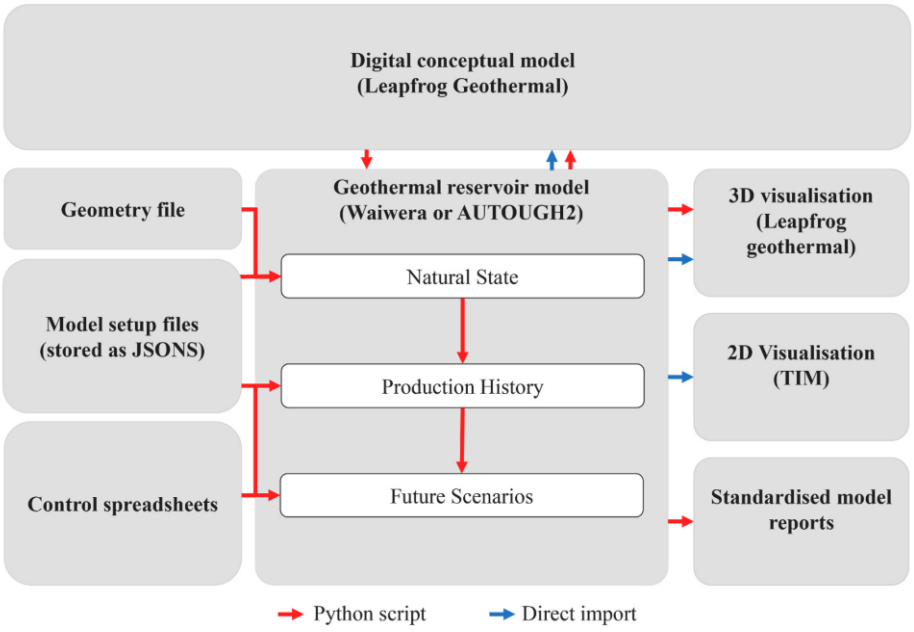


Figure 1: Integrated GMF diagram used for generating a geothermal reservoir model (O'Sullivan et al., 2023c).

Given that few existing workflows or tools fulfilled all these criteria, a novel geothermal modeling framework (GMF) was developed, which will be the central framework that will be discussed in this paper. The framework aims to store all geoscience and reservoir engineering data in a simple, transferable manner, not dependent on the model grid to be used. The data are stored as part of a digital conceptual model created in Leapfrog Geothermal (Alcaraz et al., 2015), with most of the rest, including well-by-well reservoir engineering data, stored in human- and machine-readable JSON files. Figure 1 below shows the workflow of all the involved data to generate reservoir models for the Natural State, Production History, and Future Scenario.

The GMF is novel in two respects: it uses scripts to break down the modeling process into executable steps, and it uses Python scripts for each step. These scripts are designed to be easy to use, easy to modify, and easily applicable to new projects. The GMF can be applied to any digital conceptual model built with Leapfrog, allowing for flexibility and easy modifications. The model grid in the GMF is chosen to capture the important physical processes in sufficient detail. The grid can be refined as necessary. The GMF is designed to be flexible and easily updated with measured downhole well data when they become available. The corresponding changes are easily transferred through to the reservoir model. The GMF also allows for the mapping of a permeability structure from an older model. If there is an older, well-calibrated version of the model with a different grid, it can be used for mapping over the old rock-type parameters onto the rock-types of the new model. This process provides a good starting point for calibration of the new model.

3. GMF APPLICATION IN COMMERCIAL PROJECTS

The Geothermal Modelling Framework (GMF) has seen progressive development throughout the past decade. Considerable effort has been dedicated to ensuring the smooth and consistent operation of the GMF through the standardization of its Python scripts and the enhancement of data storage techniques. The practical application of the GMF has been observed in real-world scenarios across multiple geothermal locations globally, including Ohaaki in New Zealand, Namora-I-Langit, Kamojang, Lahendong in Indonesia, Lihir in Papua New Guinea, San Jacinto in Nicaragua, and the Paris Basin in France. Two of the most recent and prominent projects have used GMF as a framework for the independent resource verification of the Kamojang and Lahendong fields in Indonesia as part of PT. Pertamina Geothermal Energy (PGE) IPO Process. This was a collaborative project initiated between PT. Pertamina Geothermal Energy, the Geothermal Institute at the University of Auckland (UoA), Geoenergis Solusi Indonesia (Geoenergis) and independent New Zealand geothermal experts.

3.1 Kamojang Geothermal Field

As stated by O'Sullivan et al. (2023a), GMF used as the basis framework to develop a new numerical model of the Kamojang Geothermal Field (KGF) and calibrated it against measured field data. The Kamojang area, located in Central Java, is part of the Guntur-Rakutak volcanic complex and is characterized by seven main lithological units. The area features a significant regional, fault-controlled structure, with the Kendang Fault outlining the NE-SW boundary.

The updated model was set up in the Leapfrog software and used to develop the numerical model using GMF. This model encompasses a significantly expanded spatial scope and offers a more intricate depiction of the geothermal system in comparison to the pre-existing Leapfrog model employed by the PGE. The numerical model can be run in AUTOUGH2 (Yeh et al., 2012), a local variant of the industry-standard simulator TOUGH2, or in Waiwera, an open-source simulator developed by the University of Auckland and GNS Science.

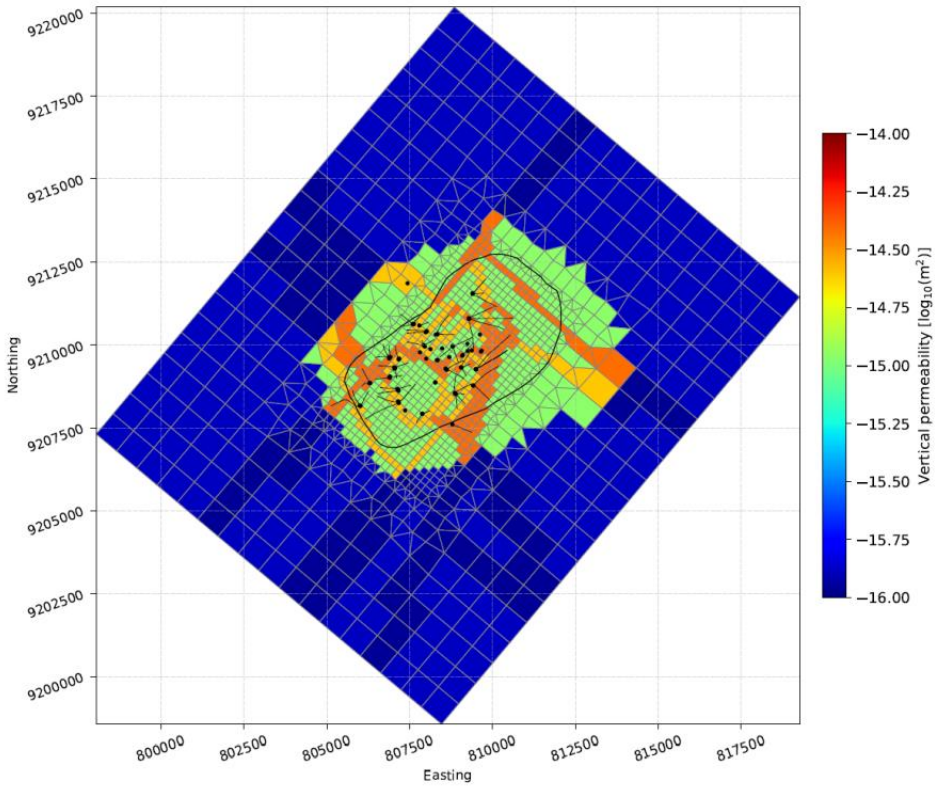


Figure 2: Plan view of KGF calibrated model shows distributed vertical permeabilities in the basement (O'Sullivan et al., 2023a).

The new numerical model of Kamojang exhibits distinct characteristics that differentiate it from the previous existing model. Notable differentiators include a significantly expanded spatial coverage, encompassing the entire area defined by the resistivity boundary of the resource in the northeastern region and peripheral recharge zones. Additionally, the model extends vertically to the earth's surface, closely following the topography and incorporating the unsaturated zone for improved representation of shallow pressure dynamics. Furthermore, the model extends vertically to a base situated at -3000 meters above sea level (masl), approximately 1900 meters below the reservoir's base, enhancing the accuracy of deep reservoir representation. The model is effectively integrated with geological and geophysical data within the digital conceptual framework, ensuring coherence and robustness. Moreover, the model employs a dual-porosity approach, explicitly simulating flow within fracture pathways, leading to a more precise depiction of pressure and enthalpy changes over time. The new numerical model was subjected to calibration procedures, employing the industry-standard techniques and utilizing measured data supplied by PGE. Calibration involved the alignment of the natural state model with available downhole temperature profiles, followed by fine-tuning of the production history model through comparison to available pressure decline and enthalpy response data. This calibration process yielded a satisfactory correspondence with temperature profiles and an exceptional alignment with pressure decline and enthalpy response data. The achieved state of model calibration is robust, instilling a high level of confidence in the model's capacity to aptly capture the intricacies of the Kamojang Geothermal Field, thereby rendering it suitable for forecasting purposes.

3.2 Lahendong Geothermal Field

The Lahendong Geothermal Field (LGF), located in the north-east of the Sulawesi Island, has a current installed capacity of 80 MWe and is influenced by two collapse structures: Pangalombian Caldera and Linau Crater. O'Sullivan et al., (2023b) in their paper explained the used of GMF to create a numerical model of LGF from a Leapfrog-based digital conceptual model. The new numerical model was created following well-established numerical modelling techniques that ensure the model is consistent with the conceptual model and capable of accurately representing the behaviour of the Lahendong Geothermal

Field over time. The new model was developed to overcome the limitations of previous models, such as not including production data or not accurately capturing key processes. It was directly coupled to the Leapfrog digital conceptual model, which included the geology, structural framework, and hydrothermal alteration. The model was set up to be run in either AUTOUGH2 or Waiwera, a simulator developed by the University of Auckland and GNS Science.

The new model was calibrated to achieve a maximum temperature at the bottom of the reservoir of ~ 350 °C, represent the main flow directions, broadly represent interpreted natural state temperatures and pressures, and achieve an appropriate match to natural surface features. The calibrated model provides insights into the heat source and the permeability structure of the LGF. It suggests that different compartments of the system are likely to have different upflow characteristics, and that several of the faults are likely to have high vertical permeability. The model also suggests that the highest vertical permeabilities are likely to be found on faults above the diorite intrusion and at the intersection of faults. The calibrated production history model has been used to make a range of forecasts about the future behaviour of the LGF. Scenarios investigated so far include targeting future make-up wells, scheduling make-up wells, and assessing the resource potential through various make-up well scenarios. The future scenarios are all run using the same dual porosity model set up as the production history model.

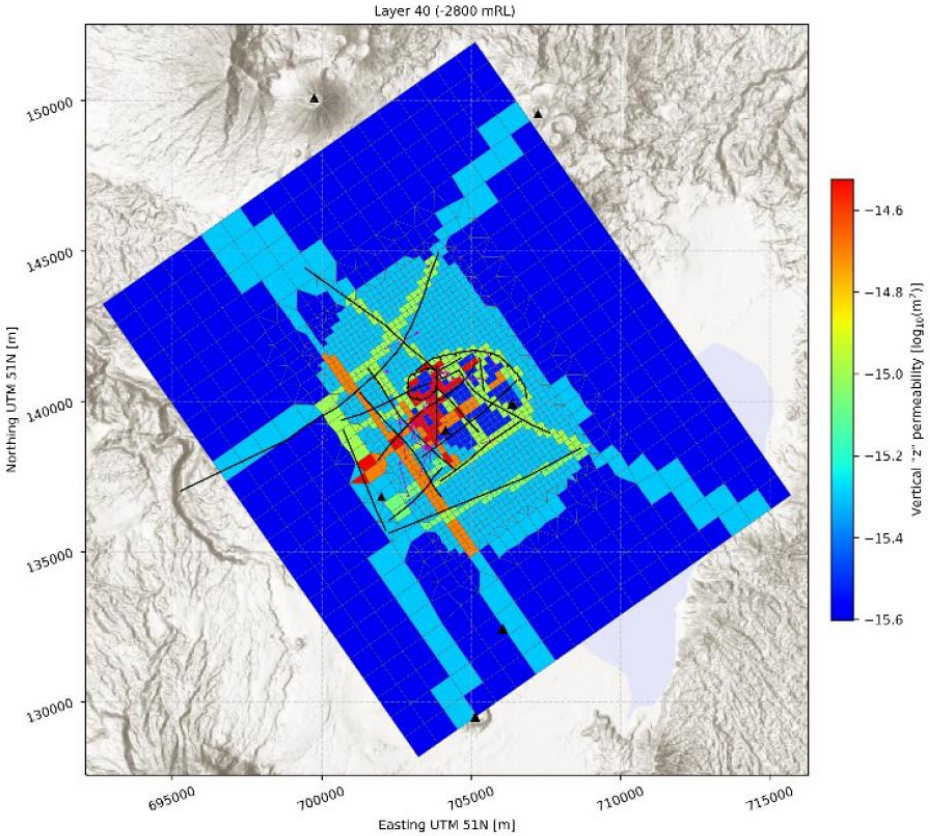


Figure 3: Plan view of LGF calibrated model shows distributed vertical permeabilities in the basement (O'Sullivan et al., 2023b).

Comparative analysis reveals significant distinctions between the newly developed numerical model of Lahendong and the pre-existing PGE model. Firstly, the new model boasts an extended coverage area surpassing that of the PGE numerical counterpart. Secondly, its vertical extension reaches the ground surface, closely tracing the natural topography and encompassing the unsaturated zone within the model structure, thus enhancing the fidelity of shallow pressure simulations. Thirdly, the model's depth extension spans to a base at -3000 masl, affording a more precise representation of the underlying

production feedzones. Notably, the model is intricately interwoven with the geological and geophysical data encapsulated within the digital conceptual framework, thereby ensuring coherence and congruence. Additionally, the new model operates as a dual-porosity system, explicitly simulating fluid flow through fracture pathways, thereby yielding a more accurate portrayal of pressure and enthalpy dynamics over temporal progression. The new numerical model was calibrated against the measured data provided by PGE using the industry-standard approach. The natural state model was calibrated against all the available downhole temperature profiles and then the production history model was calibrated against the available pressure decline and enthalpy response data. A satisfactory match to the temperature profiles and a very good match to the pressure decline and enthalpy response data were obtained. The state of model calibration achieved is good and therefore provides a good representation of the Lahendong Geothermal Field and is appropriate to use for forecasting.

4. GMF APPLICATION FOR EXPLORATION FIELD RESOURCE ASSESSMENT

As discussed in the preceding sections, GMF has been extensively employed across a diverse spectrum of geothermal projects, resulting in the refinement of models. This integrated workflow facilitates the development of numerical reservoir models from the inception of geothermal projects. Presently, the Geothermal Institute is leveraging GMF to undertake two commercial resource assessment projects for exploration fields in Indonesia. Both fields have successfully completed their exploration phases and seek to validate the potential resources identified through exploration activities. These resource assessments are anticipated to furnish comprehensive reservoir modeling analyses for the Plan of Development (POD) of both fields, encompassing the identification of optimal well targets for production and injection wells. The proposed development scenarios put forth by the Client will also undergo scrutiny via calibrated reservoir models to identify the most viable scenarios for the future development of these fields. The projects remain ongoing, and the authors intend to share a glimpse of the progress achieved thus far, coupled with the employed methodology.

The Geothermal Institute employs Waiwera (Croucher et al., 2020) as its geothermal reservoir simulators, alongside TIM (Yeh et al., 2013) and Leapfrog Geothermal for model visualization, while utilizing Python executables for automated reporting. Digital conceptual models have been meticulously developed for both fields using Leapfrog Geothermal, ensuring alignment with all gathered exploration data. Moreover, the Geothermal Institute has designed new Natural State models for the two fields, establishing a tight coupling with the digital conceptual models, subsequently calibrating them through utilization of available geoscientific and exploration well data. Lastly, the Uncertainty Quantification method for Resource Assessment, a proven technique, will be implemented to generate a multitude of conceivable models that align with available data, thereby testing the potential geothermal resource for each variant. Figure 4, depicted below, illustrates the overarching workflow of the geothermal modeling study employed in these projects. Elaboration on each step of the workflow is presented in greater detail below.

Data Review: There are two types of data to be reviewed: (i) geoscientific data used to update the conceptual model and inform the Leapfrog model, and (ii) reservoir engineering data used to set up and calibrate the reservoir models. Reservoir engineering data includes well tracks, feed zones, temperature profiles, production/injection rates, pressure vs. time, and production enthalpy vs. time. Geoscientific data encompasses geological formations (stratigraphy, lithology), fault locations and orientation, other structures, MT and gravity profiles, hydrothermal alteration (especially clay mineralogy), geochemistry, and surface manifestations.

Virtual Site Visit and Discussion with Client: Upon receiving all geoscience and exploration well data from the Client, a virtual site visit to the two fields is planned to ensure data accuracy. This visit can take the form of a sharing session where the Client presents field conditions, including information on surface manifestations in the area. Simultaneously, discussions will address the scope and quality of geoscience and well data, identifying data gaps and proposing strategies to rectify potential ambiguities. Collaborative solutions will be sought to address any data-related concerns that might impact the fidelity of the models.

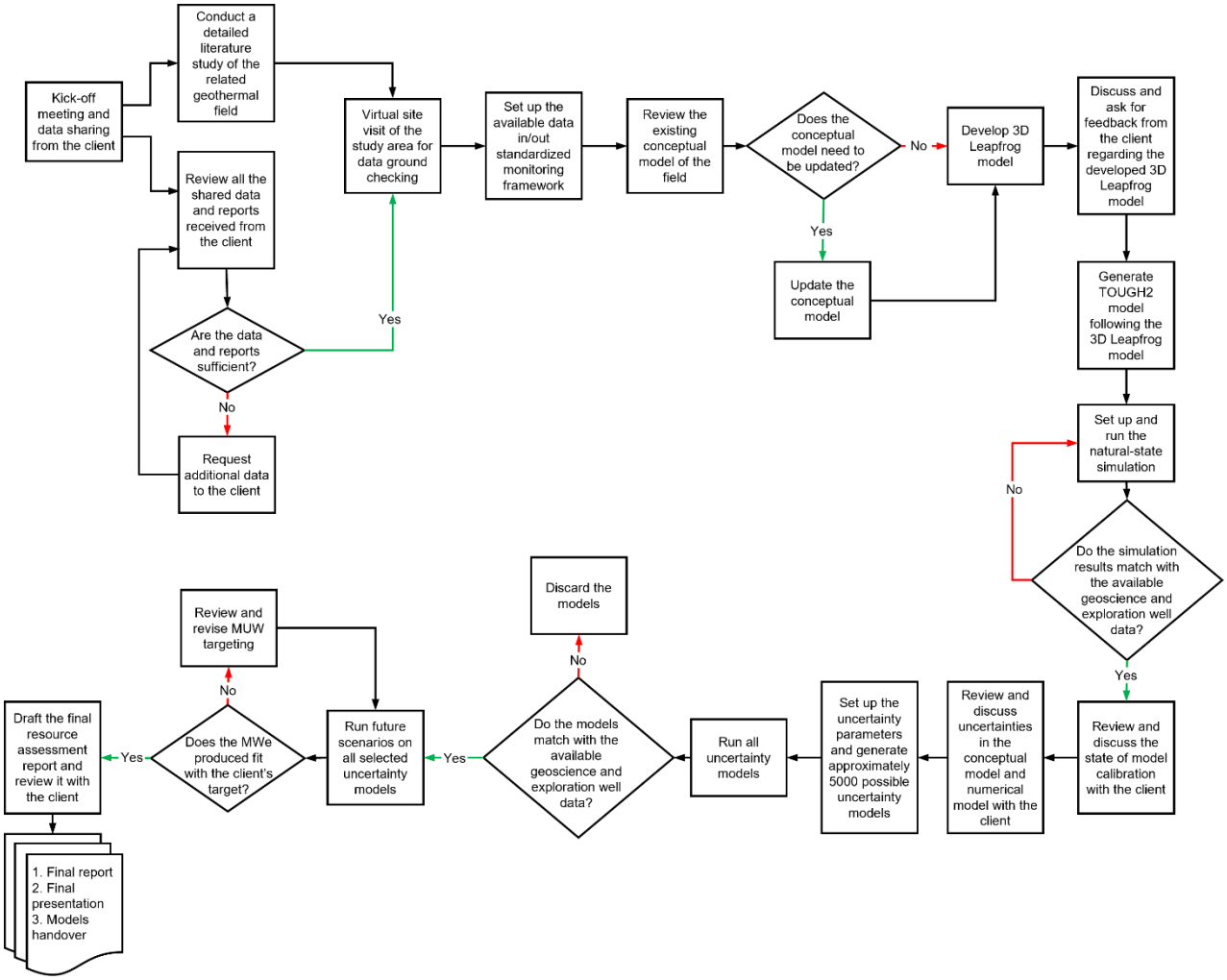


Figure 4: General workflow of the geothermal modelling process for resource assessment of an exploration field.

Setting Up Data in Standardized GMF: Subsequently, the organized well-specific data will be translated into standardised JSON data files, facilitating human and machine readability. These files play a pivotal role in configuring models, defining production histories, and juxtaposing model results with empirical data. Leveraging our standard GMF, the reservoir models will be formulated.

Reviewing Conceptual and Leapfrog Models: An integral aspect of the process involves a meticulous examination of the current conceptual and Leapfrog models of the BDN field. This evaluation will be conducted in conjunction with provided data and publicly available information. The findings will be shared with the client, leading to informed decisions and, if necessary, update the conceptual model to enhance alignment.

Enhancing Existing Leapfrog Model: Further refinement will target the enhancement of the existing Leapfrog 3D geological framework model, ensuring harmonization with the conceptual understanding of the geothermal system. This enhanced model will be tightly integrated with the reservoir model to ensure consistency.

Engaging in Leapfrog Model Discussions: Collaborating with the client, we will strive to perfect the Leapfrog models by accurately reflecting the salient features of the conceptual models from the geothermal fields. Drawing from experience garnered from past projects, such as Kamojang, Lahendong, and Karaha, we will craft new numerical models for each geothermal field, considering potential implementation of dual porosity models if required.

Creating New Numerical Models: Drawing from experience garnered from past projects, such as Kamojang and Lahendong, new numerical models for each geothermal field will be generated, considering potential implementation of dual porosity models if required.

Calibrating the Natural State: The ensuing phase involves meticulous calibration of the Natural State models over a span of approximately 2-3 weeks. This calibration process involves adjusting factors like the upflow zone location, rock permeabilities (K1, K2, and K3), and the mass rate and enthalpy of hot fluids. Manual adjustments will be made until a satisfactory match between model simulation results and field data is achieved.

Discussing Model Calibration, Future Scenarios, and Uncertainty: Collaborating with the Client to evaluate model calibration, contemplate the inclusion of planned make-up wells for future scenarios, and address uncertainties within the system.

Implementing Uncertainty Quantification: The establishment of uncertainty quantification using a proven methodology will involve the creation of numerous model versions, nearing a count of ~5000. This approach, backed by published papers, has been effective in commercial contexts.

Running Future Scenarios: Each likely future scenario will be run, accommodating five different make-up well schedules provided by the Client. This will be done across all possible model versions consistent with available geoscience and exploration well data. The results will yield MWe estimates from each well, offering a range of forecasts for make-up well performance. This data will empower the Client to make well-informed decisions about optimal drilling candidates and preferred well targets based on calibrated model outcomes.

Revising Make-Up Well Targeting: The conclusive phase involves collaborative scrutiny of model forecasts for make-up wells with the client and Geothermal Institute's modelling team. If necessary, adjustments to make-up well targeting will be discussed, and scenarios will be rerun accordingly.

Drafting Report and Discussion: A comprehensive report alongside the models will be prepared, with discussions aimed at ensuring precision and alignment.

Final Report Submission and Model Handover: Upon finalization, the comprehensive report and models will be submitted, marking the culmination of the project.

5. ADVANTAGES OF USING GMF FOR EXPLORATION FIELD RESOURCE ASSESSMENT

As discussed in the previous sections, utilising GMF to accomplish a tight coupling in both the conceptual and reservoir models adds substantial benefits to the geothermal modelling process in any stages of development, including exploration phase. Some of those benefits can be described as follows:

- The integrated GMF ensures consistency reservoir model with all available data, following best practices, and increases knowledge of the system.
- Fast, reliable reservoir modelling allows the temperature distribution to be estimated more accurately with less assumptions required.
- Uncertainty quantification systematically tests large range of possible reservoir models to support robust POD.
- Exploration reservoir modelling provides a platform for future modelling reducing costs and accelerating resource potential estimates.

Additionally, the calibrated Natural State model resulting from the modelling works of an exploration field can be used to identify the most likely high permeability zones with high temperatures. Thus, it could give a clear target zone for the next drilling campaign (deep slim hole or standard hole) through 3D visualization. Figure 5 shows the rationale process of well targeting development in our previous study (Nugraha et al., 2018).

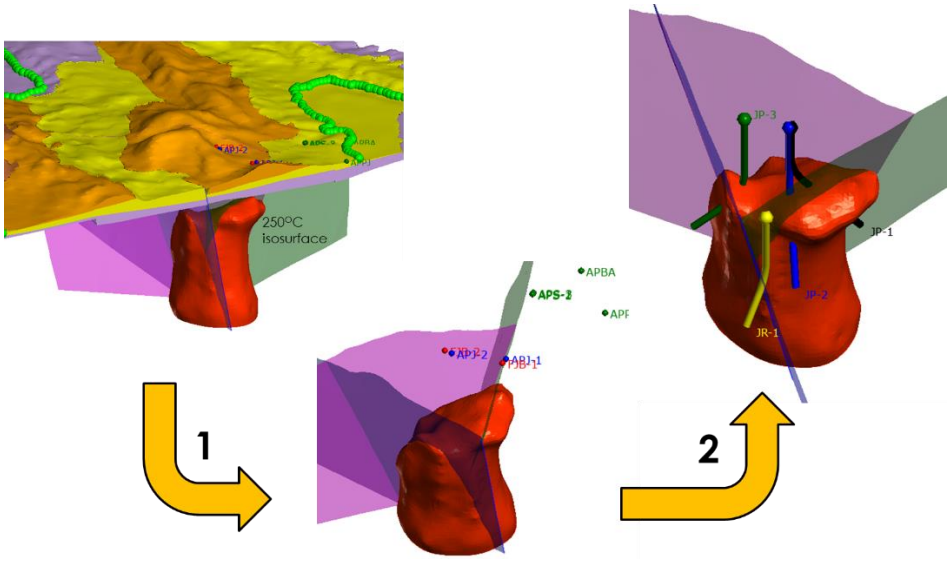


Figure 5: Well targeting development using the Natural State simulation results.

As seen above, the process of devising well targets commence with the amalgamation of temperature distribution outcomes from the Natural State simulation into the 3D conceptual model. Subsequently, the inferred upflow is delineated through the visualization of the ~250°C isosurface. The primary focus of drilling targets lies within high permeability structures, which significantly influence the distribution of upflow. Construction of production wells is then directed toward the main target area, with these planned wells serving as the foundation for future scenarios to assess the prospective production capacity of the field.

6. CONCLUSION

The practical application of the Geothermal Modelling Framework (GMF) in real commercial projects is expounded in this paper. This framework, developed by the Geothermal Institute, establishes a robust connection between the conceptual model and reservoir models (comprising Natural State, Production History, and Future Scenario models). The standardized tools employed within this framework facilitate data storage, model setup, and result plotting. The reservoir models generated through GMF applications exhibit exceptional versatility, allowing for continuous updates in response to new data availability and future study requirements. GMF's adaptability extends across all stages of modeling work.

The incorporation of standardized Python scripts and modeling tools in this framework substantially accelerates the modeling process, granting additional time for calibration and enhancing model outcomes. The authors aspire that this paper will stimulate geothermal operators in Indonesia to initiate geothermal modeling projects early in the development phase. Through adherence to this integrated framework, the resultant geothermal models can align with industry standards, thereby contributing significant value to the comprehensive development of the geothermal project.

ACKNOWLEDGEMENTS

Waiwera network development has been supported by the “Empowering Geothermal” project and the Geothermal Supermodels Programme (C05X1306), funded by the New Zealand Ministry of Business, Innovation and Employment (MBIE). Contact Energy Ltd and Newcrest Mining Ltd have also provided funding throughout the project.

The authors thank our partners Polaris Energy Nicaragua S.A. and Jacobs for their collaboration and allowing the presentation of the San Jacinto geothermal field. We would also like to thank Sam Alcaraz at GNS for work on the geological model used in the Synthetic reservoir model. The authors acknowledge the use of New Zealand eScience Infrastructure (NeSI) high performance computing facilities as part of this research. New Zealand's national facilities are provided by NeSI and funded

jointly by NeSI's collaborator institutions and through the Ministry of Business, Innovation & Employment's Research Infrastructure programme. URL https://www.nesi.org.nz.

All the research projects described in this paper made extensive use of Leapfrog Geothermal and the authors gratefully acknowledge the support of Seequent for making research licenses available.

REFERENCES

Alcaraz, S. A., Chambefort, I., Pearson, R., & Cantwell, A. (2015). An Integrated Approach to 3-D Modelling to Better Understand Geothermal Reservoirs. *Proceedings World Geothermal Congress 2015*. Melbourne.

Croucher, A. (2011). PyTOUGH: A Python Scripting Library For Automating TOUGH2 Simulations. *Proceedings New Zealand Geothermal Workshop 2011*. Auckland.

Croucher, A. (2015). Recent Developments In The PyTOUGH Scripting Library For TOUGH2 Simulations. *Proceedings 37th New Zealand Geothermal Workshop*. Taupo.

Croucher, A., O'Sullivan, M., O'Sullivan, J., Yeh, A., & Burnell, J. (2020). Waiwera: A parallel open-source geothermal flow simulator. *Computers and Geosciences*, 141.

Nugraha, R. P., & O'Sullivan, J. (2018). A Natural State Model of Jaboi Geothermal Field, Nangro Aceh Darussalam, Indonesia. *Proceedings 7th ITB International Geothermal Workshop 2018*. Bandung: Institut Teknologi Bandung.

Nugraha, R. P., O'Sullivan, J., & O'Sullivan, M. J. (2018). A 3D Geological Model and Natural State Simulation of Jaboi Geothermal Field, Nangro Aceh Darussalam, Indonesia. *New Zealand Geothermal Conference 2018*. Taupo: New Zealand Geothermal Conference.

O'Sullivan, J., Abdurachman, F., Bignall, G., Bromley, C., Dekkers, K., Ghassan, M., O'Sullivan, M. (2023a). A new modelling study of the Kamojang geothermal field. *48th Workshop on Geothermal Reservoir Engineering*. California.

O'Sullivan, J., & O'Sullivan, M. (2021). Geothermal Reservoir Modelling. *Geothermal Project Management Course for Indonesia and Philippines*.

O'Sullivan, J., Abdurachman, F., Bignall, G., Bromley, C., Dekkers, K., Ghassan, M., O'Sullivan, M. (2023b). Multidisciplinary collaboration to create a new numerical model of the Lahendong geothermal field. *48th Workshop on Geothermal Reservoir Engineering*. California.

O'Sullivan, J., Dempsey, D., Croucher, A., Yeh, A., & O'Sullivan, M. (2013). Controlling Complex Geothermal Simulations Using PyTOUGH. *Proceedings 38th Workshop on Geothermal Reservoir Engineering*. Stanford.

O'Sullivan, J., Popineau, J., Gravatt, M., Renaud, T., Riffault, J., Croucher, A., O'Sullivan, M. (2023c). An integrated, mesh-independent geothermal modelling framework. *Environmental Modelling & Software*, 163, 105666. doi:10.1016/j.envsoft.2023.105666.

Wellmann, J. F., Croucher, A., & Regenauer-Lieb, K. (2012). Python scripting libraries for subsurface fluid and heat flow simulations with TOUGH2 and SHEMAT. *Computers & Geosciences*, 43, 197-206.

Yeh, A., Croucher, A. E., & O'Sullivan, M. J. (2012). Recent Developments in The AUTOUGH2 Simulator. *TOUGH Symposium 2012*. Berkeley: Lawrence Berkeley National Laboratory.

Yeh, A., Croucher, A., & O'Sullivan, M. (2013). TIM - Yet Another Graphical Tool for TOUGH2. *Proceedings 35th New Zealand Geothermal Workshop*. Rotorua.

Brine Pressure Management for Preventing Flashing in Sarulla GPP

Saeful Romadhon

Kauman Utara No.60 RT 05 RW 14, Wonosobo, Central Java

saeful.romadhon@sarulla-geothermal.com

Keywords: Sarulla, binary, brine, flashing, pressure control

ABSTRACT

Geothermal energy is a sustainable source of electricity generation, and the Sarulla geothermal power plant in Indonesia utilizes brine in a binary system for efficient power production. However, flashing, a phenomenon where brine rapidly vaporizes due to a sudden drop in pressure, poses challenges to the system's safety and efficiency.

To address the risks associated with flashing, the Sarulla power plant focuses on pressure control as a treatment measure. Through advanced pressure regulation techniques, the plant maintains a delicate balance between brine pressure and temperature, preventing sudden pressure drops that can trigger flashing. Specialized pressure control valves and monitoring systems are implemented to ensure stable and controlled pressure levels within the binary system.

Alongside pressure control, the power plant utilizes comprehensive monitoring and control mechanisms. Real-time pressure monitoring at various stages, automated pressure adjustment systems, and emergency shutdown protocols are employed to safeguard the system during unforeseen pressure variations.

The emphasis on pressure control treatment ensures the safe and reliable operation of the binary system at Sarulla. By effectively regulating pressure, the plant minimizes the risks of flashing, equipment damage, and operational disruptions. Furthermore, it enhances the overall efficiency and stability of geothermal power generation.

In conclusion, the Sarulla geothermal power plant prioritizes pressure control as a treatment measure for brine utilization in the binary system. Through advanced pressure regulation techniques and comprehensive monitoring, the plant mitigates the risks associated with flashing, ensuring the safe and efficient operation of the power generation process. These treatment measures not only enhance plant performance but also contribute to the sustainability and reliability of geothermal energy as a clean source of electricity.

1. INTRODUCTION

Geothermal energy is recognized as a sustainable and environmentally-friendly source of electricity generation, and its utilization has been steadily increasing in various parts of the world. The Sarulla geothermal power plant in Indonesia stands as an exemplar of harnessing geothermal energy for efficient power production. Located in the Sarulla geothermal field in North Sumatra, Indonesia, the power plant utilizes brine in a binary system to enhance power generation. However, the phenomenon of brine flashing poses safety and efficiency challenges to the power plant.

The Sarulla geothermal power plant distinguishes itself from other geothermal facilities in Indonesia by integrating a back pressure steam turbine system with a steam binary system plant and a brine binary system plant. The combination of these systems allows the plant to efficiently utilize brine, a byproduct of the geothermal energy extraction process, to generate approximately 25% of the total net load output from all combined units. Unlike conventional geothermal power plants that primarily use condensing steam turbines, Sarulla's approach maximizes the utilization of brine and significantly contributes to power generation.

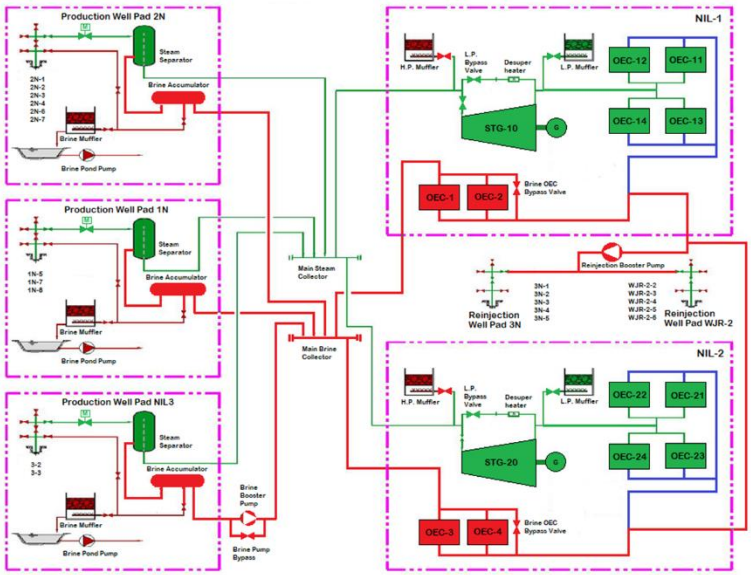


Figure 1: Flow Diagram of Namora I Langit Site.

The utilization of geothermal energy has gained immense significance globally as countries strive to transition to more sustainable and renewable energy sources. Geothermal power generation plays a crucial role in the energy mix, contributing to reducing greenhouse gas emissions and dependence on fossil fuels. The geothermal energy sector has experienced rapid growth, attracting investments and technological advancements to harness this abundant and reliable source of clean energy.

While geothermal energy offers numerous benefits, challenges related to the efficient utilization of brine in geothermal power plants need to be addressed. Brine flashing is one such challenge that poses risks to the safety and operational efficiency of geothermal facilities. Understanding and effectively managing brine pressure are critical to ensuring the reliable and sustainable operation of geothermal power plants. This paper focuses on the Sarulla geothermal power plant in Indonesia, examining its brine pressure management strategies and solutions to mitigate the impacts of flashing.

2. CHALLENGES OF BRINE FLASHING AND ITS IMPACTS

Despite the advantages of brine utilization, the flashing phenomenon presents several challenges and impacts that need careful consideration. Brine flashing occurs when brine rapidly vaporizes due to a sudden drop in pressure at elevated temperatures. This process can lead to various issues, including hammering, erosion, and scaling within the power plant infrastructure.

The Sarulla geothermal field comprises three production well pads with varying elevations. Well Pad NIL-2N is situated at an elevation of 855 meters above sea level (masl), NIL3 Old at 825 masl, while NIL-1N, with an elevation of approximately 875 masl, is further away from the plant and requires brine booster pumps for efficient transport. The NIL Power Plant itself has an elevation of 820 masl, and Reinjection Well Pad NIL-3N is located at an elevation of 835 masl.

One of the most immediate impacts of brine flashing is the hammering effect on piping systems. The sudden vaporization of brine generates pressure waves and vibrations that are acutely felt by field operators and control room personnel. The intensity of these hammering effects can lead to erosive damage, pipe rupture, and potential failures in sections with weak construction joints. Additionally, the vibrations can affect nearby equipment and structures, posing risks to the overall safety of the plant.

Moreover, brine flashing also leads to a loss of brine mass, which negatively impacts the plant's overall efficiency. The vaporized brine becomes a non-condensable gas, reducing the total mass flow through the turbines. This results in a decrease in power output and an operational inefficiency of the plant. Addressing these challenges requires careful design and operation of the brine utilization system to minimize the occurrence of flashing and its associated impacts.

3. BRINE PRESSURE MANAGEMENT STRATEGIES AND FUTURE DIRECTIONS

To overcome the challenges posed by brine flashing and ensure safe and efficient operations, the Sarulla geothermal power plant employs various brine pressure management strategies. These strategies aim to optimize brine flow, minimize pressure drops, and prevent occurrences of flashing. Additionally, the plant is actively exploring future directions to further enhance brine pressure management and improve overall power plant efficiency.

The Sarulla power plant has implemented advanced pressure monitoring and control systems throughout the brine utilization process. By continuously monitoring brine pressure levels at key points in the system, operators can quickly detect any anomalies or potential flashing events. Real-time data from pressure sensors enables operators to adjust flow rates, valve positions, and pump operations promptly to maintain stable and safe brine pressure levels. This proactive approach ensures that brine remains in a liquid state, minimizing the risk of hammering and other associated impacts.

There are 3 brine parameters that always appear simultaneously in the HMI and must be observed by the Control Operator in the CCR, namely real-time pressure, real-time temperature, and real-time saturation pressure, which is calculated based on real temperature referencing the steam table. As shown in the diagram below, saturation pressure is a critical point where brine is still in liquid form with a certain temperature.

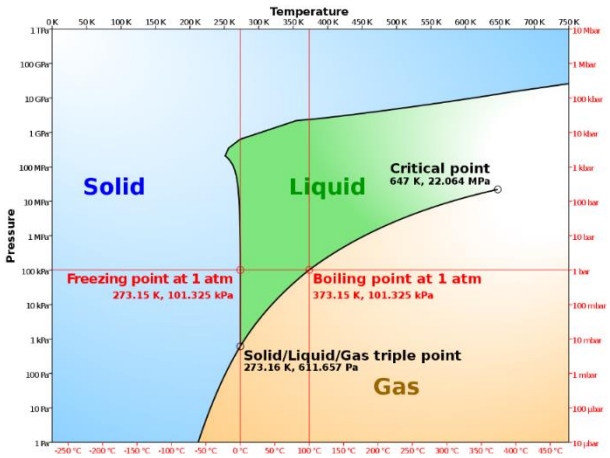


Figure 2: Phase Diagram of Water.

Therefore, the real-time pressure must be maintained higher than the saturation pressure displayed on the HMI. In the HMI, as shown in the image below, real-time pressure is indicated by the orange color, real-time temperature by the light blue color, while saturation pressure is indicated by the pink color.

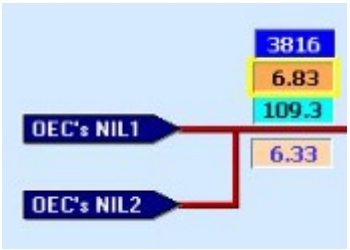


Figure 3: Parameters screenshot of NIL Power Plant HMI.

Continuously, the Control Operator must monitor the real-time pressure value to always be above the saturation pressure value and take necessary actions if the real-time pressure drops, such as adjusting the equipment installed on the brine path.

Generally, the brine pressure regulation at the Namora I Langit site is divided into four sections: pre-production, production, post-production, and reinjection. The pre-production section consists of well head equipment, separation system, and header pipeline. The production section consists of the OEC

brine unit. The post-production section consists of the outlet pipeline of the OEC brine unit and the condensate pipeline from the bottoming unit OEC. Meanwhile, the reinjection section consists of reinjection booster pumps, reinjection pipeline, and reinjection well head.

3.1 Pre-Production Section

In this section, the two-phase steam from the wellhead is divided into single-phase steam and brine through the separation system. The brine pressure in this section is controlled by the opening of valves as shown in the diagram below.

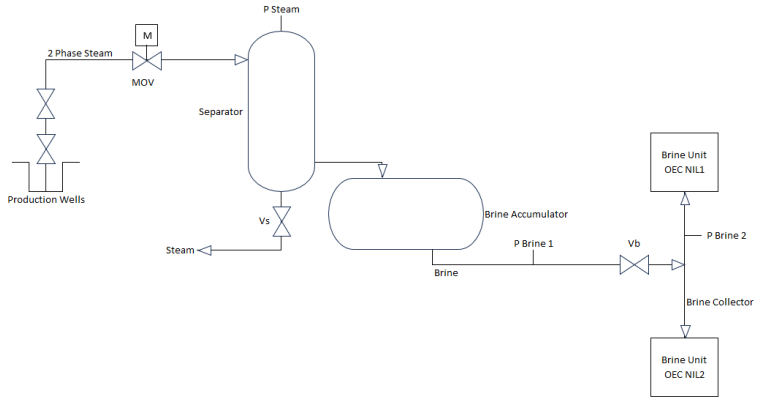


Figure 4: Pre-Production Section Diagram.

The first brine pressure to be regulated is P Brine 1, which is controlled by the opening of MOV on the 2 Phase Steam line and Vb, which is the brine outlet header from each production well pad. However, the regulation of brine pressure can also be assisted by the opening of Vs, which is the steam outlet from the separator. An increase in the separator pressure will help to push the brine in the brine accumulator towards the brine outlet header. Meanwhile, for P Brine 2 in the brine collector, it is controlled by Vb and the inlet valve on the OEC brine unit. The average brine temperature in the pre-production section is 185 degrees Celsius with a saturation pressure of 10.2 barg. Therefore, the brine pressure in the pre-production section must be maintained at about 2 barg above the saturation pressure or at an average brine temperature of 185 degrees Celsius, the brine pressure should be at 12 barg or higher. In the wells located at the same elevation as the power plant, Vb's role is replaced by the booster pump, and the valve opening is replaced by the motor speed on the booster pump unit.

3.2 Production Section

In this section, brine from the brine collector will be used in the OEC brine unit to generate electricity. The brine pressure regulation in the production section can be seen in the diagram below.

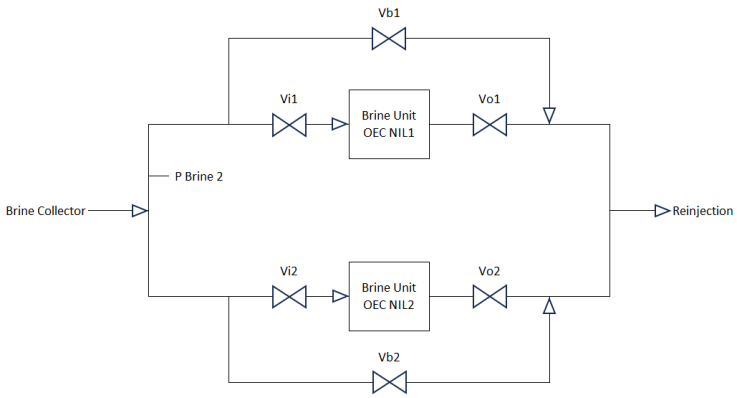


Figure 5: Production Section Diagram.

Under normal conditions, the regulation of brine pressure in the production section is controlled by Vo1 and Vo2, which are the brine outlet valves in each OEC brine unit. Vi1 and Vi2 are more of a safety feature in case the OEC unit trips because these valves are ON-OFF valves that only open at 100% opening. Vo1 and Vo2 are also brine flow regulators into the OEC brine unit according to the desired MW output. However, in the event of a trip in the OEC brine unit, either all or partially, the brine pressure in the production section will be controlled by Vb1 and Vb2, which are bypass valves. This is also useful to ensure that brine continues to flow, so the overall system remains safe even if there is a trip in the OEC brine unit. Generally, the average brine temperature working in the production section is 185 degrees Celsius, the same as the output from the brine collector.

3.3 Post-Production Section

In the post-production section, there is a mixture of brine from the OEC brine unit with condensate from the bottoming unit OEC. Mixing also occurs with brine from the bypass line in case one or all of the OEC brine units trip. The post-production section is located in the power plant area and is the most vulnerable to brine flashing. This can occur due to sudden pressure loss caused by a trip in the OEC brine unit. During such an event, the brine flow on the outlet side of the OEC brine unit may decrease or disappear if all OEC brine units trip. Meanwhile, the equipment on the downstream side is still operating at full opening or the pump at maximum speed.

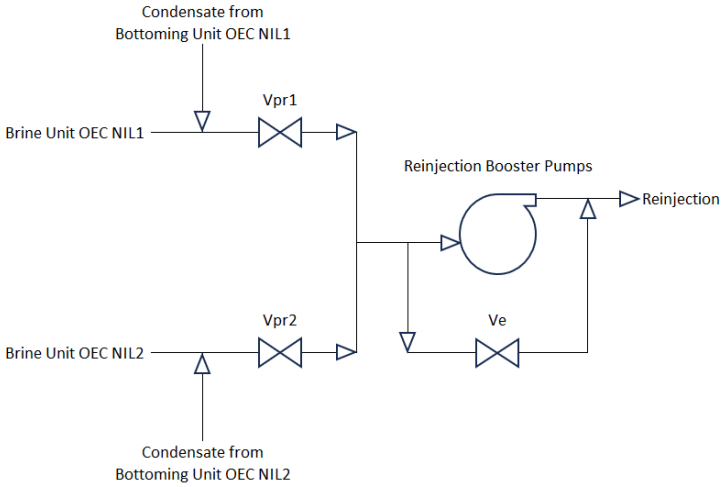


Figure 6: Post-Production Section Diagram.

In the post-production section, brine pressure is regulated by Vpr1 and Vpr2, which are pressure regulators that can be set at a specific pressure setpoint. Therefore, if the brine flow decreases drastically and the brine pressure drops, Vpr1 and Vpr2 will close, adjusting to the desired setpoint to prevent brine flashing. In addition, the speed of the reinjection booster pumps must also be adjusted to ensure that the pressure on the suction side remains above the saturation pressure of the brine present in the suction line. If the speed remains high while the brine flow decreases, the suction pressure will quickly drop and become vulnerable to going below the saturation pressure, causing brine flashing. During such a trip event, field operators and control operators must be more alert to parameter changes in the field, including indications of ground vibrations, noises in the piping, and vibrations in the control room.

With variations in the placement of pressure transmitters, temperature transmitters, and flow transmitters along the brine path, sometimes the readings on the HMI do not show actual parameters in certain areas where those transmitters are not present. Hence, indications such as vibrations can be used as references if brine flashing still occurs in specific areas. Consequently, some equipment such as valves and pumps need to be manually adjusted by operators to adapt to the field conditions. The "Ve" in the diagram is used only if the reinjection booster pumps fail to maintain brine flow to the reinjection section. The average brine temperature exiting the OEC brine unit is around 120 degrees Celsius, while the condensate temperature from the bottoming unit OEC is between 70-80 degrees Celsius. The temperature of the mixture of brine and condensate in this section ranges from 110-115 degrees Celsius.

However, during OEC brine unit trips, either partial or total, the brine temperature can reach 150-180 degrees Celsius. Such significant temperature differences necessitate prompt adjustments to the brine pressure during trips. Under normal operating conditions, the brine pressure is maintained above 7 barg, but during OEC trips, the brine pressure should be adjusted between 10 to 12 barg, depending on the resulting temperature.

3.4 Reinjection Section

Pressure regulation in this section is essential not only to prevent brine flashing but also to maximize brine flow towards the reinjection wells.

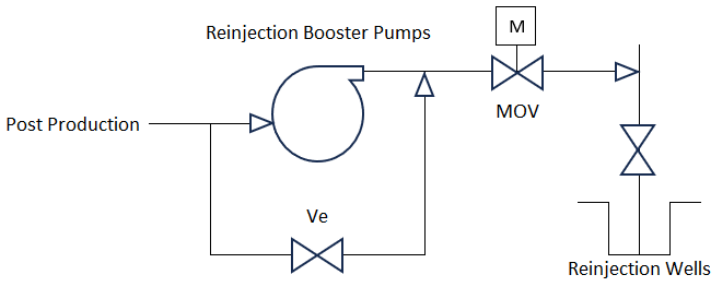


Figure 7: Reinjection Section Diagram.

The ability of reinjection wells to receive brine varies and can also be influenced by the incoming brine temperature. If the temperature is low, reinjection wells tend to be able to receive more brine, but at high temperatures, reinjection wells tend to receive less brine, thus requiring higher pressure. The pressure in the reinjection section is affected by the speed of the reinjection booster pumps and the opening of MOV in each reinjection well. The speed of the reinjection booster pump significantly affects the brine pressure in this section. With higher speed, brine flow increases, leading to higher brine pressure, and vice versa. Large opening of the MOV in a reinjection well, which has better absorption capacity, will cause the brine pressure to be lower, and vice versa. The brine temperature in this section is the same as in the post-production section.

In the brine pressure regulation, adjustments in one section may affect other sections; thus, each part must be well-coordinated. However, the division of sections makes it easier for operators to analyze events and their direct impact, allowing them to take appropriate and swift actions. For example, if the pre-production section experiences problems resulting in reduced brine supply and lowered brine pressure, the production, post-production, and reinjection sections must adjust to maintain high pressure while adapting to the available temperature to avoid temperature drops that could lead to scaling in the piping and heat exchangers in the OEC brine unit. Similarly, if there are issues with the reinjection wells that cause the brine pressure in the reinjection section to rise, adjustments must be made in other sections to ensure that brine continues to flow smoothly and that production is not disrupted.

As the Sarulla geothermal power plant continues to strive for efficient and sustainable energy generation, it will continue to explore technological advancements and conduct further research to enhance brine pressure management strategies. The integration of new developments and innovations will lead to improved overall efficiency and sustainability of geothermal power generation.

4. CONCLUSION

In conclusion, the Sarulla geothermal power plant has successfully utilized brine in a binary system for efficient and sustainable electricity generation. However, the flashing phenomenon, where brine rapidly vaporizes due to a sudden drop in pressure, poses significant challenges to the system's safety and efficiency. To address these risks, the power plant prioritizes pressure control as a crucial treatment measure.

Through advanced pressure regulation techniques and comprehensive monitoring systems, the Sarulla power plant ensures that brine pressure is maintained above the critical saturated pressure. Specialized pressure control valves and monitoring instruments are strategically implemented to safeguard the binary system's stability and prevent brine flashing incidents. Real-time pressure monitoring at various stages, automated pressure adjustment systems, and emergency shutdown protocols further enhance the system's reliability during unforeseen pressure variations.

The precise control and management of brine pressure in different sections, such as pre-production, production, post-production, and reinjection, are critical to optimizing the overall power generation process. Operators play a pivotal role in continuously monitoring and adjusting the brine pressure to avoid operational disruptions and potential equipment damages caused by brine flashing.

As the Sarulla geothermal power plant operates with an integrated geothermal combine cycle unit (IGCCU), it showcases an exemplary model for utilizing geothermal resources effectively and responsibly. The plant's emphasis on pressure control treatment ensures the safe and efficient operation of the binary system, while contributing to the sustainability and reliability of geothermal energy as a clean source of electricity.

To further improve brine pressure management strategies, ongoing research and development efforts are necessary. Continuous exploration of advanced technologies and best practices in the geothermal industry will enable the Sarulla geothermal power plant to enhance its operational efficiency and further reduce potential risks related to brine flashing.

In the future, the Sarulla geothermal power plant remains committed to sustainable practices and will continue to explore innovative solutions to optimize brine pressure control. The continuous dedication to safe and efficient geothermal power generation reinforces its position as a role model for clean and renewable energy production worldwide.

With a strong foundation built on responsible brine pressure management and continuous improvements, the Sarulla geothermal power plant will continue to play a vital role in contributing to Indonesia's renewable energy targets and global efforts to combat climate change.

REFERENCES

Hariadi, B., & Kurniawan, A. (2022). Brine Pressure Management in Geothermal Binary Power Plants: A Case Study of the Sarulla Geothermal Power Plant. *Journal of Sustainable Energy and Environment*, 8(2), 112-126.

International Geothermal Association. (2022). *Geothermal Power Generation: Best Practices and Case Studies*. Retrieved from https://www.geothermal-energy.org/

Sarulla Operations Team. (2023). *Internal Data and Reports on Brine Pressure Management*.

Trisnanto, A., & Widodo, A. (2021). Brine Utilization Strategies in Geothermal Power Plants: A Review. *Renewable and Sustainable Energy Reviews*, 137, 110341.

Wibowo, D. A., Prasetyo, E., & Hidayat, M. (2020). Flashing Phenomenon and its Impacts on Geothermal Power Plants: A Case Study of Sarulla Geothermal Power Plant. *International Journal of Geothermal Research*, 4(2), 96-103.

Steam Cap Development Monitoring of HCE-28A Well in the Dieng Geothermal Field Based on Fluid Geochemistry Data

Aditya Yudha Kencana, Elfina, RA Julia Satriani Alibazah, Reza Jamil Fajri, Ichwan Agusta Elfajrie, Marchel Christian Supijo, and Zahratul Kamila

PT Geo Dipa Energi (Persero), Jl. Warung Jati Barat No. 75, Jakarta Selatan, 12740, Indonesia

aditya.yudha@geodipa.co.id

Keywords: Dieng, geochemistry, monitoring, steam cap

ABSTRACT

The development of steam caps is the common characteristics changes in the liquid-dominated reservoir. The boiling process that naturally occurred or is triggered by the production forms the steam zone in the upper part of the reservoir. This phenomenon is observed by using enthalpy from Tracer Flow Test (TFT), brine chemistry, NCG, and subsurface temperature from PT Logging. The HCE-28A well which was initially a two-phase well has turned into steam due to the continuous boiling process in the reservoir. This well has a cyclic WHP due to the presence of multiple feed zones; high WHP when the upper and lower feed zone contributes, conversely low WHP when the lower feed zone does not contribute. The upper feed zone has more steam cap contribution and higher steam fraction rather than the lower feed zone. The enthalpy changes sharply from 1619 kJ/kg to 2448 kJ/kg. The produced fluid decreases in brine, captured by steam fraction changes from about 0.53 to 0.85 after about 20 years of production. Monitoring of the total discharge NCG in steam from 2012 to 2022 results in a higher concentration between 0.54 – 0.81 %wt compared to the initial condition that has NCG of about 0.23 %wt. The total discharge Cl concentration is also increasing from 11185 ppm to 15324 ppm in 2022. Gas analysis result from initial to 2022 shows the dynamics of reservoir fluid in HCE-28A. The fluids are enriched with CO_2 during production compared to the initial condition caused by the boiling process in the reservoir as shown by the N_2-CO_2-Ar diagram. The magmatic fluid contribution also becomes more dominant over time as shown by the H_2-H_2S-CH_4 diagram; the fluid is increasingly heading toward the H_2 gas point. The existence of magmatic contribution is proved by the SO_2 gas from 2022 sampling with concentration of about 0.7 ppmWt in the total discharge condition. Estimation of the evolution of y value and reservoir temperature is done by using FT-HSH3 diagram (Fischer-Tropsch Pyrite-Pyrrhotite) because it seems to provide better correlation with reservoir temperature from PT data at the initial stage compared to the FT-HSH1 and FT-HSH2. The FT-HSH3 diagram shows an increase of y value and temperature related to the presence of vapor addition. This phenomenon probably caused by lateral input of steam or the boiling process that occurs in the reservoir which may be triggered by a pressure drawdown or decrease in the liquid level. The steam cap development in this well is also indicated nearby well HCE-28A, which shows lower liquid level. In addition, the numerical simulation shows the similar indication, that the steam cap develops surround HCE-28A and another production well nearby. It shows that the bottom of the steam cap area becomes thicker from an elevation of about +700m to an elevation of +500 m (Dieng Unit 2 well). Therefore, the development of the steam cap in the Dieng Geothermal Field can be attributed to the continuous boiling process taking place in the reservoir, which may be caused by a combination of geothermal fluid production (causing pressure drawdown or decrease in the liquid level), continuous heat influx, and/or continuous magmatic fluid input from the heat source.

1. INTRODUCTION

The exploitation of geothermal fluids will affect the reservoir processes and performances. Injection breakthrough and development of steam cap are observed in several liquid-dominated fields, e.g., Salak-Indonesia (Wijaya et al., 2021) and Tiwi-Philippines (Sugiaman et al., 2004). Scoot (2020) mentioned that the steam cap can be formed naturally or as a response to the production. In this paper, the steam cap is defined as vapor zones in the shallow depths (around the top of reservoir) with steam fraction above 70%. The production from the steam cap zone is usually sustainable and has a high enthalpy,

therefore the production from this area is economically attractive. For example, in the Salak Geothermal Field, the make-up wells were drilled in the steam cap area (East Salak) due to the higher initial production compared to other area and produce almost no brine (Golla et al., 2020).

The Dieng Geothermal Field which is located in Central Java is a liquid-dominated to two-phase geothermal system and has steam cap in several areas. The current generation of this field from Unit 1 is about 60 MW and under development of Unit 2 with 60 MW capacity as well. Based on geoscience and wells data, there is one geothermal system that divided in to 2 reservoir areas, i.e., Sileri and Sikidang. The current production and development wells are located in the Sileri Area with several production wells from Unit 1 is produced from steam cap area and the two Dieng Unit 2 wells have targeted the steam cap area. The wells that produced fluid from steam cap have stable production over time and contribute higher to the total steam production.

In the Dieng Geothermal Field, the steam cap seems to be naturally formed and developed during the production of geothermal fluids. Monitoring of the production fluid's enthalpy, steam fraction, and fluid geochemistry can identify not only the development of steam cap, but also reservoir dynamics. In this study, well HCE-28A which located on the steam cap area, was selected to represent the development of steam cap in the Dieng Geothermal Field. Due to the existence of liquid and steam produced feed zones, this well has a cyclic WHP; high WHP when both the upper and lower feed zones contribute, and low WHP when the lower feed zone does not. The HCE-28A well contributes around 20–25% of Dieng Unit 1's total generation. The monitoring data from surveillance program, e.g., enthalpy and steam fraction (from Tracer Flow Test/TFT), brine chemistry particularly chloride content, and gas chemistry, as well as subsurface temperature and pressure will be combined to get a better understanding in the reservoir processes that affected to the steam cap development in the Dieng Geothermal Field.

2. DATA AND METHOD

The monitoring data that available for HCE-28A well is TFT (enthalpy & steam fraction), brine chemistry, gas chemistry, and PT Logging (Table 1). The TFT and complete brine & gas chemistry data are collected once to twice in a year, but partial chemistry data (brine Cl, brine Mg, total NCG, CO_2, H_2S, and residual gas) is collected monthly. In this study, yearly monitoring data will be used to get a big picture of reservoir dynamics. Other data that will be used is production data and PT logging data from the nearby well from HCE-28A (Dieng Unit 2 well) to compare the liquid level elevation.

Table 1: The summary of monitoring data from HCE-28A well.

Data	Date												
	Initial	May-2007	Sep-2012	Oct-2015	Nov-2016	Mar-2018	Feb-2019	Oct-2019	Feb-2020	Sep-2020	Mar-2021	Oct-2021	Jun-2022
Tracer Flow Test (TFT)	■		■			■	■	■		■	■	■	■
Brine Chemistry	■		■			■	■	■		■	■		■
Gas Chemistry	■		■		■	■		■		■	■	■	■
Stable Isotope	■									■			■
PT Logging	■	■		■					■				

3. RESULT AND DISCUSSION

3.1 Geochemistry Monitoring

Monitoring of brine from the HCE-28A well shows that the fluid that produced fluid is a mature and fully equilibrium fluid based on the Cl-HCO_3-SO_4 and Na-K-Mg diagrams in Figure 1. Not much has changed in the water type since initial to 2022, the fluid produced still shows characteristics of mature chloride brine. The condition of full equilibrium on the Na-K-Mg diagram shows that the hydrothermal fluid is in the equilibrium condition due to water-rock interaction in the reservoir.

There was a significant increase in Cl content in the total discharge condition in the HCE-28A well in both high WHP and low WHP conditions (Figure 2). Under high WHP, Cl concentrations increased from 11,185 mg/kg initially (1997) to 15,324 mg/kg in 2022. A significant increase in Cl occurred in 2012, reaching 15,790 mg/kg. In line with this, an increase in Cl also occurred in low WHP conditions from 2018 (11,774 mg/kg) to 2022 (14,040 mg/kg). The consistent condition of increasing Cl is closely related to the boiling process; this process changes the concentration of chemical elements in the brine to be higher.

The presence of a boiling process in the HCE-28A well is supported by the data plot in the Cl-Li-B diagram (Figure 3). The brine is experiencing significant boron enrichment. The enrichment of boron elements can be an indication of a boiling process (Nicholson, 1993). The stable isotope composition in the HCE-28A well indicates the presence of shifting isotopes δD and δ18O of the water-rock interaction trend (Figure 4). This is closely related to the boiling process or steam heating that occurs more intensively in the well.

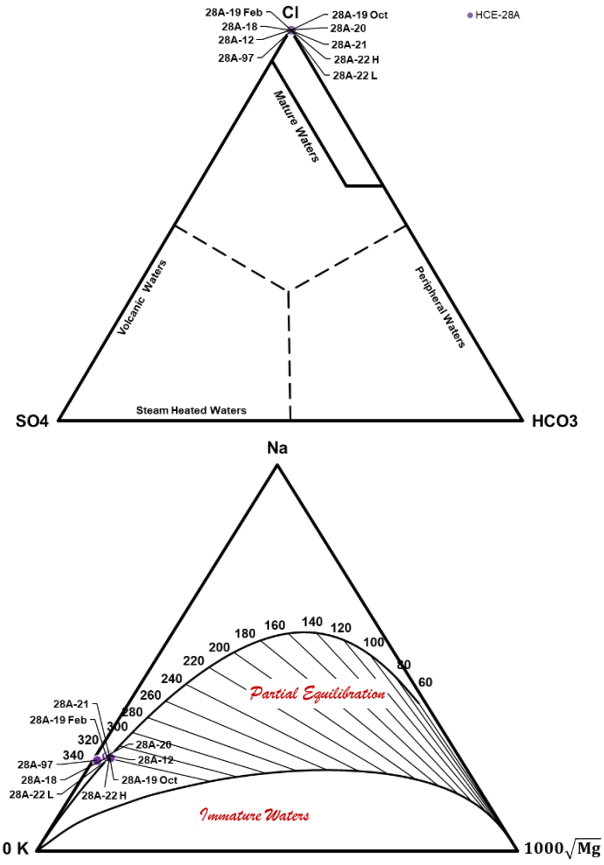


Figure 1: The Cl-SO_4-HCO_3 (left) and Na-K-Mg (right) diagrams from the HCE-28A well. Production fluid shows mature chloride fluid.

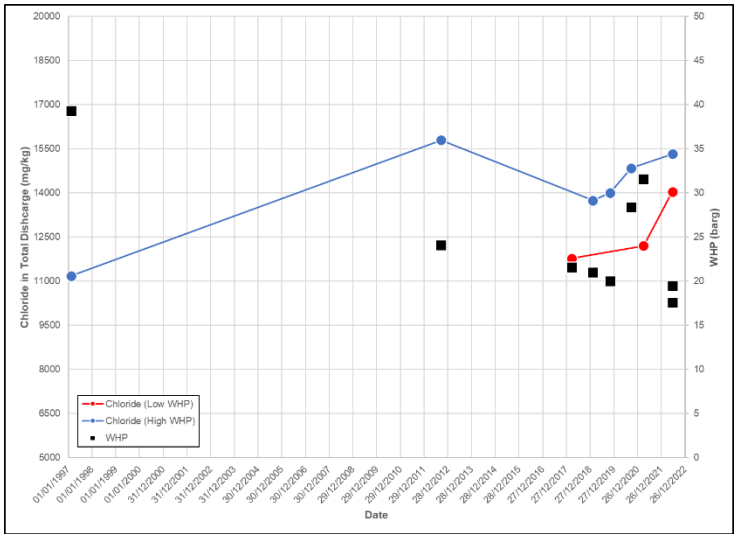


Figure 2: Diagram showing changes in Cl during production. The concentration of Cl in the total discharge condition increased both at low and high WHP.

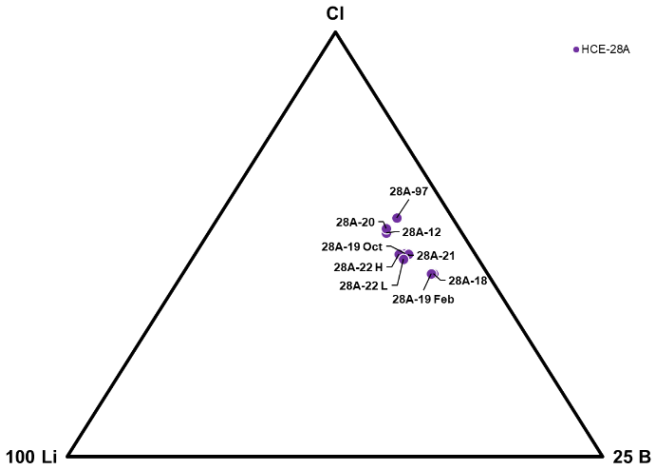


Figure 3: The Cl-Li-B diagram shows the shifting plot towards the boron side which indicates a boiling process.

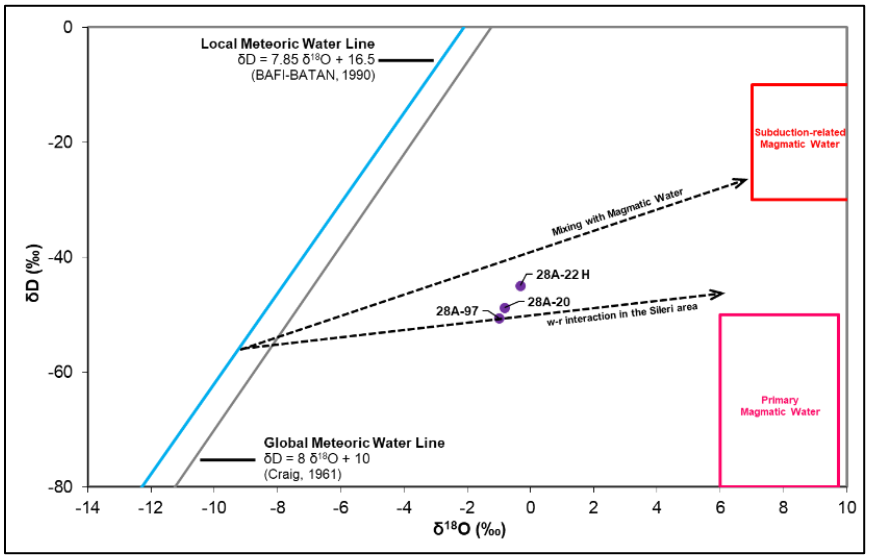


Figure 4: The stable isotopes of $\delta^{18}O$ and δD diagram.

The NCG content of the total discharged fluid from the HCE-28A well has continued to increase to greater than 0.50 %wt since 2012 (Figure 5). In high WHP conditions, NCG increased from 0.23 %wt initially to 0.68%wt in October 2019. Total NCG then decreased to 0.62 %wt and 0.55 %wt in September 2020 and October 2021, respectively. The decrease in total NCG is likely related to WHP conditions during sampling which were higher than in October 2019. Then in June 2022, total NCG experienced an increase due to the chemistry interference of the Dieng Unit 2 well; this process causes the residual gas to increase, then the total NCG also increases. In line with this, even in low WHP conditions, total NCG continued to increase from 0.57 %wt in March 2018, 0.68 %wt in March 2021, and 0.81 %wt in June 2022. Similar to high WHP conditions, that significant increase in total NCG in June 2022 due to chemical interference with the Dieng Unit 2 well. In general, the evolution of total NCG in the HCE-28A well under high and low WHP conditions showed an increase of >0.50 %wt, which according to Wijaya et al. (2021) the NCG content in steam is generally greater than 0.5 %wt. The increase in total NCG was interpreted due to the boiling process and the development of the steam cap in the reservoir.

Process boiling in the reservoir is also shown with a gas plot on diagram N_2-CO_2-Ar (Figure 6). Compared with the initial data, the HCE-28A well experienced CO_2 enrichment which was characterized by a trend shifting towards the CO_2 side on the N_2-CO_2-Ar diagram. This indicates that the boiling process has continued to occur from the initial until the present in the HCE-28A well. However, gas data in 2022 is experiencing shifting to the air contamination area due to an increase in N_2 and Ar gases which is quite significant in June 2022 data when compared to previous data. This is confirmed due to the chemistry interference by drilling the Dieng Unit 2 well.

On the H_2-H_2S-CH_4 diagram (Figure 7), fluid from HCE-28A well shifted towards the H_2 area which indicates that the influence of the magmatic fluid has become more intensive in the well. The contribution of magmatic fluid to the produced fluid of HCE-28A is proved by the SO_2 gas from 2022 sampling with a concentration of about 0.7 ppmWt in the total discharge condition. Although there are indications of magmatic influence, this does not make the pH of the fluid in the reservoir acidic. This is probably caused by the neutralization process through water-rock interaction dominant in the reservoir area.

The FT-HSH3 (Fischer-Tropsch Pyrite-Pyrrhotite) diagram is used to evaluate the vapor fraction (y) and reservoir temperature in the Dieng Geothermal Field (Figure 8). The choice of the FT-HSH3 diagram compared to FT-HSH1 or FT-HSH2 is because the FT-HSH3 diagram shows a better correlation with reservoir temperature from PT logging data in initial conditions. The plot of gas in the FT-HSH3 diagram shows an increase in y value and temperature from initial to 2022. related to the presence of vapor addition. This phenomenon is related to the presence of vapor addition by lateral input of steam or the boiling process that occurs in the reservoir. The boiling may be triggered by a pressure drawdown or a decrease in the liquid level.

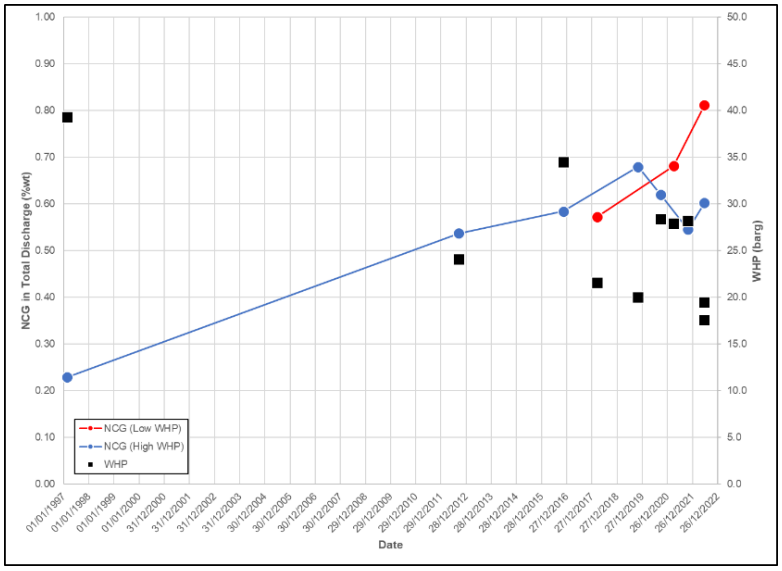


Figure 5: The changes in NCG content during production. The total NCG increased both at low and high WHP.

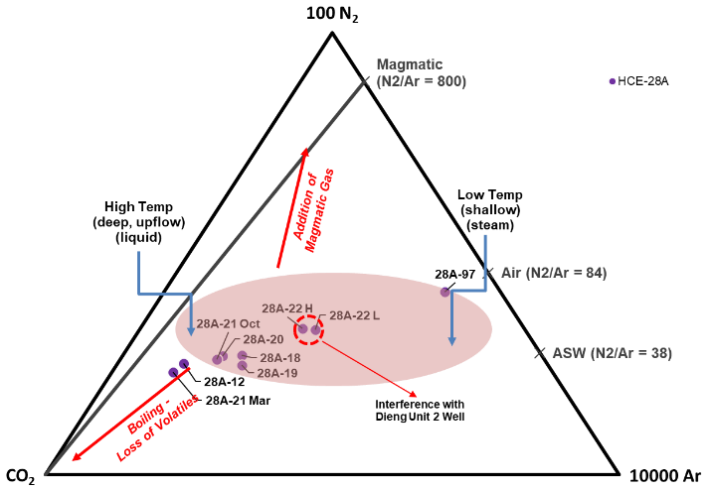


Figure 6: The N_2-CO_2-Ar diagram indicates a shift towards the CO_2 side due to the boiling process.

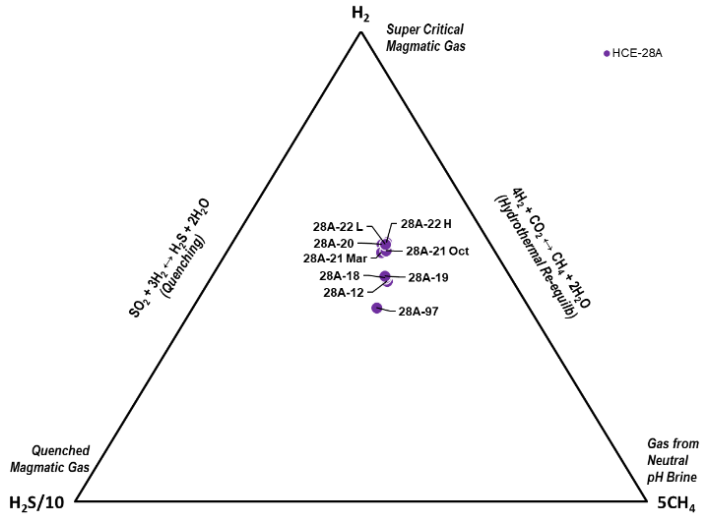


Figure 7: The H_2-H_2S-CH_4 diagram indicates an increasing contribution of magmatic fluid.

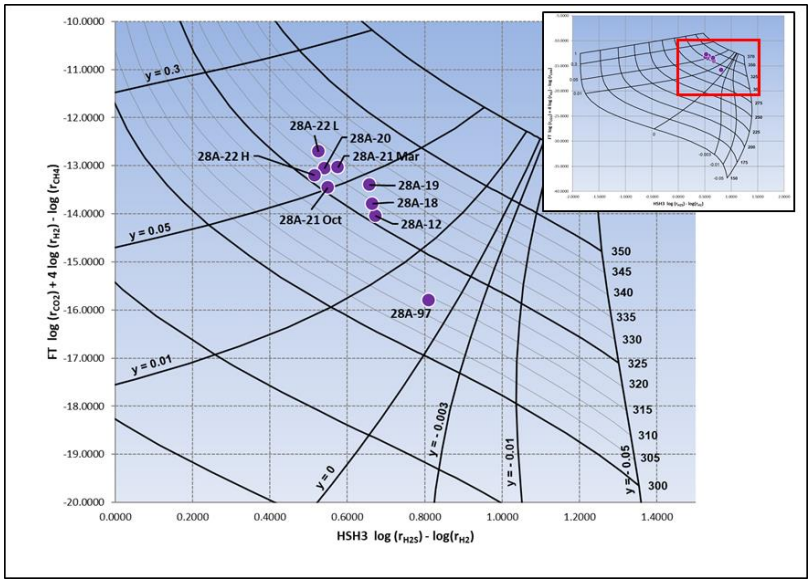


Figure 8: The FT-HSH3 diagram. Gas from the HCE-28A plot shows an increase in y value and temperature during production.

The boiling process indicated by fluid chemistry and the change in the fluid phase from two-phase to vapor-dominated can be seen from the enthalpy and steam fraction (Figures 9 and 10). Initially, the produced fluid by the HCE-28A well has an enthalpy of around 1,619 kJ/kg with a steam fraction of about 0.53. The enthalpy values and vapor fractions are included in the 2-phase fluid range. Along with production, the enthalpy of the HCE-28A well has increased in both low and high WHP conditions. The enthalpy of well HCE-28A in June 2022 under high WHP conditions in June 2022 is around 2114 kJ/kg, in contrast to low WHP conditions which increased significantly to 2,488 kJ/kg. The highest enthalpy for well HCE-28A is around 2,644 kJ/kg in September 2020. As with the enthalpy, the steam fraction of well HCE-28A, particularly in low WHP conditions, increases to greater than 0.70 from 2019 to 2022 (0.77 to 0.85, the highest value was achieved in September 2020 with a value of 0.93). This shows that the fluid produced by the HCE-28A well at low WHP originates from the vapor zone or steam cap. Meanwhile, despite an increase in the steam fraction, in high WHP conditions the value is still below 70%. This indicates that there is still a contribution of the liquid feed zone at high WHP.

Based on the monitoring of geochemical data, the boiling process is the main thing in the formation of the vapor zone and the development of the steam cap in the HCE-28A well area. The boiling process can be caused by the continuous influx of heat in this area, considering that the trajectory of the HCE-28A well is close to the upflow area. A continuous magmatic fluid input is also a factor that cannot be ignored. In addition, the process of producing geothermal fluids which then causes a pressure drop in the reservoir can also cause boiling. Whatever the factor that triggers boiling, the process causes the concentration of chemical elements in the brine, NCG, enthalpy, and vapor fraction to continue to increase along with production.

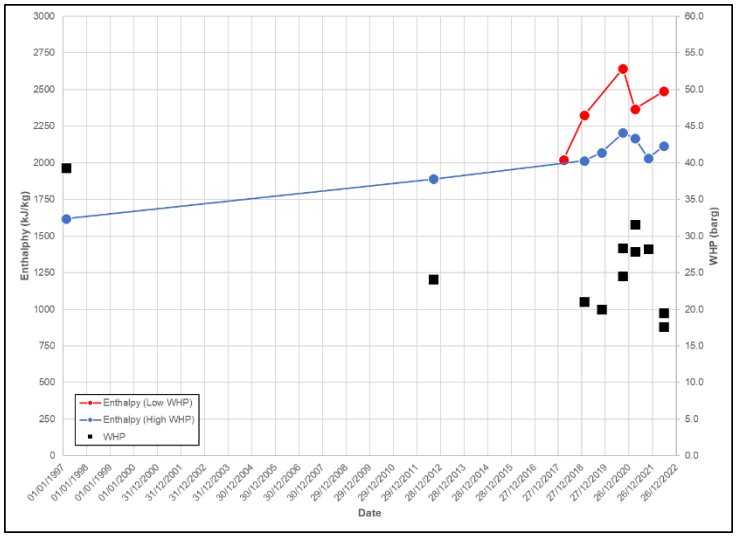


Figure 9: Diagram showing an increasing of the discharged enthalpy during production of HCE-28A well.

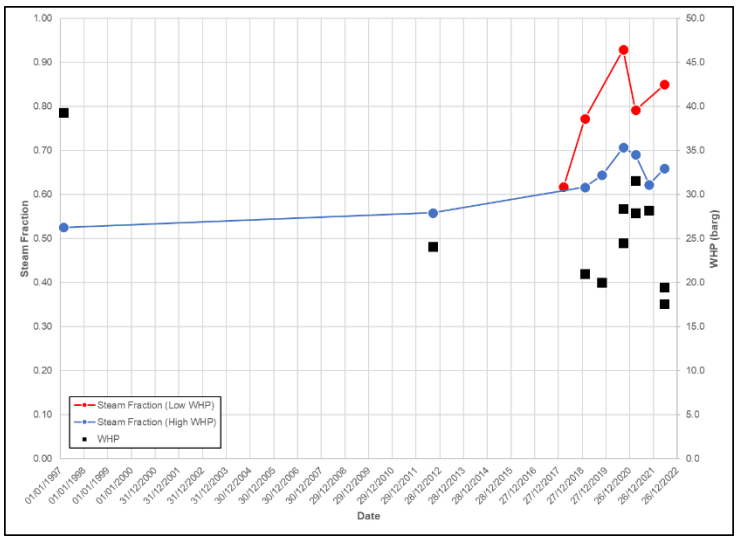


Figure 10: The steam fraction profile during production of HCE-28A well. The increasing trend of steam fraction is quite similar with the enthalpy changes.

3.2 PT Logging

The static temperature profile of the HCE-28A well is shown in Figure 11. The temperature data for the HCE-28A well is of poor quality. There is a convective temperature build-up up close to the surface. This could be due to issues casing integrity of the production casing; thus, the reservoir fluid can penetrate the annulus area of the HCE-28A well. Figure 12 is the result of PT matching the HCE-28A well that has reached a natural state. The temperature of the HCE-28A well model looks relatively higher than the actual data (8 – 10^{o}C in the liner area). The HCE-28A well has actual data quality which tends to be not good enough, therefore the temperature model is not too adapted to actual conditions. This is indicated from the temperature data which tends to decrease with increasing depth, where this anomaly does not occur when the well heads to the upflow zone.

The actual pressure profile and model of the HCE-28A well under natural state conditions (Figure 3.12) show the transition zone between the water level and steam cap zone is at an elevation of about +700 m. After the production and injection activities are carried out, the temperature, pressure, and vapor saturation conditions will change. The fluctuations in these three parameters will depend on the amount of mass extracted and the mass injected into the reservoir. The more mass extracted, the more massive

the pressure drop and increase in vapor saturation will be. In the vicinity of the HCE-28A well, there are two Dieng 2 wells (wells A and B) whose temperature and pressure profiles can be used to validate changes in temperature and pressure conditions and the development of a steam cap in the area. Although the two Dieng 2 wells already have heating-up data, the temperature has yet to reach an equilibrium condition because there are still indications of reversal in the bottom hole area.

Figure 13 shows the graph of PT matching to the condition of the model after production history matching is done. The temperature profiles of the two wells indicate the same pattern, where the steam area temperature already matching because it has reached equilibrium. However, the actual temperature of the brine area still shows a reversal with indications that it has not yet reached an equilibrium condition. Actual pressure profiles and models of wells A and B show the transition zone between the water level and steam cap is at an elevation of +500 m. When compared with the natural state based on well HCE-28A, the thickening of the steam cap occurred about 200 m from 2002 to 2022.

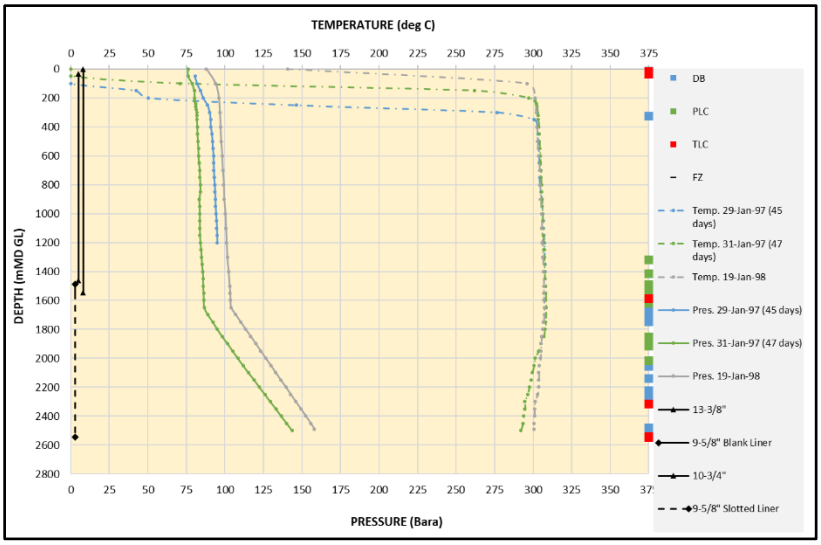


Figure 11: The actual PT Shut In profile of the HCE-28A well.

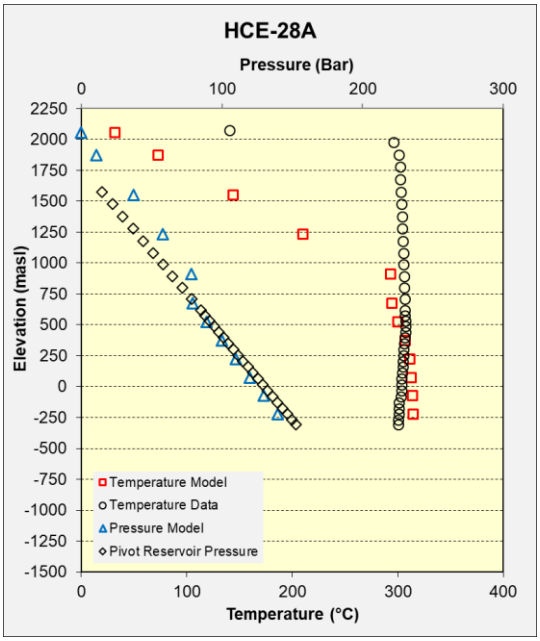


Figure 12: The PT matching profile of the HCE-28A well.

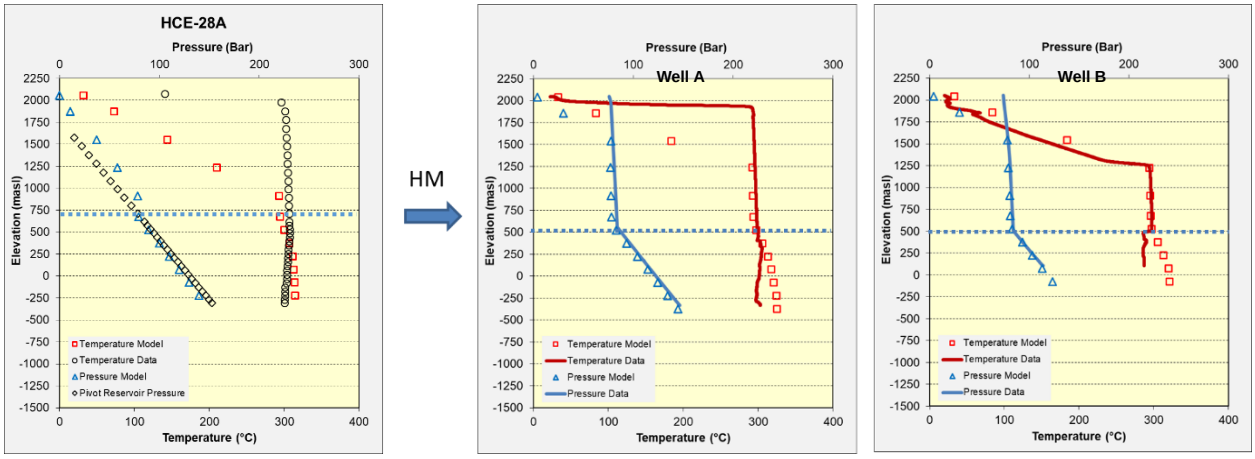


Figure 13: The PT matching profile of the well A and B, and the correlation with the thickening of the steam cap.

4. CONCLUSION

After 20 years of production, the HCE-28A well, which began as a two-phase well with an initial enthalpy and steam fraction of around 1,619 kJ/kg and 0.53, has changed into a vapor-dominated well with an enthalpy and steam fraction of about 2,448 kJ/kg and 0.85 in 2022. Following these changes, total discharged Cl increased from 11,185 mg/kg to 15,324 mg/kg and total discharged NCG increased from 0.23%wt to 0.81%wt. The N_2-CO_2-Ar diagram illustrates how the boiling process in the reservoir causes the fluids to be more CO_2 enriched than they were at the beginning of production. The H_2-H_2S-CH_4 diagram demonstrates how the magmatic fluid contribution likewise becomes more predominate over time. The SO_2 gas from the 2022 sampling, with a concentration of around 0.7 ppm Wt in the total discharge condition, provides evidence of magmatic contribution. The FT-HSH3 diagram demonstrates an increase in y value and temperature in relation to the presence of vapor addition brought on by lateral steam input or the reservoir's boiling process. The nearby HCE-28A well, which displays lower liquid level, likewise indicates the development of the steam cap in this well. It demonstrates how, at an elevation of roughly +700 m to an elevation of +500 m (Dieng Unit 2 well), the bottom of the steam cap area thickens. As a result, the development of the steam cap in the Dieng Geothermal Field can be attributed to the continuous boiling process occurring in the reservoir, which may be triggered by a combination of the mass extraction (reservoir pressure tends to decrease and has a direct impact on the formation of steam caps in the surrounding area), continuous heat influx, and/or continuous magmatic fluid input from the heat source.

REFERENCES

Golla, G. U., Julinawati, T., Putri, R. P., Nordquist, G. A., Libert, F. T., and Suminar, A. R.: The Salak Field, Indonesia: On to the Next 20 Years of Production, *Geothermics*, **83**¸ (2020).

Nicholson, K., 1993. *Geothermal Fluids: Chemistry and Exploration Techniques*, 1st Edition. Springer-Verlag, Berlin/Heidelberg, Germany.

Scoot, S. W.: Decompression Boiling and Natural Steam Cap Formation in High-Enthalpy Geothermal Systems, *Journal of Volcanology and Geothermal Research*, **395**, (2020).

Sugiaman, F., Sunio, E., Molling, P., and Stimac, J.: Geochemical Response to Production of the Tiwi Geothermal Field, Philippines, *Geothermics*, **33**, (2004), 57-86.

Wijaya, B. A., Pratama, H. B., Ashat, A., Sutopo, and Hidayaturrobi, A. D.: Reservoir Dynamics Monitoring in A Liquid Dominated Geothermal Field Based on Surveillance Data and Tracer Flow Test, *Proceedings*, 10th ITB International Geothermal Workshop, Bandung, Indonesia (2021).

Analysis of Geothermal Field Development Scenario: A Case Study in the Ulumbu East Nusa Tenggara Geothermal Field as Efforts to Maintain National Energy Resilience

Angela Benedicta Horta, Allen Haryanto Lukmana,
Damar Nandiwardhana, Fefria Tanbar, and Soniawan R Temot

angelhorta313@gmail.com, allenharyanto@upnyk.ac.id, nandiwardhana@upnyk.ac.id,
fefria.t@pln.co.id, soniawan49@yahoo.com

Keywords: Geothermal, Ulumbu, Development, Scenario

ABSTRACT

Indonesia has the world's second-largest geothermal potential, with a total potential of 29,000 MWe. Flores Island is one of Indonesia's islands that contribute to the geothermal potential, with a resource of 959.5 MWe. However, until now, only one field has been actively producing geothermal energy, namely the Ulumbu field, with a potential of 112.5 MWe. The development of this field is the government's step toward realizing the Flores Geothermal Island program. This paper aims to analyze the optimum scenario for increasing production in the Ulumbu field to reach 20 MWe and achieve the government's target. This research requires geological, geochemical, geophysical, well, and production data. The process begins with the reconstruction of the conceptual model to map the geothermal system, followed by the creation of a natural state model to match the pressure and reservoir temperature with the actual model. The next step is history matching, which is used to equalize the pressure and temperature flowing data, as well as the enthalpy data and flow rate models, with the actual production data. The last step is to forecast the data to increase production to 20 Mwe by adding the number of production wells and injection wells. Based on the results of examination through simulation analysis, it was found that there was an increase in the utilization of geothermal potential in the Ulumbu field, which initially had a utilization of 10 MWe and increased to 20 MWe without reducing the lifetime of the field. This result will be very beneficial considering the high potential utilization of this field, which is currently at 8.89% and is expected to continue to increase through further studies. The simulation in the Ulumbu field in this paper is the first to be done and can be used as a reference for the government to achieve the 20 Mwe target.

1. INTRODUCTION

Indonesia is a country with the second-largest geothermal potential in the world, boasting a total capacity of 29,000 Mwe. Flores Island is one of the islands that has contributed to this potential, providing 959.5 Mwe. Unfortunately, this potential has not been fully utilized; out of the total 959.5 Mwe, only 12.5 Mwe has been developed, specifically in the Ulumbu and Mataloko fields. The Ulumbu Field has a potential of 112.5 Mwe, with a total development of 10 Mwe, and the Mataloko Field has a potential of 74.5 Mwe, with a total development of 2.5 Mwe.

The Ulumbu Field itself is located in Manggarai Regency, 13 km from the city of Ruteng, East Nusa Tenggara. The geothermal system in the Ulumbu field is vapor-dominated, with temperatures ranging from 230-240 °C (Kurniawan, Iqbal. Sutopo, 2018). Based on Minister of Energy and Mineral Resources regulation No. 40 of 2014 and the 35 GW program discussion meeting, the Ulumbu PLTP is targeted to produce 20 Mwe of electricity. To achieve this target, an effective and economical scenario for developing the Ulumbu field is needed.

Scenario creation itself can be accomplished through simulation. The simulation process begins with the creation of a simulation model using geological data in the form of geological maps, geochemical data such as water content from geothermal manifestations, and geophysical data from MT. Furthermore, the model is initialized to match the simulated pressure and temperature with field conditions. If the model has reached the desired state condition, it continues with history matching, which aligns the production rate and enthalpy between the model and production data. The matched

model will serve as the basis for determining scenarios for the Ulumbu field. The development scenario derived from the simulation will guide Ulumbu's development in the future.

2. MODELLING SIMULATION

2.1 Ulumbu Conceptual Model

To model a geothermal reservoir using a computer, the first step involves creating a conceptual model. This conceptual model serves as a physical representation describing the potential structure, flow processes, and heat transfer within the reservoir. The general model comprises at least five essential components: cap rock, heat source, reservoir, water source, and surface manifestations in the geothermal area. Additionally, the model often includes other features like rock distribution and subsurface flow direction. The modeling process relies on evaluating data from various sources, such as geological, geohydrological, geophysical, geochemical, and well data. Figure 1 below illustrates the conceptual model of the geothermal system in the Ulumbu field.

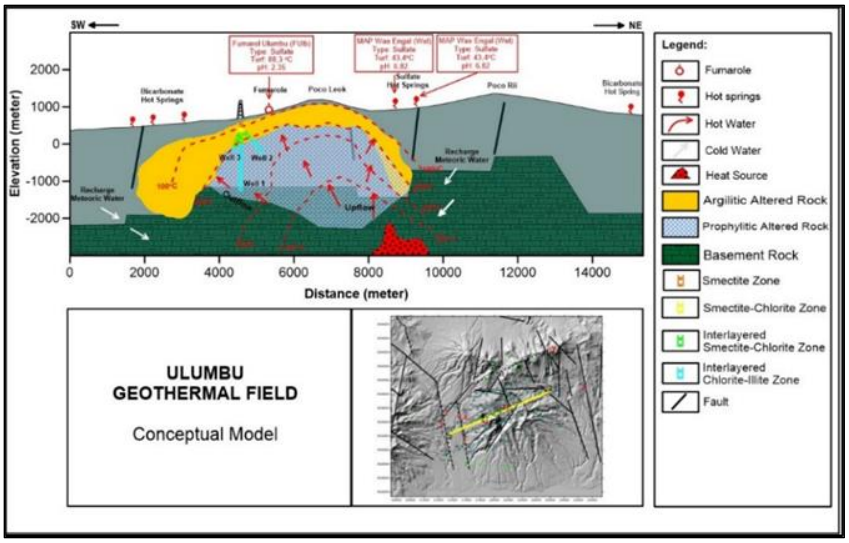


Figure 1: Ulumbu Conceptual Model (Yuono & Daud, 2020).

As demonstrated in Figure 1, the conceptual model indicates that the heat source most likely originates from beneath the Poco Rii-Poco Leok volcanic center, inferred to be an up-flow zone. Meteoric water recharges and descends through faults, interacting with deep-degassing magma, resulting in mature chloride water. Subsequently, this water rises and encounters a highly permeable zone, represented by the yellow line, which acts as the reservoir for the Ulumbu geothermal system. The increasing temperature reaches the boiling point, creating a vapor zone that is then confined by argillic alteration rock, serving as caprock due to reduced pressure at depths of approximately 500 to 800 meters. Some steam may ascend more rapidly, forming fumaroles on the surface of the Wai Kokor Valley, while others may mix with groundwater and emerge as hot springs.

2.2 Natural State Model

2.2.1 Model Dimensions and Layering

Reservoir modeling is conducted over an area of 196 km2, encompassing the entire geothermal region in the Ulumbu field, as depicted in Figure 2. In this model, the EOS1 equation of state simulator TOUGH2 is selected, which utilizes the heat balance equation and adheres to the thermodynamic properties of water fluids within the reservoir. The Ulumbu field model is designed with dimensions of 14000x12000x4500 meters, divided into eight layers, with each layer's vertical thickness based on the rock penetrated in the well and geophysical data. Figure 3 illustrates that the cap rock zone has resistivity values ranging from 1-11 ohm-meters and is approximately 200-500 meters thick. Additionally, the heat source is located at depths ranging from -2000 masl to -3000 masl, identifiable by a blue zone with resistivity values of approximately 200 ohm-meters.

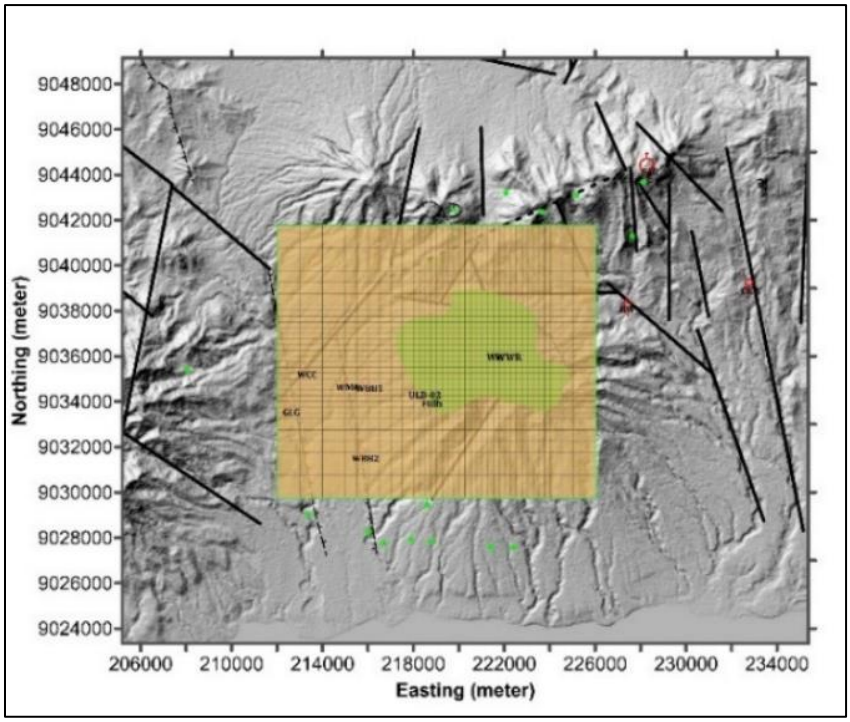


Figure 2: Geothermal Field Area (Yuono & Daud, 2020).

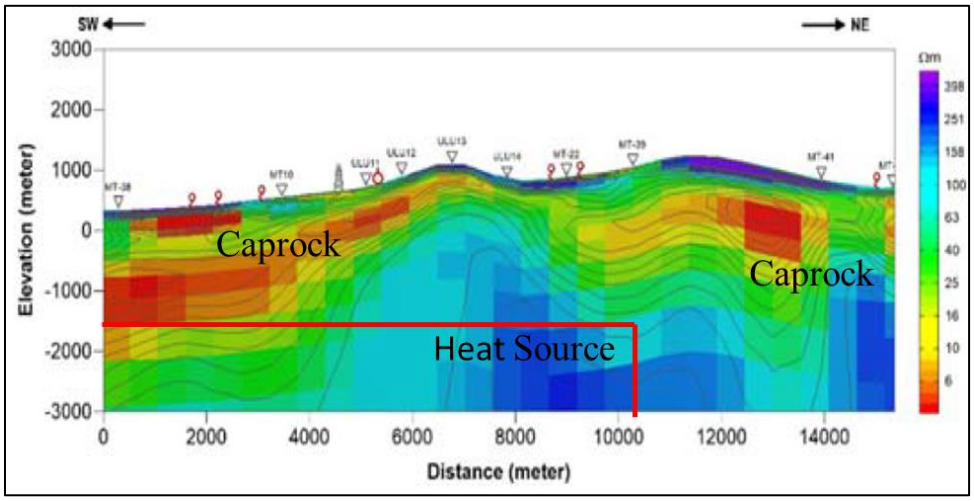


Figure 3: Heat Source and Cap Rock Location (Yuono & Daud, 2020).

The "Ulumbu" Field reservoir grid is divided into 36 grids in the X-axis direction and 30 grids in the Y-axis direction. The X-axis direction consists of three 1000-meter grids, followed by six 500-meter grids, twenty-four 250-meter grids, two 500-meter grids, and finally, one 1000-meter grid covers the area. On the Y-axis, two grids measure 1000 m, followed by three grids measuring 500 m, 20 grids measuring 250 m, three grids measuring 500 m, and closing with two grids measuring 1000 m, as shown in Figure 4 The total number of grids in this simulation model is 8640 elements, and the grid size will influence the results obtained from the simulation. Smaller grid sizes will yield more precise results.

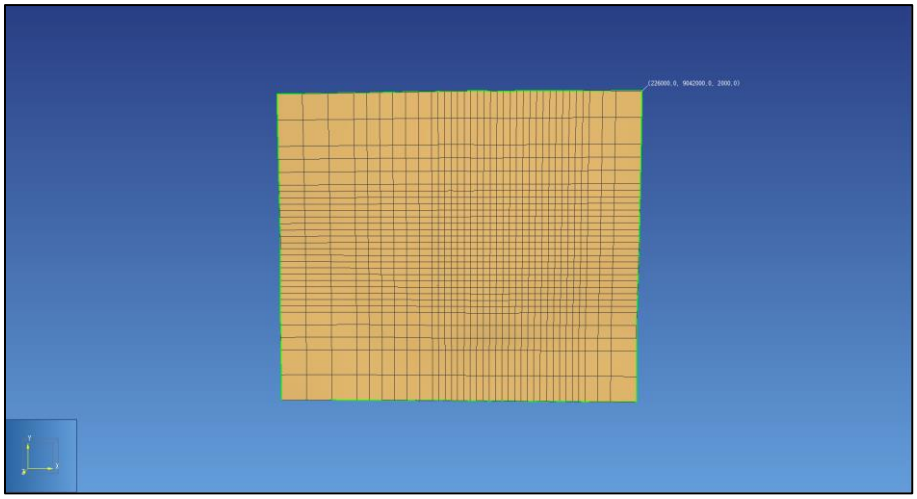


Figure 4: 3D Simulation Grid.

2.2.2 Material Distribution and Boundary Definition

The material plays an important role in representing the actual condition of the reservoir. The rock parameters used include rock density (kg/m3), porosity (%), permeability in the X, Y, and Z directions (m2), rock heat conductivity (W/m°C), and rock-specific heat capacity (J/kg °C). Table 1 below displays all the physical parameters of the rock.

Table 1: Input Material.

Material	Densitiy ($kg/m^{3)}$	Porosity (Fraction)	Kx ($m^{2)}$	Ky ($m^{2)}$	Kz ($m^{2)}$	Heat Conductivity (W/m-C)	Spesific of Heat (J/Kg-C)	Notaion
ATM	1	0,8	1,00E-14	1,00E-14	1,00E-14	2,5	9,00E+05	
LAND	2500	5,00E-02	1,00E-16	1,00E-16	7,00E-16	1	2000	
CLAY	2250	5,00E-02	3,00E-16	3,00E-16	3,00E-17	2,2	1000	
RES1	2300	0,8	1,00E-15	1,00E-15	2,00E-15	1,8	950	
RES2	2200	0,8	2,00E-15	2,00E-15	1,00E-15	1,8	950	
RES3	2300	0,8	1,00E-15	1,00E-15	1,00E-15	1,8	950	
ROCK1	2500	1,00E-02	1,00E-16	1,00E-16	1,00E-17	2,5	1000	
ROCK2	2500	1,00E-02	2,00E-16	2,00E-16	2,00E-18	2,5	1000	
KALDE	2500	1,00E-02	7,00E-18	7,00E-18	7,00E-18	0,8	3350	
HEAT	2500	0,6	8,00E-13	8,00E-13	8,00E-13	0,5	700	

The reservoir boundary conditions are divided into three parts: upper boundary conditions, side boundary conditions, and lower boundary conditions of the model. The upper limit conditions utilize atmospheric pressure and temperature, specifically 1 bar and 25°C. The side boundary conditions apply hydrostatic pressure and a normal temperature gradient within the region, with a volume factor of 1, and it is assumed that the area around the reservoir consists of impermeable rock. These conditions are determined based on the presence of heat source rock material under Poco Leok-Poco Rii, as depicted in the location of the heat source area using Magnetotelluric survey data. The heat source temperature and pressure are fixed at 157 bar and 306°C, respectively (Kurniawan et al., 2019). These values are part of the calibration process during the natural state stage. Once the boundary conditions are set, the simulator is run, and the results show a simulation time of 1E13 s or 321.502 years. Based on the extended simulation time, it can be concluded that the natural state conditions have been achieved.

2.2.3 Pressure & Temperature Calibration

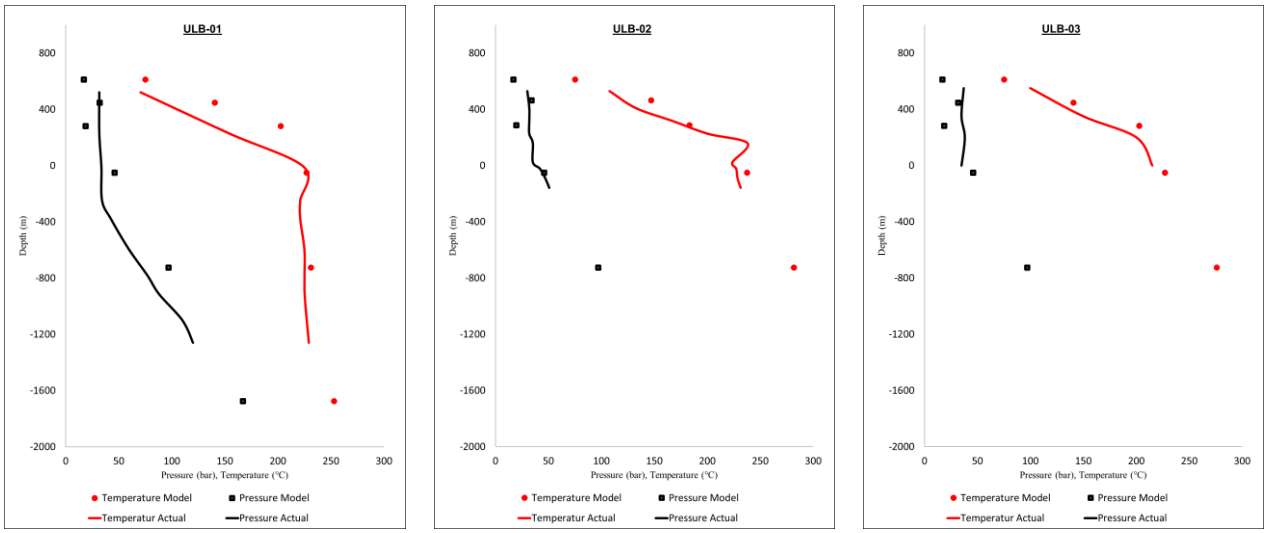


Figure 5: Pressure & Temperature Graph Calibration.

The next step is to validate this model by comparing the simulation results with actual data. The alignment of field data and simulation results includes matching pressure and temperature with depth, as shown in Figure 5 The actual temperature and pressure in wells ULB-01, ULB-2, and ULB-3 align with the temperature and pressure of the modeling results, indicating a successful match. This demonstrates that the modeling process has reached a natural state and has been calibrated against the distribution of temperature laterally in each block, as observed in Figure 6. The modeling conducted is in accordance with the conceptual model shown in Figure 1.

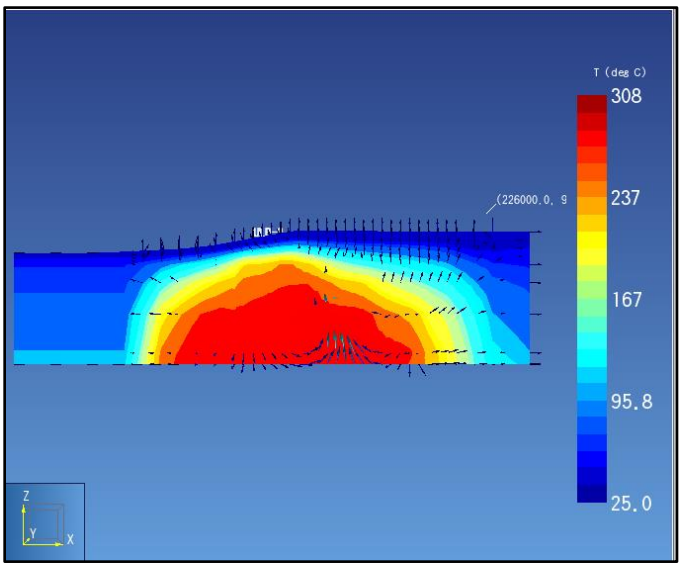


Figure 6: Isotemperature Reservoir Map.

2.3 History Matching

Production matching was carried out on the ULB-02 well since it has been the only well in production from 2012 until the present. The data that needed to be equated were the data rate (kg/s) and enthalpy data (kJ/kg) from 2015 to 2021. The matching process was not conducted from the first year of production due to an error during data retrieval. The results of the production matching based on the selected conditions for the 2015-2021 data are shown in Figure 7 and Figure 8 In the history matching process, the parameters that were altered were the PI (Productivity Index) or transmissivity. The PI is correlated perpendicular to the rate. If the model rate value is lower than the actual value, the PI can be increased. Conversely, if the model rate is higher than the actual value, the PI is decreased in the

parameters of the ULB-2 well. Another factor that affects the history matching process is the material's permeability; however, it is necessary to review the natural state process to determine whether the pressure and temperature.

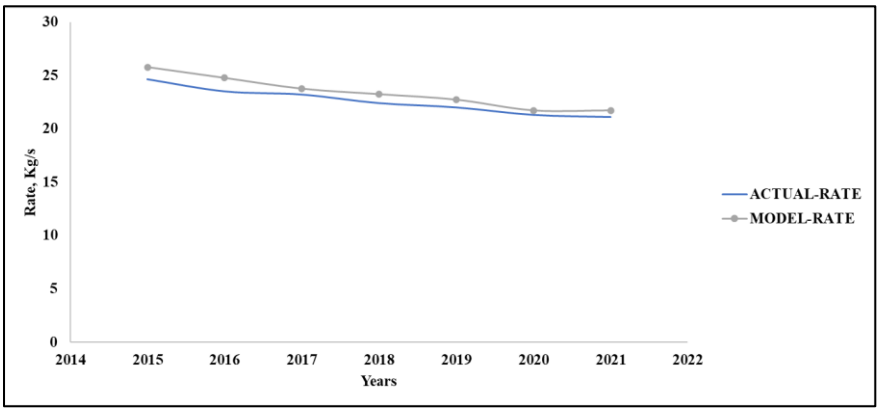


Figure 7: Rate Matching.

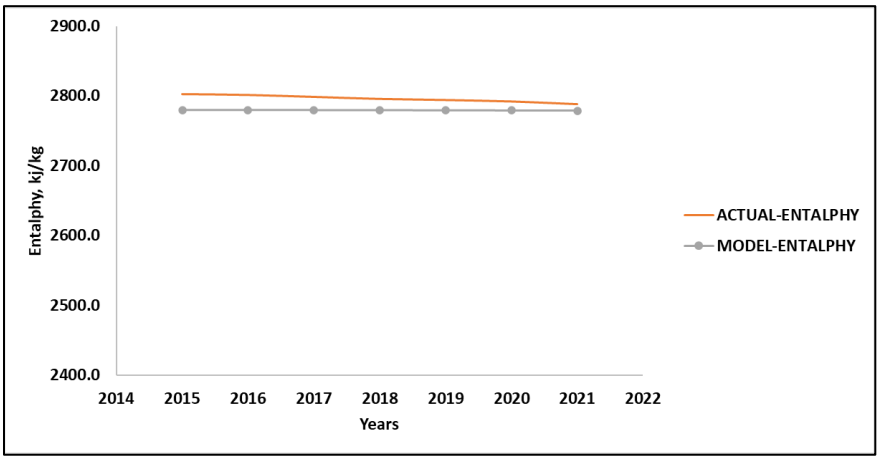


Figure 8: Entalphy Matching.

To validate whether the history matching of the rate has been successful, a plot is generated, combining the actual data and the model data on one graph. The data is considered to be matching if the distribution of the actual data and the model data forms a 45° angle with a deviation tolerance of 5%. The deviation tolerance value is assumed to be the same as the error tolerance used in oil history matching since there is no specific reference regarding the % error limit for geothermal history matching rates. Figure 4.16 shows the validation of history matching rates.

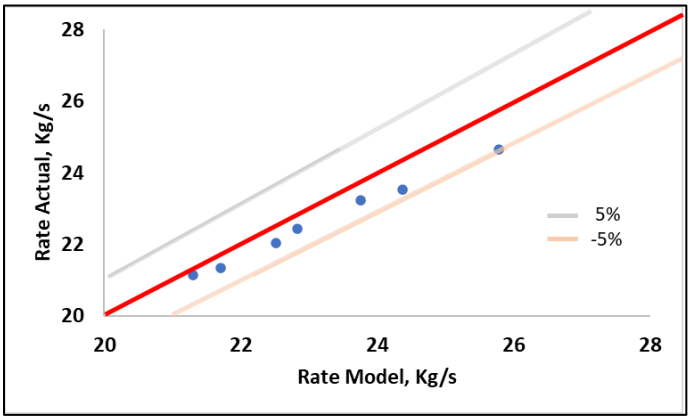


Figure 9: Validation of History Matching Rate.

2.4 Development Scenario

The Ulumbu Geothermal Field is planned to be developed to 20 Mwe, which requires several scenarios to increase production. The production forecasting involves several steps: planning the mass rate to be produced, determining the location of wells, and conducting an analysis to ascertain whether the planned production capacity has been achieved. This analysis also helps in understanding the temperature and pressure conditions of the reservoir. The existing installed capacity of PLTP Ulumbu is 4 x 2.5 Mwe, based on calculations from history matching results, assuming a required rate of 25.77 kg/s and enthalpy of 2779.6 Kj/kg. To achieve the target of 20 Mwe, it is necessary to add 1 production well with the same output rate and enthalpy as the ULB-2 well. The selection of well locations is based on temperature and permeability distribution maps, favoring locations with high temperature and permeability while ensuring a minimum drainage radius between wells of 360 meters.

After the simulation, the rate and enthalpy of the Prod-1 well were 20.04 kg/s and 2267 Kj/kg, equivalent to 6.97 Mwe. As a result, another production well, Prod-2, was added. Following the addition of Prod-2 well, a rate of 20.05 kg/s and an enthalpy of 2712 Kj/kg, or equivalent to 7.14 Mwe, was achieved. By combining 1 existing well and 2 additional wells, the total electricity generated reached 23.56 Mwe. Over time, there was a decrease in production, leading to the failure to achieve the 20 Mwe production target. To maintain production, additional production wells needed to be added called make up well. The installed capacity of the PLTP is 20 MWe, with an excess supply of 10% (Sukhyar, 2010), requiring a minimum steam supply of 22 MWe. Based on the simulation results carried out for 30 years, it is necessary to add 3 make up wells. The timing and location of these production wells can be observed in figure 10 and figure 11 below.

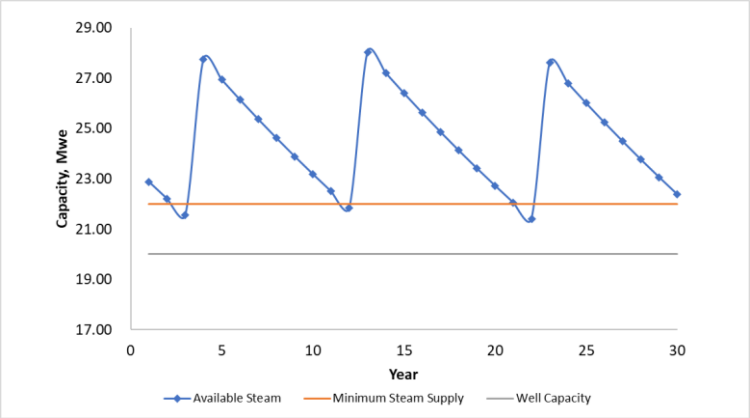


Figure 10: Make Up Well Scheduling.

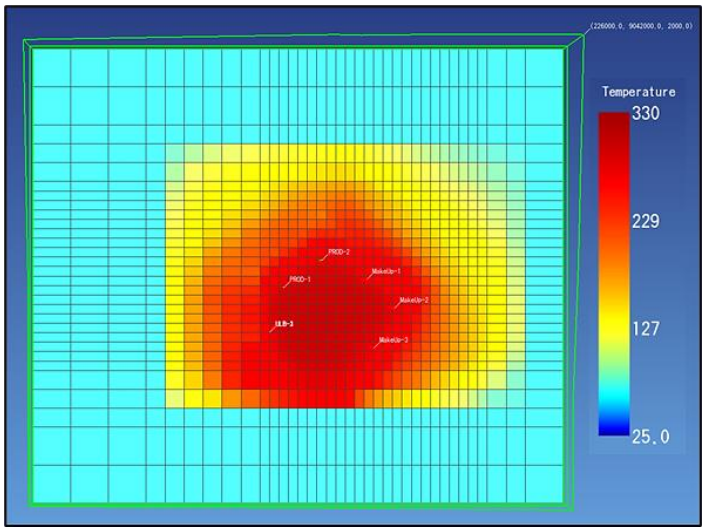


Figure 11: Placement Of Bottom Well Elevation Proposed Well in High Temperature Reservoir.

3. CONCLUSION

Based on the reservoir simulation results using the TOUGH2 simulator at the Ulumbu Geothermal Field, the following conclusions can be drawn:

1. The Natural State process has been achieved with a simulation time of 321.502 years, and the model pressure and temperature data are quite aligned with the actual data, which aims to determine the distribution of temperature, pressure, and rock permeability values in the model
2. The data rate and enthalpy models in dynamic conditions have matched the actual conditions where the PI and P used are 3.5E-13 m^3 and 2.37518E6 Pa
3. The simulation results of the Ulumbu Geothermal Field to produce 20 Mwe require the addition of two production wells and three make up wells to maintain production above the minimum steam supply for 30 years

REFERENCES

Kurniawan, I., Sutopo, S., Pratama, H. B., & Adiprana, R. (2019). A natural state model and resource assessment of Ulumbu Geothermal field. *IOP Conference Series: Earth and Environmental Science*, *254*(1). https://doi.org/10.1088/1755-1315/254/1/012017

Sukhyar, R. (2010). *Energi panas bumi di Indonesia: kebijakan pengembangan dan keputusan investasi*. Badan Geologi.

Yuono, R. T., & Daud, Y. (2020). Reservoir simulation of Ulumbu geothermal field using TOUGH2 and ITOUGH2 simulator. *IOP Conference Series: Earth and Environmental Science*, *538*(1). https://doi.org/10.1088/1755-1315/538/1/012059

NOMENCLATURE

Mwe : Megawatt Electric
GW : Gigawatt Electric
PI : Productivity Index
Pa : Pascal

Existing Well Monitoring During Patuha-2 Drilling as a Preventive Action to Maintain Patuha Unit 1 PLTP Generation

Wien Pratama Abi Wicaksono and Saltsa Prehtina Muryani

PT. Geo Dipa Energi, Aldevco Octagon, Jl. Warung Buncit Raya No.75,
Kalibata, Pancoran, Jakarta Selatan, DKI Jakarta, Indonesia, 12740

wien@geodipa.co.id, saltsa@geodipa.co.id

Keywords: Patuha geothermal field, drilling campaign, geothermal gas content, aerated drilling, powerplant and steam field monitoring parameter

ABSTRACT

PT. Geo Dipa Energi (PERSERO) is currently developing each unit (Dieng 2 for 60 MW) and (Patuha 2 for 60 MW) to increase the generation's existing capacity. The activity starts in 2021 with a drilling campaign program for each unit. 10 Wells for Dieng 2 (D2) and 12 Wells for Patuha 2 (P2). Especially in Patuha, the drilling campaign starts in November 2021 with PTH-7A Well, and the current progress is the 8th well is being drilled.

The drilling activities in the existing area can impact (interference) the existing wells. Interference can occur in production wells with the same fault as drilled wells. As a preventive action, offset well monitoring is carried out to find out whether drilling activities affect the existing wells.

Many monitoring parameters include wellhead pressure (WHP), production flow rate, NCG content, CO_2, H_2S, and Residual gas. The schedule of offset well monitoring is carried out routinely and when the drilling already enters the reservoir, the time of the monitoring becomes even tighter than before.

In Patuha's drilling campaign, when the 6th well (PTH-2B) already entered the reservoir, there was an impact/connection to the existing well (PPL-02, PPL-2A, PTH-V-7A, and PTH-V-7B) look from the residual gas content. There are shifting to the "air" point (triangular diagram CO_2 – N – Ar). The significant impact when the PTH-2B drilling at 1507 mMD. NCG one of the existing production well (PPL-2A) increased from 0,5% to 10,5% and increasing the vacuum condenser pressure and gross output PLTP drop around 2,12 MW. From that identification, mitigation is needed. The action is decreasing trim valve/throttle valve which control supply steam from PPL-2A well to powerplant from 61% to 22% and the laboratory crew continue to monitoring this well until all parameter normal.

1. INTRODUCTION

Patuha geothermal field is located about 40 km southwest from Bandung, West Java Province, Indonesia as presented in Figure 1. Patuha geothermal field and was developed by state owned company PT. Geo Dipa Energi (Persero) and started operating in September 2014 with capacity of 60 MW.

Patuha is a vapour dominated reservoir with temperature reservoir between 230 deg.C. For the present PT. Geo Dipa Energi (Persero) is developing for the Patuha 2 by drilling 12 (twelve) wells for capacity 60 MW. The drilling campaign starts in 2021 and is planned for finish at the end of 2023. When drilling campaign, the existing field team especially the laboratory and steam field teams do the monitoring for offset well to know if there are connections/interference between the existing well and the new well. There are many parameters that we collect and observe in offset well monitoring and the SOP becomes our guideline to do this activity.

The first well that we drilled for Patuha 2 is PTH-V-7A with 1864 mMD total depth and spud in September 2021 and finish in Desember 2021. After the first well finish, the drilling team move to the next well until the 8th (eight) well at the present from the target 12th (twelve) wells.

Aerated drilling was carried out in all drilled wells but there was no significant impact to the production electricity of the existing plant but different when the same program was applied in the 6th (sixth) well

– PTH-H-2B with 2106 mMD total depth. In addition, the use of this system is expected to lift cutting from the loss circulation zone to the surface (Pudyastuti, 2015). Because there is an effect to the production electricity, we have to analyze more parameters to know the source of the effect based on the SOP that we approved before.

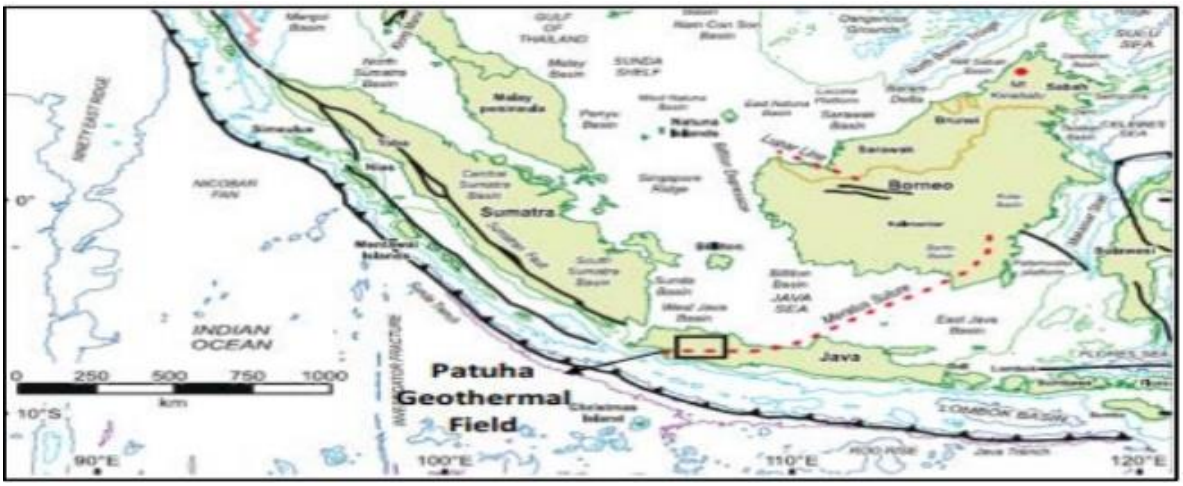


Figure 1: Location of Patuha Geothermal Field (Elfina, 2017).

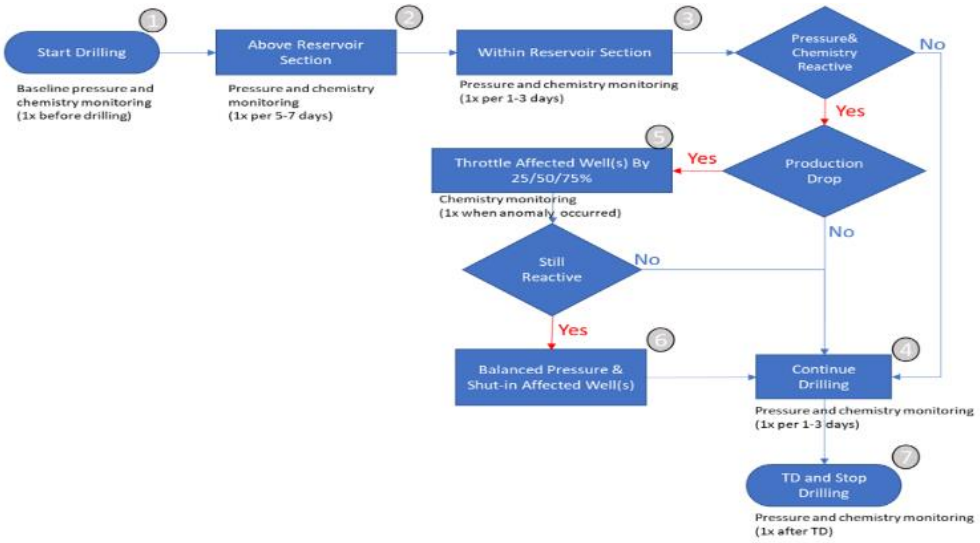


Figure 2: Standard operating procedure of offset data monitoring and interference mitigation plan (Geo Dipa Energi, 2021).

2. METHODS

In this research, the offset well monitoring was done by collecting the data of the parameters at wells, like mass flow rate, wellhead pressure, and powerplant parameters like vacuum condenser, gross output, steam dryness, chemical, and NCG content. Based on figure 3. The concern/focus of the monitoring is PPL-2A because that is an existing well and the powerplant parameter data.

2.1 Geochemistry Monitoring

In Patuha, geochemistry monitoring conducted in production wells, injection wells, power plant, and surface thermal manifestation routinely. During the P2 drilling campaign, monitoring of offset wells is required as initial well identification. Because one of the impacts of drilling in developed field is the interference issue or well connectivity. Selection of wells are based on the existing geological fault modelling which connect some wells through the similar fault. Several offset wells are monitored during the drilling of PTH-H-2B, including PPL-02, PPL-2A, PPL-06, PPL-07, PTH-V-7A, and PTH-V-7B.

The parameter for monitoring consists of gas and water chemistry and Wet Test Meter (WTM) for direct measurement of Total Gas Content (TGC). Below is the detailed monitoring schedule.

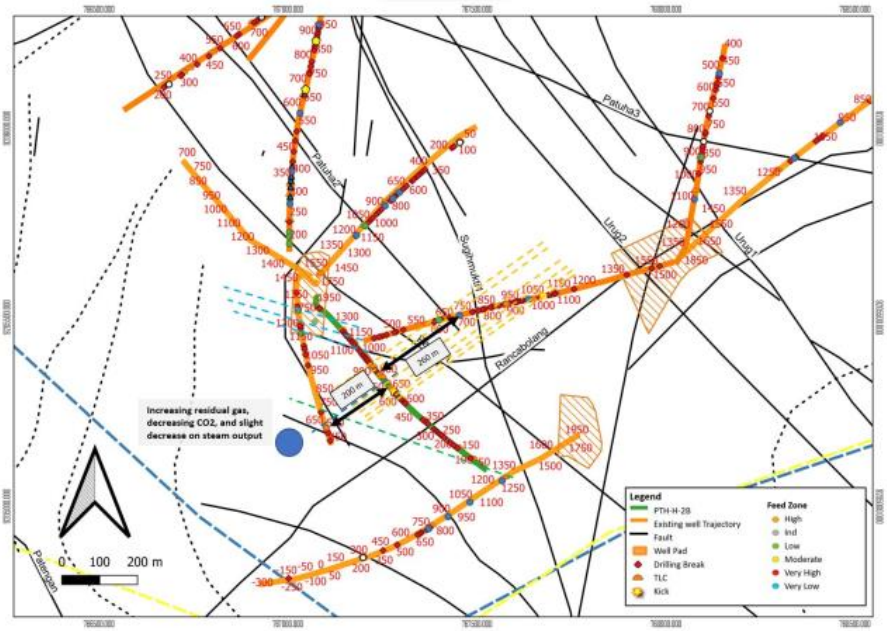


Figure 3: Well connection possible from PTH-H-2B to PTH-V-7A and PPL-2A based on geochemistry indication (Geo Dipa Energi, 2022).

Date	Drilling Day-	PPL-02	PPL-02A	PPL-06	PPL-07	PTH-V-7A	PTH-V-7B	Remark
7-Nov-22		√	√	√	√	√	√	Background
2-Dec-22	2	√	√	√	√	√	√	Well Spud In, Depth 82 mMD / 82 mTVD / 1939 mASL
8-Dec-22	8	-	√	-	√	√	√	Continue Run Casing 20", Depth 387 mMD / 386 mTVD / 1635 mASL
15-Dec-22	15	√	√	√	-	-	-	Depth 800 mMD / 1234 mTVD / 787 mASL
16-Dec-22	16	-	-	-	√	√	√	Depth 818 mMD / 804 mTVD / 1217 mASL, Combat Loss with LCM, Wash & Ream Down
23-Dec-22	23	√	√	√	-	-	-	Depth 841 mMD / 825 mTVD / 1196 mASL, CBL jobs, Drill out cement shoe track, FS, and formation
26-Dec-22	26	-	-	-	√	√	√	Depth 1194 mMD / 1157 mTVD / 864 mASL
30-Dec-22	30	√	√	-	-	√	√	Depth 1507 mMD / 1452 mTVD / 569 mASL
2-Jan-23		√	√	√	√	√	√	RIH 12-1/4" TCI bit + BHA #11 (Slick BHA) to 1468 mMD. Reaming down, Circulate hole clean, POOH w/ 12-1/4" TCI Bit Wiper Trip BHA to surface. Run 10-3/4" Perforated Casing Liner, Depth 1511 mMD / 1455 mTVD / 566 Masl
10-Jan-23		√	√	√	√	√	√	DOF 9-7/8" Hole section. Circulate hole clean. POOH normal 9-7/8" PDC + BHA #13, Depth 2106 mMD / 2018 mTVD / 3 mASL
14-Jan-23		√	√	√	√	√	√	Well Completion Test (Fall-off Test). PTH-H-2B released on January 14th, 2023 at 05.00

Figure 4: Offset well monitoring time PTH-H-2B.

Gas samples are collected and analysed for CO_2, H_2S, CH_4, H_2, N_2, O_2, He, Ar, and Total Gas Content (TGC). While water samples analysed for pH, EC, Cl, SiO_2, and B.

Well connectivity by the similar fault was observed along geochemistry monitoring by the response of some gas parameter as gas breakthrough. It indicates by increasing of N_2 and Ar, both are the atmospheric gases which dominantly contribute to geothermal fluid whether by meteoric water recharge or aerated drilling.

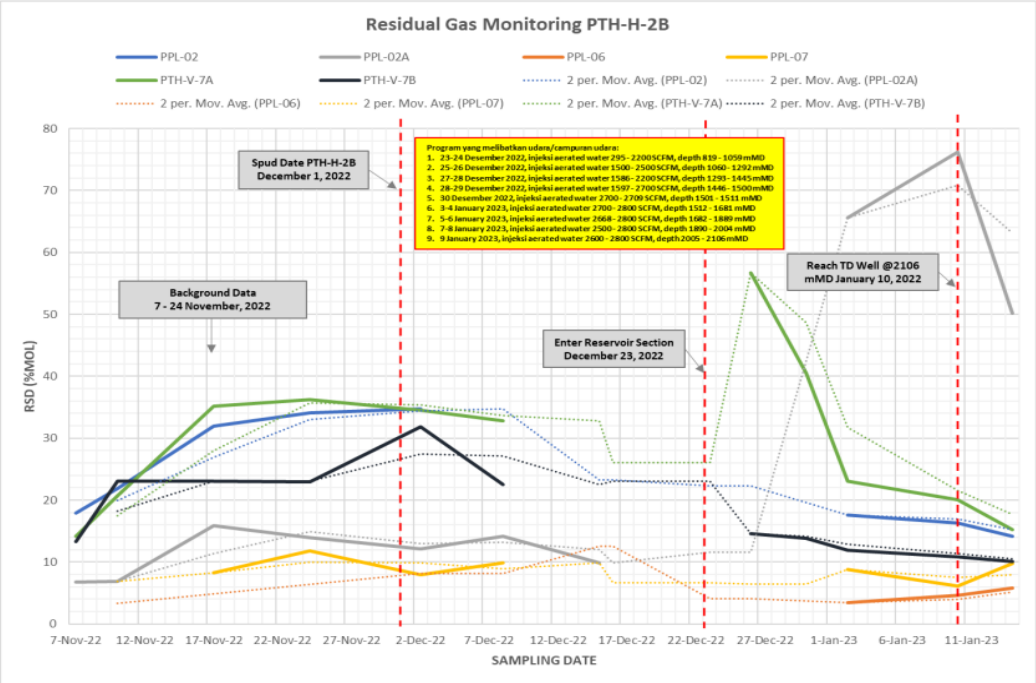


Figure 5: Offset well residual gas monitoring of PTH-H-2B.

Before drilling the reservoir section, no anomaly trend was observed. However, during entering the reservoir section, observed a sharp increase in total gas content on PPL-2A on around December 30, 2022. These suggest connectivity of PTH-H-2B with PPL-2A as also indicated by gas ratio shifting to N_2-Ar line on CO_2-N_2-Ar ternary diagram. These might be the result of a combination between water and aerated mud injection during reservoir drilling on the PTH-H-2B which is located around 200 meters from PPL-2A well.

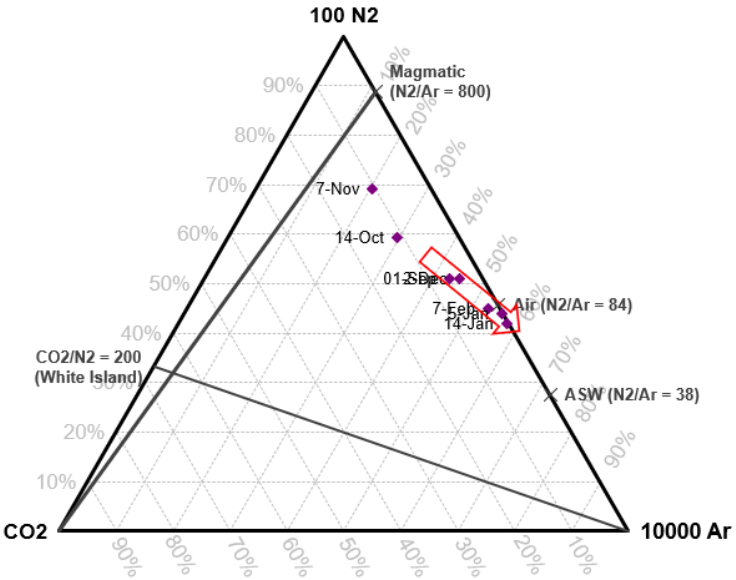


Figure 6: CO_2-N_2-Ar ternary diagram.

2.2 Powerplant Parameter Monitoring

The powerplant data is collected from the DCS/control room by the steam field and powerplant operator and we convert that data to the trend/chart to know or match the time with the geochemistry/chemical data.

This trend chart shows the anomaly trend/data at Steam NCG content. The value increases two times from 0,5% - 0,6% normally to 1,5%. The source of this anomaly is actually from production wells that are connected/interference from the well being drilled (PTH-H-2B) because at the same time in PTH-H-2B aerated drilling was running.

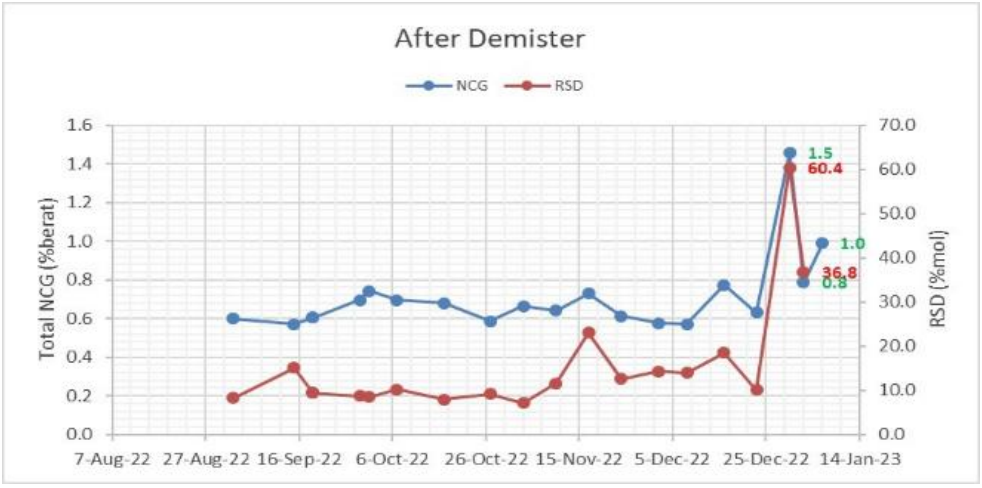


Figure 7: NCG content in after demister at PLTP Patuha.

This chart in figure 8 shows the anomaly from one of the existing wells PPL-2A. The value of NCG content increased 10 times from 0,5% to 10,5% immediately and decrease again after the aerated drilling at PTH-H-2B finish

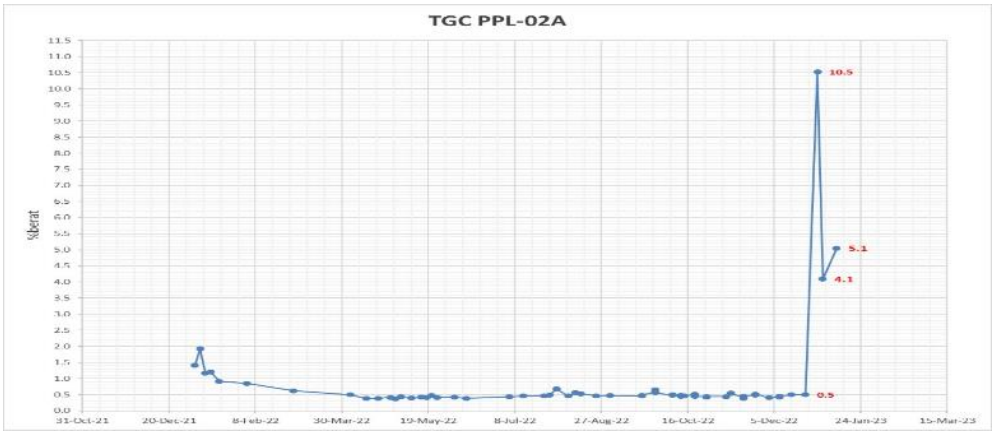


Figure 8: Total gas content in PPL-2A, one of the offset well from PTH-H-2B.

This chart in figure 9 shows the gross output of PLTP decrease until 2.12 MW from 61.88 MW to 59.76 MW. It happens because vacuum condenser increases and interrupts the system process to condense the steam. This impact/effect originated from the increase in NCG content value in one of the wells affected by the results of aerated drilling activities which then carried over to the powerplant as indicated by the increase in NCG content in the after demister.

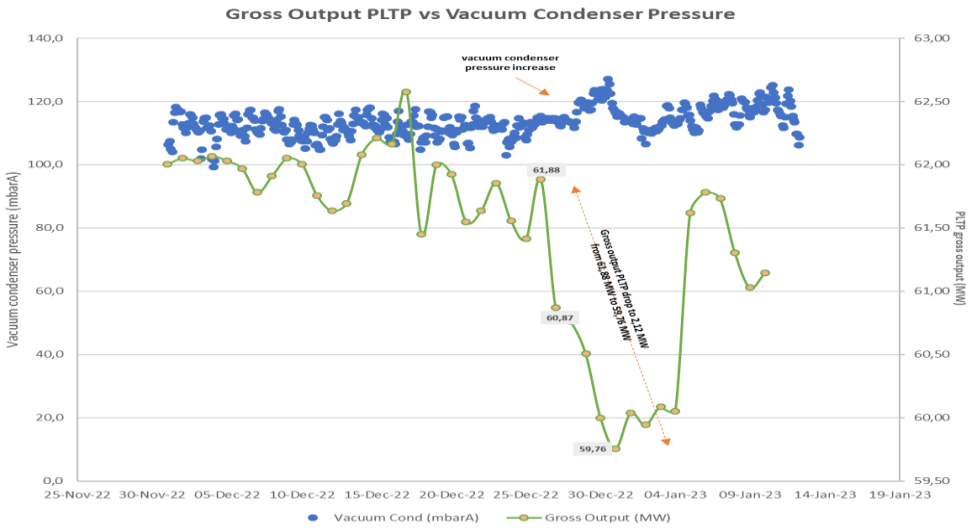


Figure 9: Gross output vs vacuum condenser pressure in PLTP Patuha.

3. CONCLUSION

Aerated drilling in PTH-H-2B is one of the methods to overcame drilling problems, but there is an impact for that activity such as:

1. The gas ratio shifting movement to N_2-Ar line on CO_2-N_2-Ar ternary diagram, indicates well connectivity
2. Increase total gas content 10 times from one of the existing wells, PPL-2A from 0,5% to 10,5%,
3. Increase total gas content at after demister (powerplant area) from 0,6% to 1,5% which cause drop gross output at PLTP value.

The geochemistry monitoring program has been carried out during drilling, and prove the effect of aerated drilling on the surrounding wells. This influence shows the existence of connectivity inter wells and prove the existence fault. By adjusting the production parameters on the affected wells, we manage to minimize the impact of aerated drilling into electricity production of exiting power plant unit.

REFERENCES

Geo Dipa Energi (Persero) Unit Patuha Powerplant Monitoring form, 2023.

Kusumawadani, et al., 2015, Aerated drilling performa at “N” well in “K” Geothermal fields, Indonesia

Malik, Abidin, 2012, Geochemistry Monitoring During Drilling in Wayang Windu Field, Indonesia

Offset Well and Interference Mitigation at Existing Wells, 2021, Geo Dipa Energi (Persero) Standard Operating Procedure.

Patuha Laboratorium report, 2023.

How Accurate Modeling of Superheated Steam Improves Field Management Strategy

Minh T. Tran[1], Minh Pham[1], Ed Voge[2], and Dylan Esquivel[2]

[1]GeothermEx, Inc., Richmond CA, USA
[2]Northern California Power Agency

Mtran18@slb.com

Keywords: The Geysers, numerical modeling, superheat steam, field management, augmented injection

ABSTRACT

There is an increasing number of mature geothermal fields in which parts of the producing formations reach the stage of superheated steam. The Geysers, the largest geothermal field in the world, is a prime example of this type. To mitigate the steam decline rate, additional sources of water were piped to the Geysers to augment the injection program, which have brought a positive impact on field performance since 1997. This study focuses on the modeling of superheated steam in the Geysers geothermal field to enable optimal field management in terms of productivity enhancement, and pressure support via injection strategies.

The short-term and long-term performance of the field depends primarily on optimizing water injection strategies, which include the amount and duration of injection as well as the locations and feedzones to inject to. These factors will impact the field longevity, overall steam production, and power generation. An ideal injection strategy requires a delicate balancing act between sufficient pressure maintenance, thermal breakthrough, reservoir cooling, and recharge potential. To effectively quantify the impact of each facet in the injection strategy on field operational metrics, a highly detailed numerical model is necessary to capture the key physics involved.

One of the objectives of this study is to accurately assess and utilize the amount of superheat in the reservoir. Low-resolution models are often inadequate in calculating the amount of steam that can be generated by the de-superheating process due to its coarse grid size. In this model, the gridblock size is significantly refined and the model contains over 780,000 blocks for improved accuracy in its calculation of steam generated from the de-superheating process. The impact of steam quenching on production-injection synergy is also thoroughly investigated to minimize the potential of steam zone collapse and steam production decline.

Overall, the model provides a valuable tool for managing the Geysers geothermal field, and more generally, active fields that reach superheat conditions. By optimizing injection strategy in terms of rate and location, geothermal plant operators can efficiently exploit the available resource.

1. INTRODUCTION

1.1 Field Geology

The Geysers geothermal field is situated within the Geysers-Clear Lake volcanic field, which is part of the larger California Coast Ranges, consisting of andesitic to rhyolitic rocks, which were formed from the cooling and solidification of magma during past volcanic eruptions (see Figure 1). It lies along the active tectonic boundary where the Pacific Plate is subducting beneath the North American Plate, leading to intense geothermal activity. The primary mechanism for geothermal energy production at The Geysers is the presence of a naturally fractured reservoir. The volcanic rocks have undergone extensive fracturing due to tectonic forces, providing pathways for geothermal fluids to circulate via the dense natural fracture network. The rock matrix is generally tight with low permeability, acting as a source of fluid support as well as a pressure maintenance mechanism for long-term production. The Geysers is considered a closed system with little aquifer support or external water encroachment. The unique geological features of The Geysers make it one of the most productive and long-standing

geothermal power fields in the world, providing a sustainable and renewable source of energy. The location of NCPA's steam field within The Geysers geothermal field is shown in the Figure 1.

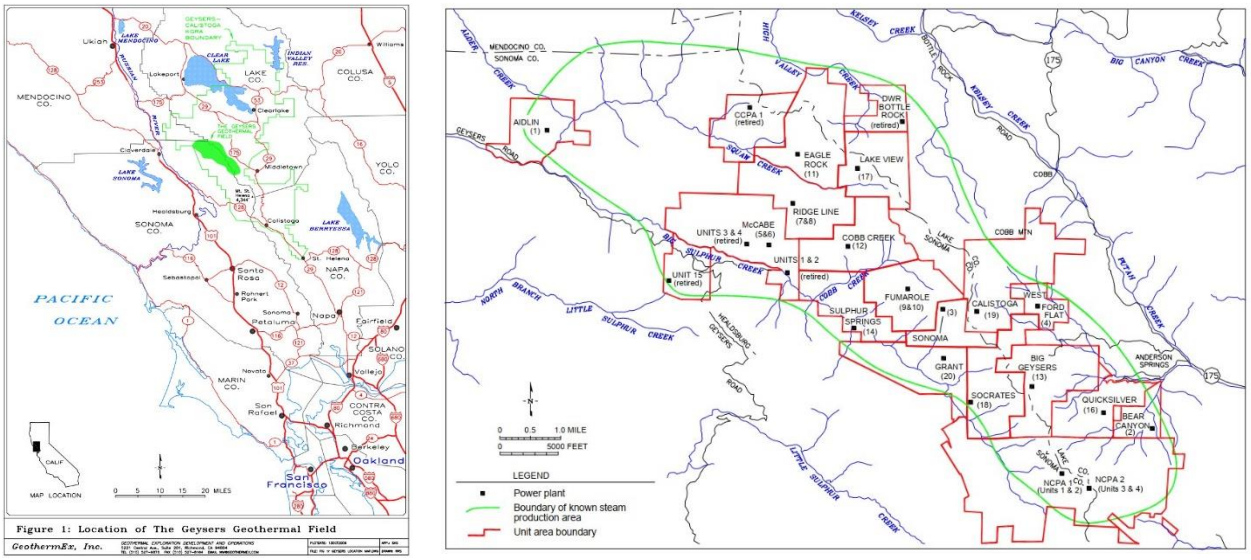


Figure 1: Left: Location of the Geysers Geothermal Field in the green shade. Right: Location of NCPA's steam field within The Geysers geothermal field in the southeastern corner.

1.2 Field Development History

The Geysers is the largest geothermal field in the world, and one of only five operating geothermal fields worldwide that produce "dry" steam, a feature that reduces both capital and operating costs of power generation. Geothermal power has been generated continuously at The Geysers since 1960. After peaking near 2,000 MW in 1987, the output of the field declined to about 835 net MW in 2021. This decline has occurred in response to the retirement of several older power plants, and to high well productivity declines caused by over-development of the field in the 1980s. As more power plants were built and mass withdrawals increased, reservoir pressure and well productivity started declining rapidly. To sustain generation capacity despite the productivity decline, excessive make-up wells were drilled in some parts of the field, causing interference between wells, and further reducing productivity.

The rapid rate of well productivity decline experienced during 1987-1995 was eventually arrested by augmented injection of water into the reservoir. Meanwhile, operators at The Geysers started optimizing the use of lower-pressure steam by modifying steam turbines and upgrading the surface pipeline network. In The Geysers geothermal power plants, approximately 70 to 80% of the produced mass is lost through evaporation in cooling towers, while the remaining portion is reintroduced to the reservoir by injecting the steam condensate (Butler and Enedy, 2009). Initiated in 1997, pipelines were constructed to transport treated sewage effluent from Clear Lake for injection into the field, known as the Southeast Geysers Effluent Project (SEGEP) followed by Santa Rosa Geysers Recharge Project (SRGRP) in 2003. These augmented injection programs have raised the level of mass injected to about 100% of the mass produced. The rate of reservoir pressure decline was significantly decreased, and by 2006, the decline in steam production from the previous year was only 0.5%.

Established in 1968, the Northern California Power Agency (NCPA) is a California Joint Action Agency. NCPA membership is open to municipalities, rural electric cooperatives, irrigation districts and other publicly owned entities interested in the purchase, aggregation, scheduling, and management of electrical energy. NCPA operates two geothermal power plants of 110 megawatts each at The Geysers geothermal field, located in the Mayacamas mountains of Sonoma and Lake Counties, 70 deep production wells that supply these power plants with steam. The geothermal project also includes 8 deep injection wells used to re-supply the geothermal reservoir with water to create additional steam, 10 miles of surface pipelines to deliver the produced steam to the plants, two surface water collection

ponds, and a co-owned major wastewater delivery system consisting of five pump stations and 26 miles of underground pipeline that are used to supply additional fluids for injection.

1.3 Previous Numerical Simulations of The Geysers Reservoir

The first comprehensive field-wide reservoir model of The Geysers was developed by GeothermEx during 1991-1992, as part of a Technical Advisory Committee (TAC) industry consortium. The TAC model was based on a model originally developed by Unocal (Williamson, 1990) for the Unocal-NEC-Thermal lease areas of the field. The TAC model extended the Unocal model by incorporating reservoir and production data from other field operators (Calpine, NCPA, and CCPA). Later on, an integrated model was developed, combining reservoir simulation with mathematical modeling of wellbores, pipelines, and power plants within the NCPA area of the field (Butler and Enedy, 2009). Historically, reservoir pressures derived from shut-in wellhead pressures were one of the important matching parameters used in model updates. Model updates have been performed frequently to match with more recent historical dynamic data.

2. NEW, HIGH-RESOLUTION RESERVOIR MODEL

2.1 Introduction

Previous models have used conventional geothermal simulators with limited resolution due to a lack of parallel computing capability. There is an increasing urge to upgrade and refine the existing models to accurately capture increasingly complex physics such as steam quenching, superheat, and water pooling. Geothermal modeling with ECLIPSE, an industry-reference simulator for the oil and gas industry, has been proven to accurately capture critical reservoir physics such as two-phase condition, well drawdown, cold injection, aquifer encroachment, and counter-current steam water flow in the benchmark of 6 Stanford test problems (Stacey and Williams, 2017). Moreover, the parallel processing capabilities of ECLIPSE have shown significant advantages in terms of computational speed compared to existing single-processor geothermal simulators. When running in parallel, ECLIPSE can achieve a remarkable 40 times increase in computational speed compared to operating with a single processor (Stacey and Williams, 2017).

With ECLIPSE, it is possible to create a high-resolution model to accurately assess and utilize the amount of superheat in a reservoir and to improve the accuracy of calculating the steam generated by the de-superheating process. In addition, this model can capture the complex physics of superheat and water pooling, allowing the operator to efficiently manage the field. The study also investigates the impact of steam quenching on production-injection synergy. Steam quenching refers to the rapid cooling of steam upon contact with the cold-water injection, which can lead to potential issues like steam zone collapse and a decline in steam production efficiency.

2.2 Model Construction

2.2.1 Database

NCPA provided a comprehensive database for its area of the field including well completion details, feedzone locations, wellhead pressure, and temperature, as well as the production and injection history of each well. Most of the wells inside NCPA lease have complex completion histories with sidetracks, redrill, or fork completion. Outside of the NCPA leases, publicly available data from the California Department of Conservation's Division of Oil, Gas, and Geothermal Resources ("CDOGGR") was utilized. The combination of data from these two sources results in a data set containing records for essentially all active wells in the field. As a quality-control step, the monthly production and injection from all wells in the database were summed and compared to field-wide monthly total production and injection rates available from the CDOGGR. A plot of the total monthly production and injection data from this combined database is shown in Figure 2 for both NCPA and "non-NCPA" leases.

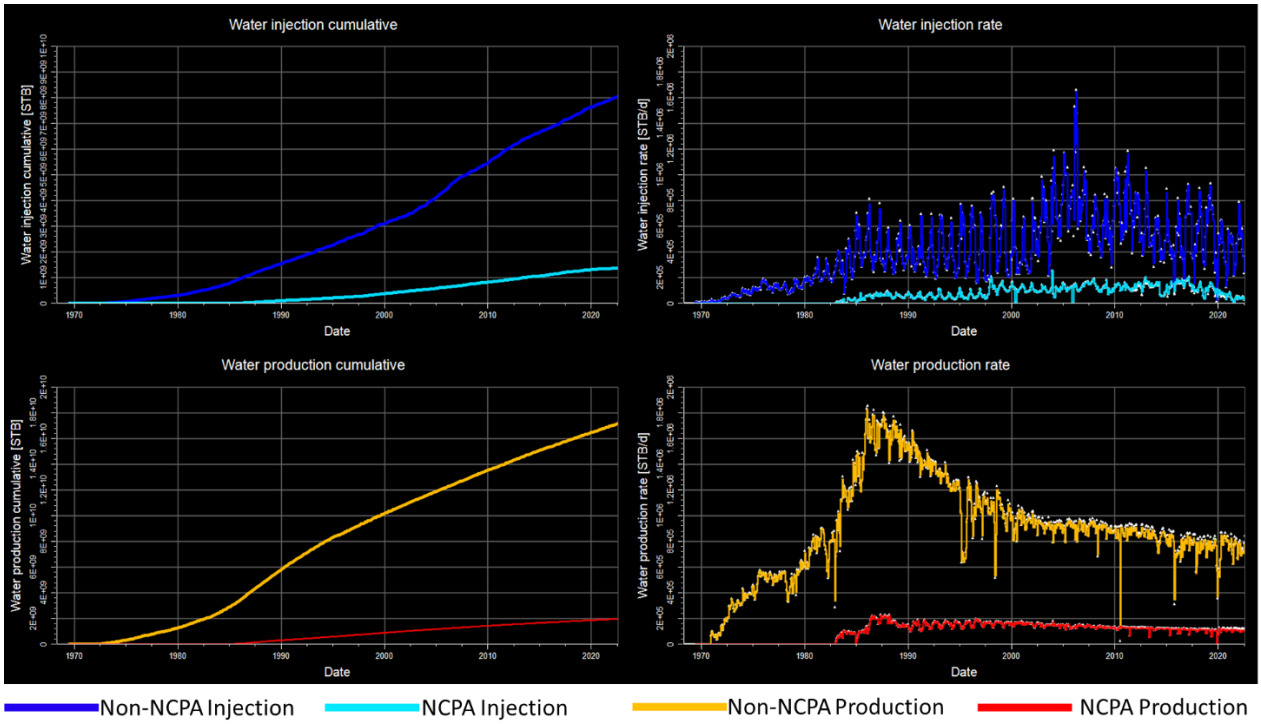


Figure 2: Historical Geysers field-wide production and injection.

2.2.2 Simulation Grid

In this study, we constructed a three-dimensional, dual-permeability numerical model which utilizes a highly refined grid within the NCPA area and a coarse grid in the rest of the field. The simulation grid for the NCPA reservoir model covers an area of nearly 140 square miles, and it is oriented in the NW-SE direction, parallel to the main structural features of the field. The rectangular outline of the grid is approximately 15 miles long in the NW-SE direction and 9.5 miles long in the SW-NE direction, and it covers all the active areas of the field. The size of the grid block ranges from 4,000 ft by 2,000 ft by 1,000 ft near the edge of the model to 300 ft by 300 ft by 200 ft in the NCPA lease, which is deemed sufficient to model the key physical phenomena and still warrants a reasonable runtime. The model has 50 layers with the thinnest layer measured at 200 feet located in the main feedzone. It extends from the surface to 12,000 feet below sea level, considering the conductive heat loss to the cap rock as well as the water pooling storage capacity in the basement. Double-porosity formulation was used for this work, where the fractures are interconnected with each other, while a matrix block is connected to the fracture located next to it. Under this arrangement, the geothermal fluids mainly move through the fracture network, while the matrix rock blocks act as storage tanks. The use of the double-porosity option effectively doubled the number of grid blocks in the base grid (390,000 matrix blocks and 390,000 fracture blocks, for a total of 780,000 blocks) (Figure 3).

2.2.3 Well System

The wells in the reservoir model are assumed to be completed in both the matrix and the fracture blocks, whereas the matrix blocks provide the bulk of the reservoir storage capacity. Considering the substantial number of wells drilled in the field (totaling more than 700) and the limited well trajectory available outside of the NCPA area, there are production and injection wells outside NCPA grouped to the same surface wellpad location, resulting in having production and injection within the same grid block. Because of a numerical limitation of having a cell under both cold injection and steam production at the same time, production is derived from shallower layers in the feedzone section, while injection occurs in the deeper section. Although certain injection wells may be completed at relatively shallow depths, the prevailing consensus is that injection water tends to gravitate and sink towards the bottom of the reservoir, i.e., water pooling. Within the NCPA refined grid, the refined gridding scheme and detailed well trajectory allow removal of this restriction. Also, the observed steam entry data provided by NCPA

guides the selection of the production and injection layers of individual wells, better capturing the depleted zones as well as identifying regions flooded by cold water injection.

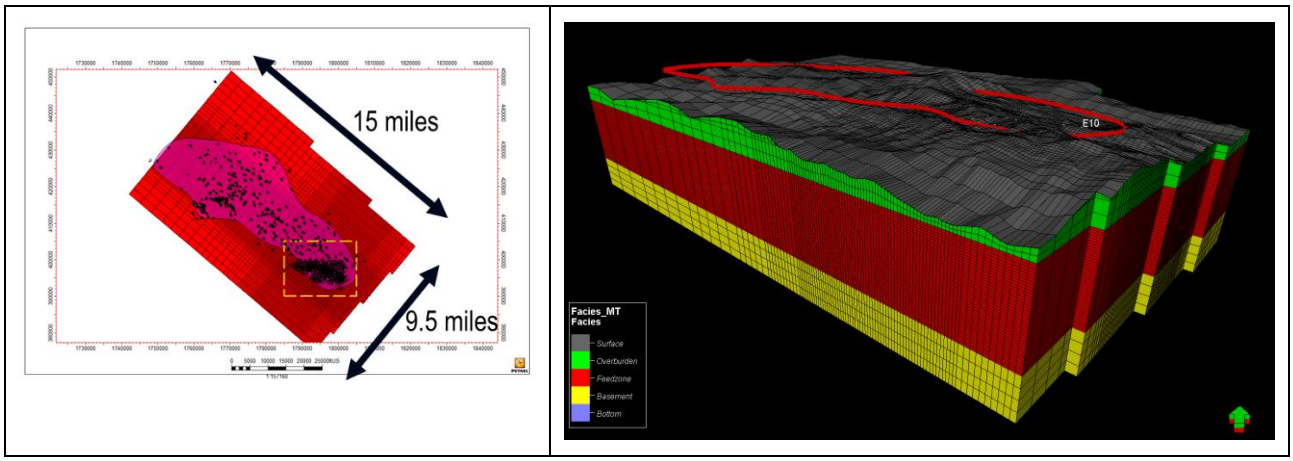
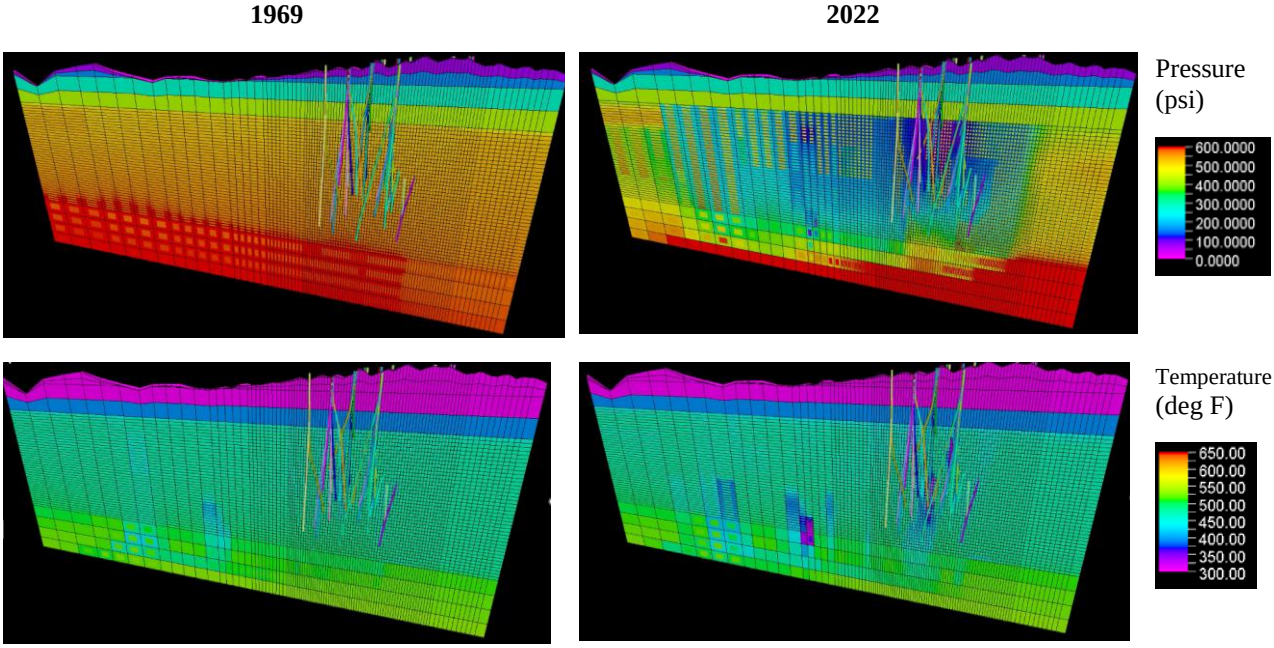


Figure 3: Setup of the simulation grid with refined grid in the NCPA area. Left: bird-eye view with the NCPA lease in dashed orange rectangle. Right: side view with refined layering in the feedzone. The surface, overburden layers, the main feedzone, and the basement are represented.

2.3 Model Calibration

As the Geysers is a steam-dominated field, where the steam decline rate is mainly dictated by the pressure trend in the reservoir, the model is calibrated by matching pressure data from the active wells as well as from observation wells. This model focuses on recalibrating the numerical model to match trends of reservoir pressure seen across the Geysers and evaluating the degree of superheat match within the NCPA area. The updated historical production and injection data were input to the model, and the model was run for 50 years from 1969 to 2022 (Figure 4). Reservoir pressures calculated by the model were then compared with the observed pressures, while the degree of superheat calculated by the model was also calibrated against the measured superheat degree at the wellhead. The model was then "tuned" to match the observed pressure and degree of superheat data as closely as possible. Numerous runs of the model were made, adjusting the above parameters on a trial-and-error basis, until a good match was obtained between observed and calculated pressures and superheat degree.



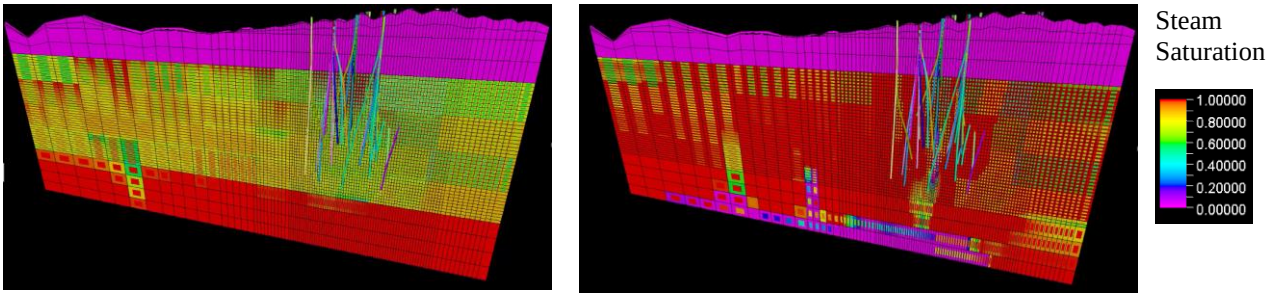


Figure 4: Evolution of pressure, temperature, and steam saturation from 1969 to 2022 in the Geysers.

2.3.1 Wellbore simulation

Static reservoir pressure data used for comparison with model results were derived from two sources. The first was the CDOGGR database, which included a useful number of shut-in wells scattered throughout the field with relatively long wellhead-pressure histories. Later on, when a plant is overhauled, the steam from its associated wells is shipped to nearby power plants. This has essentially curtailed the amount of shut-in wellhead pressure data for use in calibrating the reservoir model. The second source of observed shut-in pressure data, provided by NCPA, was well F-4 located on the western side of the NCPA steam field.

A wellbore modeling subroutine was developed to convert these wellhead pressures, using information on wellhead elevation and steam density, to absolute pressures at the top of the feedzone depth. This enabled the ECLIPSE model results to be compared directly to the observed shut-in wellhead-pressure data. To back calculate downhole pressure from wellhead pressure, we use the multi-feedzone geothermal wellbore simulator HOLA. Using the location of the first steam entry and detailed well trajectory provided by NCPA, directional wellbore descriptions were developed for each production well within the NCPA area. Assuming that fluid properties remain relatively constant, the pressure drop of single-phase fluid flow in pipes consists of three components: friction, potential, and acceleration (Aunzo et al., 1991).

$$\frac{dP}{dL} = \left[\frac{dP}{dL}\right]_{friction} + \left[\frac{dP}{dL}\right]_{potential} + \left[\frac{dP}{dL}\right]_{acceleration} = \frac{fG^2}{4r_w\rho} + \rho g sin(\theta) + \frac{d(Gu)}{dL} \qquad (1)$$

where d*p/dL, f, G, rw, ρ, g, θ, u* is pressure drop over pipe length L, friction factor, mass velocity, wellbore radius, fluid density, gravity constant, wellbore deviation angle from horizontal, and average fluid velocity, respectively. NCPA has been measuring reservoir pressure trend by shutting in production wells occasionally, measuring its wellhead pressure, and determining the reservoir pressure at the well location. This method has provided a reasonably accurate pressure trend in the reservoir since the start of the project; however, as the magnitude of the pressure decline is much smaller at this stage, the current method may not yield sufficient resolution for the purpose of optimizing injection in the field. One needs to be able to detect small pressure changes in the reservoir in real-time to effectively assess the small impacts on individual production wells during the injection optimization process.

2.3.2 Pressure history match

Reservoir pressure trends obtained from NCPA's production wells and pressure data from observation wells located within or near the NCPA leasehold were matched to ensure that pressure decline patterns at or near the leasehold boundaries are reasonable. Although pressure observation data are generally sparse, particularly in recent years, their general trends do provide reasonable patterns for use in model calibration. Because reservoir behavior from areas outside the NCPA leasehold does have an impact on the fluid flow patterns inside the NCPA area, pressure trends from observation wells located outside of the NCPA leasehold were also matched to provide additional confidence that external areas are not exerting unaccounted impacts on the reservoir behavior within the NCPA leasehold. The location of these observation wells is shown in Figure 6.

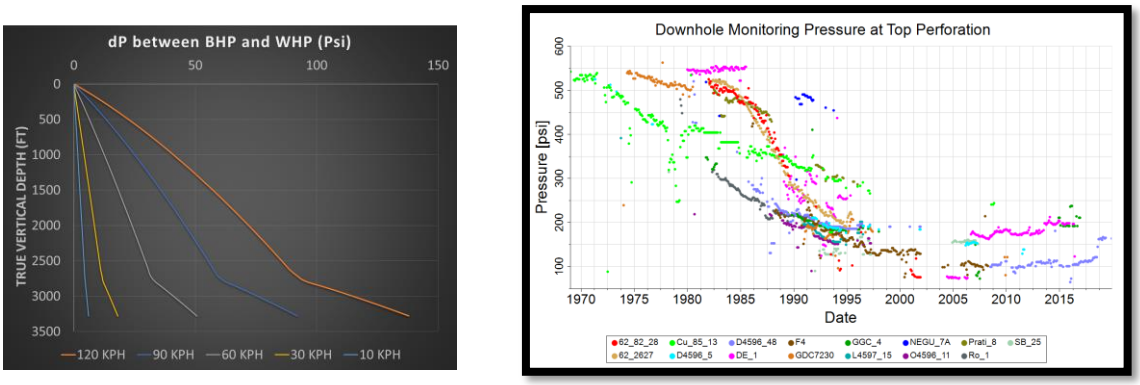


Figure 5: Left: Wellbore modeling shows the difference between wellhead pressure and bottomhole pressure for different flow rates at different depths. Right: monitoring pressure is converted to downhole pressure signal of individual monitoring well in the Geysers.

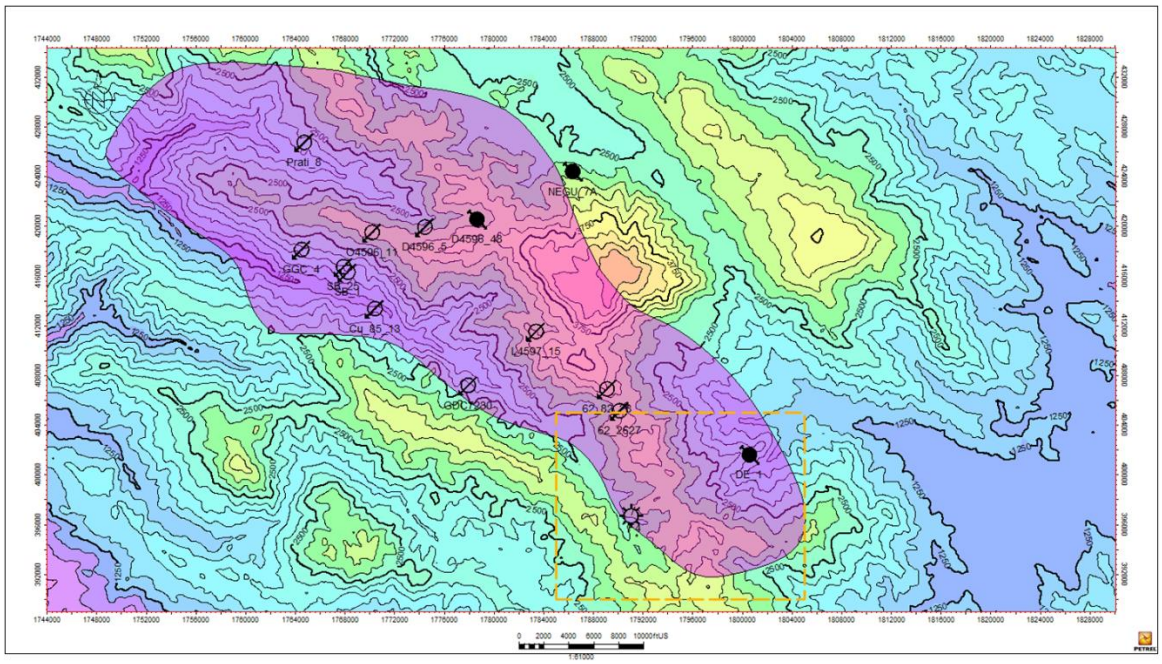


Figure 6: Location of the observation wells used in history matching in the integrated model. The NCPA lease is highlighted in the dashed orange box. There is one well F-4 in the area and another three wells Davies-Estate 1, CA-1962-2627, CA-1962-8226 nearby.

Important parameters that were adjusted during the history-matching period were the fracture and matrix porosities, fracture, and matrix permeabilities, initial steam saturation, and fracture spacing. Each parameter impacts the pressure behavior differently and the holistic tuning of the parameters yields the combinational effect on the pressure match. The final matches to the observed pressure data for the wells are shown in Figure 7. These figures show that the pressures calculated by the model are reasonably close to the observed pressure trends.

These results demonstrate the model's ability to match the generalized pressure decline throughout the field and thereby represent the proper pressure boundary for the refined grid system used to model the NCPA area. This provides assurance that not only has reservoir behavior within the NCPA lease hold been faithfully duplicated but impacts from external areas were also well represented. Once the pressure outside NCPA is well-matched, ECLIPSE offers an NCPA-only sector model run option with a simulated flux boundary condition to reduce a sizable portion of the runtime. Within the refined grid system, the pressure declines at wells F-4 and Davies Estate-1 are closely matched. The pressure behavior of other NCPA wells is depicted in Figure 8, demonstrating a general alignment with the

average reservoir pressure trend. The results of the history matching show that the model successfully simulates the behavior of the reservoir under the historical conditions of production and injection. Pressure trends measured from the production wells and observation wells were closely replicated by the numerical model. Thus, the model is adequately calibrated for use in forecasting future reservoir behavior under various production and injection scenarios.

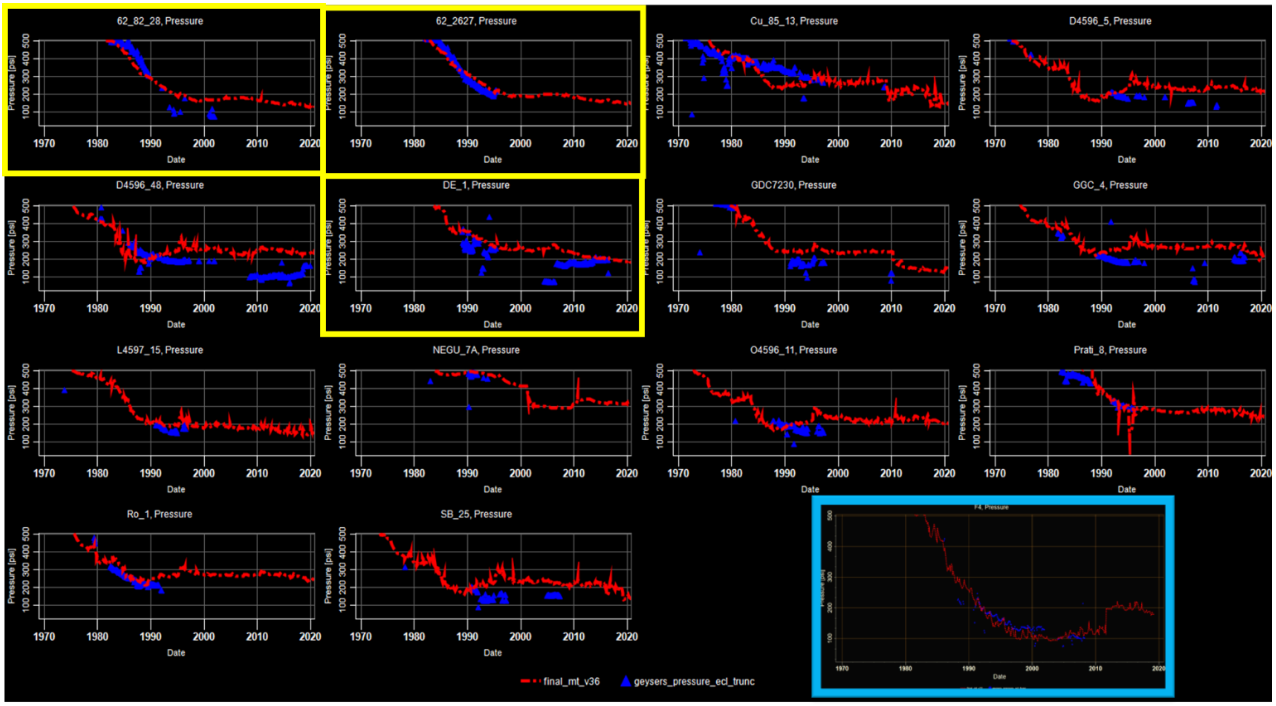


Figure 7: Observed and calculated reservoir pressures for all observational wells in the Geysers. Wells that are close to the NCPA leases are highlighted in orange boxes. Wells that are in the NCPA leases are highlighted in the blue box. Measured reservoir pressure is represented by the dark blue triangles while calculated reservoir pressures from various wells in the field are denoted by red solid lines.

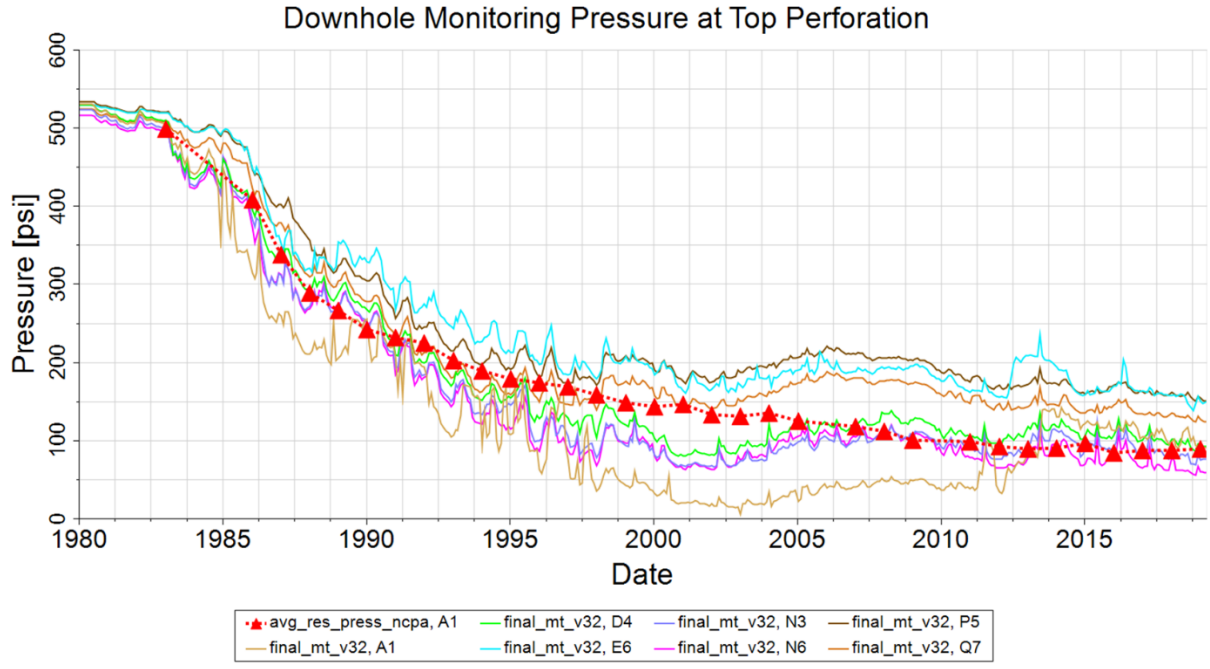


Figure 8: Modeled reservoir pressures for various wells in different clusters in the NCPA leases.

2.3.3 Degree of superheat history match

Pressure magnitude and initial steam saturation are the driving factors in finetuning the degree of superheat matching. The model demonstrates that it can capture the magnitude as well the general trend of superheated conditions in most representative NCPA wells.

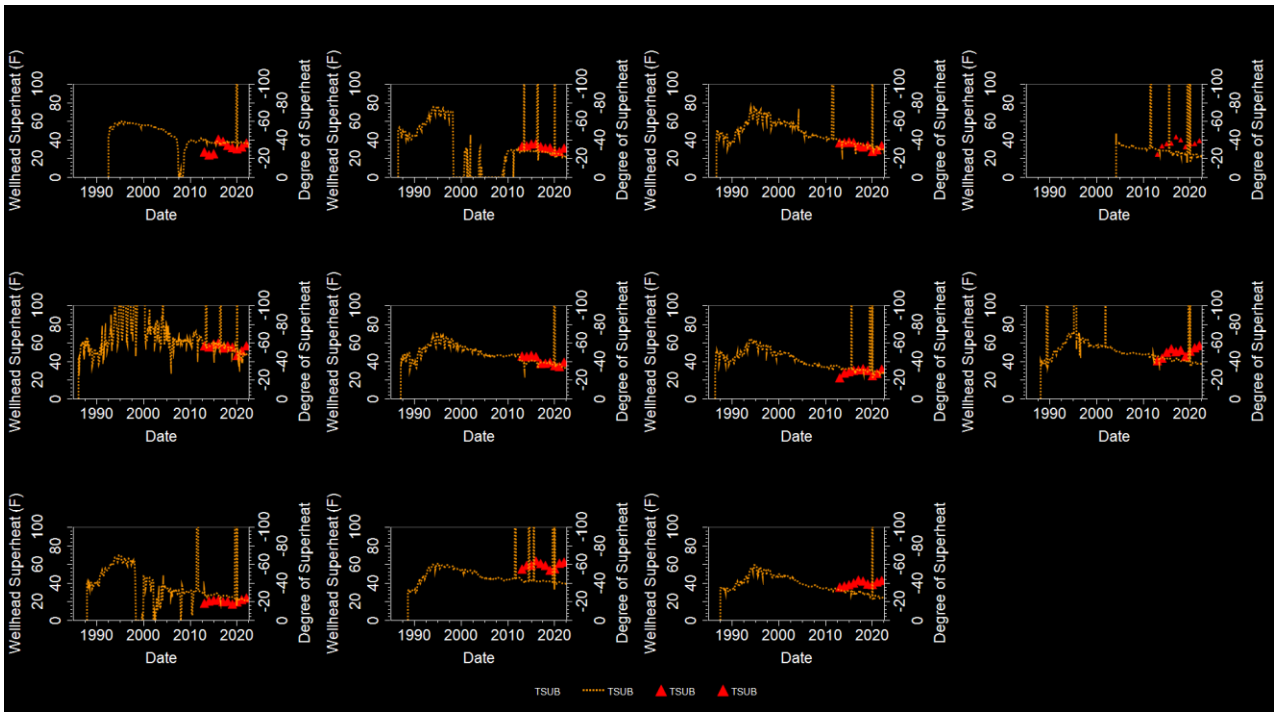


Figure 9: Observed and calculated degree of superheat for various wells in NCPA leases.

2.3.4 Model forecast

During history matching, the flow rate histories are specified for each production or injection well, and the model calculates the pressure changes. However, in the forecasting mode, the model predicts how the flow rate will change with time, and to do this, the model needs to have a specified pressure constraint. In actual field operation, turbine inlet pressures constitute the ultimate pressure constraint on the system. To use the turbine inlet pressures as the pressure constraint on the reservoir model, downhole pressures must be linked to turbine inlet pressures by simulation of the wellbores and the pipeline network (Butler and Enedy, 2009).

In forecasting field performance, the production wells outside of the NCPA area are allowed to flow under the terminal bottom hole pressure constraint based on the current flowing wellhead pressure (CDOGGR database). The productivity indices for each well or group of wells were adjusted in an iterative fashion until a reasonable match was obtained between the flow rates predicted by the model and the flow rates reported in the CDOGGR database. GeothermEx modeled several scenarios of supplemental injection to assess how variations in the rate and geographic distribution of injection could affect MW output. The scenarios did not consider limitations on the amount of supplemental injection water that might become available. The runs were intended to investigate whether there was a point of diminishing returns on supplemental injection, for the hypothetical situation of an unlimited water supply. In this effort, the major questions to be answered by forecasting are the impact of reduced injection and the optimal level of mass replacement (or water injection) for production maintenance.

3. DISCUSSION AND CONCLUSION

The process of optimizing the distribution of augmented injection throughout the field and making necessary adjustments to plant and pipeline facilities is complex and intricate, involving numerous interdependencies. Distributing supplemental injection over a broader area allows the injected water to contact a larger volume of reservoir rock, which results in more boiling. Distributing injection amongst

wells in spread-out locations significantly slows down production decline, compared to injecting in a concentrated area. With the same amount of condensate water but distributed over all the active injectors, the model suggests the evenly distributed nature of the injection helps provide pressure support and minimize over-saturation, resulting in a clear benefit. Unfortunately, there are only a limited number of existing wells that could be used for supplemental injection and drilling new wells for injection would be very costly. A thorough evaluation of options for supplemental injection would have to consider the costs of drilling new wells and upgrading pipelines for water supply, as well as the parasitic loads and operating costs of pumping the additional water.

The results from the model suggest that effluent injection may have reached its upper limit at present. Whereas effluent injection has clearly reduced the production decline rate in the past since it was implemented in the mid-1990s, it is possible that the continued effluent injection has changed the reservoir conditions such that the bottom part of the reservoir is now fully saturated, and the amount of heat available to quickly evaporate the injected fluid has been diminished, resulting in less efficient generation of secondary steam. The quantification of actual contributions from injection-derived steam (IDS) and normal steam poses challenges, which can be addressed through tracer studies or passive geochemical methods. Numerical simulation results demonstrate that the benefits of IDS increase notably during the initial years compared to scenarios without injection. However, these benefits tend to diminish over time due to reservoir cooling, which leads to a decline in boiling efficiency.

Furthermore, the injection scheme, including well location and injection rate, has not been optimized. With the shallow part of the reservoir still having intense superheated conditions, it is possible to fine-tune the injection program (at a reduced rate or at the currently produced condensate level) to further take advantage of the available superheat. Based on current understanding of the reservoir basement, the model suggests that not all of the injected water undergoes boiling; instead, some of it accumulates in the bottom of the reservoir. Although this accumulated water does offer pressure support, especially when injection into shallower layers is reduced, past tracer test results indicate that not all of the injected water is recovered over a short time period, suggesting a similar process is occurring within the reservoir. However, there is uncertainty regarding the depth to which this residual water travels and the fraction that can ultimately be recovered from the reservoir. Further research and investigation are required to determine these factors accurately. The findings from this study highlight the significant impact of boiling accumulated water in the deeper parts of the reservoir, which plays a crucial role in the long-term performance of the field. Understanding how the injected water boils within the reservoir, coupled with advanced reservoir modeling techniques, will be a vital aspect of optimizing the recovery of injected water as steam. This research will be pivotal in the long-term management and sustainable operation of The Geysers geothermal field.

REFERENCES

Butler, Steven J., and Steven L. Enedy. "Numerical reservoir-wellbore-pipeline simulation model of the geysers geothermal field, California, USA." SPE Western Regional Meeting. OnePetro, 2009.

Grant, Malcomm. Geothermal reservoir engineering. Elsevier, 2013.

Sanyal, Subir K., and Steven L. Enedy. "Fifty years of power generation at the Geysers geothermal field, California–the lessons learned." 36th workshop on geothermal reservoir engineering, Stanford, California. 2011.

Stacey, Robert W., and Michael J. Williams. "Validation of ECLIPSE reservoir simulator for geothermal problems." GRC Transactions 41 (2017): 2095-2109.

Stark, Mitchel A., et al. "The Santa Rosa–geysers recharge project, geysers geothermal field, California, USA." Proc. World Geotherm. Cong (2005): 24-29.

Williamson, K.H., 1990. Reservoir Simulation of The Geysers Geothermal Field. Proceedings, Fifteenth Workshop on Geothermal Reservoir Engineering, Stanford University, Stanford, California, 23-25 January, 1990. Report No. SGP-TR-130, pp 113-123.

Successful Downhole pH Modification Facility Recovery: Case Study of Sokoria Geothermal Well

Fabiola Pardede, Wishnu Triananda, Ryan Hidayat, and Junior Setiawan

Recapital Building 5th Fl., Jl. Adityawarman No. 55, Melawai, Jakarta Selatan

fabiola.pardede@ksorka.com

Keywords: Reservoir, Production, Capillary Tubing, Fishing, pH treatment

ABSTRACT

One of the challenges in Sokoria geothermal field (developed by PT Sokoria Geothermal Indonesia, a project of KS Orka Renewables Pte Ltd.) is finding the solution to producing some of the acidic reservoir fluid. Acidic fluid from downhole can be treated using small capillary tubing installed into the wellbore down to below casing point depth and injected with caustic soda at a rate to neutralize the acidic fluid. The implementation of downhole pH modification system in Sokoria wells has allowed well MTB A-02 to contribute steam and brine for the existing 8 MW binary power plant. However, during production and monitoring, it is observed that the wellhead pressure MTB A-02 has dropped, which was then further identified with parted capillary tubing. Parted capillary tubing had occurred with downhole pH modification system in MTB A-02, with further risk of fish in hole which restricted production capability of the well. Successful execution of fishing activity and downhole capillary tubing installation inside MTB A-02 has recovered production supply to its initial performance level and continued wellbore and facility protection from acidic fluid risk.

1. INTRODUCTION

Sokoria geothermal field is in Nusa Tenggara Timur, Indonesia, developed and operated by PT Sokoria Geothermal Indonesia, a project of KS Orka Renewables Pte Ltd. Sokoria's medium enthalpy system utilizes both steam and brine as heat source in binary power cycle to transfer heat to working fluid with low boiling point. Until Aug 2023, the total installed power capacity is 8 MW with on-going development for total resource estimate up to 30 MW. Reservoir fluid chemistry of Sokoria geothermal system had been initially discussed by Sarmiento et al (2019) and its evolution observed during initial production is discussed by Pradipta and Hidayat (2023).

Reservoir fluid enthalpy has been identified in Sokoria which ranges from ~850 kJ/kg to ~950 kJ/kg. Sarmiento et al. (2019) A typical pressure and temperature flowing profile of medium enthalpy well such as in Sokoria is simulated as an example below. For a well with medium enthalpy of ~900 kJ/kg and total productivity index of ~1.5 kg/s/bar, the flowing profile in Figure 1 indicates that reservoir fluid enters the wellbore as single-phase water. Flashing of the reservoir fluid occurs in flowing condition with its initial flashing point inside the wellbore and additional flashing occurs along the wellbore until surface. In the case of liquid dominated flow from a standard hole configuration, the expected discharge pressure is reflected through output curve simulation in Figure 2. Sokoria generation with binary power plant Unit-1&2 allows the utilization of wells with maximum discharge pressure below ~3.5 bara.

Sokoria's reservoir fluid has been initially sampled during flowing with slight acidity pH 4.2 – 5.7. Sarmiento (2019) Acidic fluid from downhole wellbore can be treated using small capillary tubing installed in the wellbore down to below casing point depth and injected with caustic soda (NaOH) at an adjusted rate to create neutralization reaction. Injection of caustic soda is applied on the slightly acidic wells to increase the pH to 4.8 – 5.2 to avoid corrosion potential. Pradipta and Hidayat (2023) Several production wells in Sokoria including MTB A-02 had capillary tubing installed downhole in 2020.

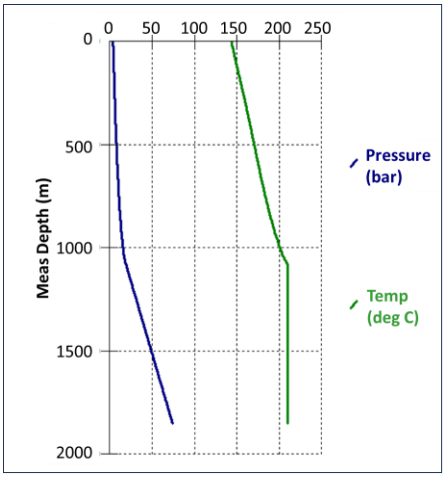


Figure 1: PT flowing profile and total mass flow output curve.

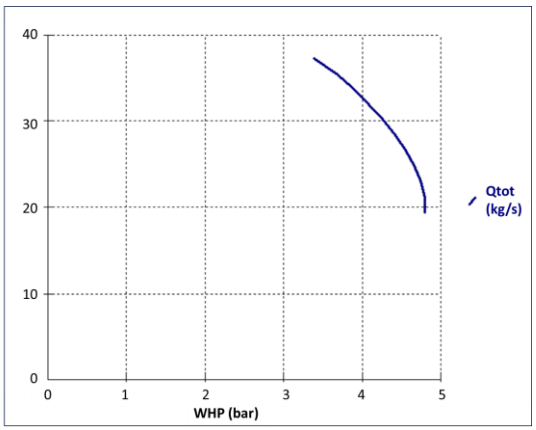


Figure 2: Total mass flow output curve for medium enthalpy reservoir.

MTB A-02 is an active production well for Sokoria binary geothermal power plant Unit-1 (5 MW), adding generation to Flores Island grid since its commissioning in March 2022. Inside wellbore MTB A-02 exists a string of stainless steel 3/8" capillary tubing connected from caustic soda (NaOH) dosing treatment facility at the surface ~40 m away from wellhead, down to 1340 mMD depth. Since the well's commissioning, the capillary tubing was continuously used for operational chemical injection treatment. Corrosion coupon installed on A-02 flow line was analyzed and shows no corrosion nor scale deposition, good indication of NaOH treatment in MTB A-02 working as designed. Downhole capillary tubing exists vertically along the wellhead and obstructs the well from being shut in at the wellhead. Safely isolating the well is to be conducted from the block valve on the two-phase line, at immediate downstream of the main master valve.

During normal production and operations, routine monitoring observed that the wellhead pressure MTB A-02 has experienced a step drop, which was then further identified with parted capillary tubing. Capillary tubing confirmed had parted and dropped inside wellbore, disabling the downhole pH modification system in MTB A-02, and caused fish obstruction in hole as well as restricted production capability of the well.

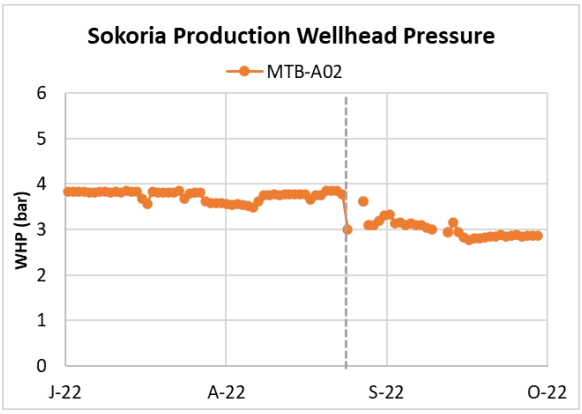


Figure 3: MTB A-02 wellhead pressure monitoring recorded step drop related to downhole capillary tubing parted.

2. METHODOLOGY

To restore production capability, the proposed method is to remove the installed tubing by retrieving the entire length of 1340m capillary tubing string through Pull Out of the Hole (POOH) technique using wireline unit and then proceed to reinstall new downhole capillary tubing. Wireline unit is mobilized to Sokoria to reel out the disconnected tubing from the pH treatment facility at A-02 wellhead and fish out the remaining parted capillary tubing until reaching clear path for new capillary tubing and restoring flowability. Assessment on capillary tubing solutions at A-02 required immediate availability, reliability, and unit capability.

2.1 Well Control by Killing and Quenching

Immediate corrective option to shut-in well and water injection began to kill the well in preparation for fishing. To support generation at Sokoria power plant, backup production well (MTB A-04) is put in service temporarily. Injection of cold water from condensate supply line performs at an improved performance during fish retrievals, especially to stabilize the ~2100mMD well hole during repeated interactions with atmosphere. Injecting mainly condensate instead of brine also reduces risk of scaling in production well. The well is maintained at vacuum WHP with quenching rate of 30-54 m^3/h from the wing valve. To avoid tubing carried over into permanent 2-phased line required unloading the liquid level observed at wellhead. A-02 was discharged to the well test silencer on 29 Jan 2023, which found several pieces of short capillary tubing at the pipe bend near wellhead. Fishing activity resumed on 31 Jan 2023 and concluded retrieval activities on 10 Feb 2023.

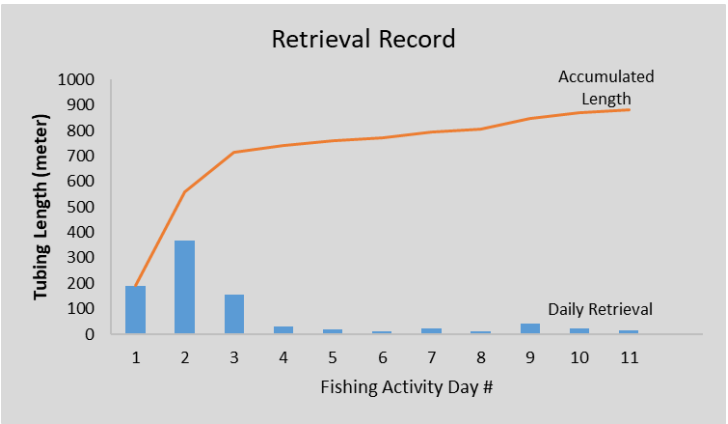


Figure 4: Fishing daily and accumulated retrieval record.

2.2 Capillary Tubing Retrievals

Fishing activity main objectives are to retrieve 3/8" capillary tube remains in well A-02 and clear path for new capillary tubing to be installed downhole. Total length of initial fish identified is 1340 m.

Fishing job used 7" wire finder and wire grab with a variety of modifications single spear, double and triple prongs. Found ~ 17m of cap-tube carried over in 2-phase line, suspect that the tubing was carried over during AA-02 flowing to system or during unload activity to atmosphere. Production pipeline and valves are cleared from debris prior to resume production A-02 to system. Observed lower tubing quality especially from shallow section potentially due to corrosion of prolonged soaking in slightly acidic reservoir fluid. Weight reduction from initial specifications was identified, with worst case scenario observed up to 60% reduction. Recovered fish has lower tensile strength ~1500 lbs compared to initial specifications 5444 lbs. However, longer fragments were still initially able to be pulled out of the hole, therefore all length of the capillary tube shows lowering of tensile strength. Possibly lower tensile strength found is secondary impact due to tubing being jarred during wire finder run then parted into fragments while being pulled out. In Figure 4, as the top of fish goes deeper, the fish is recovered in fragments. More brittle fish are found through deeper fishing depth. A-02 fishing activity executed a total of 62 runs POOH-RIH which fished out a total of 883m capillary tubing and maximum logging depth cleared down to 1550m for 5.5" diameter.

2.3 Restoration Actions

Installed new capillary tubing and new nozzle downhole to set depth 946m, reducing risks of casing corrosion due to the slightly acidic fluid in A-02. Re-installing downhole capillary tubing into MTB A-02 successfully restored connection to NaOH treatment facility at surface. Reinstallation required new capillary injector head and new string of capillary tubing that are compatible with the existing surface treatment facility. MTB A-02 production successfully restored to Unit-1 Sokoria and returned MTB A-04 to idle for future development plans. New capillary tubing can be identified with good function by monitoring pH treatment reaction time, injection pressure expected vs. measured, and stable flow rate strokes according to pump's performance. Additional forward plan on MTB A-02 is to reduce risks of thermal or mechanical fatigue.

3. CONCLUSIONS

No scaling issue had been identified in any of Sokoria's production wells. While MTB A-02 had been continuously flowing with pH maintained at pH value 5 since early 2022, the downhole capillary tubing had been previously installed since 2020. Dynamic and slightly acidic reservoir fluid was treated at point below flashing point to protect the casing section, therefore the point injection for caustic soda is through four side nozzles at 1340mMD. It could only later be identified that the capillary tubing parted inside the A-02 production well with flowing temperature ~140°C was parted near wellhead, which left 1340m of initial fish remains in wellbore. Based on the cap tube end profile, it is likely parted cap-tube occur due to fatigue over unfavorable combination of thermal expansion and thermal conductivity at the welded joints of the capillary strings.

WHP Improvement. Amid fishing operation, MTB A-02 was discharged to atmosphere with WHP 3.73 barg. This is higher than previous discharge attempt with WHP 2.5 barg on 2022 when suspect captube parted and dropped. Continued fishing was executed to ensure for deeper wellbore clearance that allowed new capillary tubing to be installed and protect casing section on the following production period. Fishing job was concluded which recovered total length of **883 m (~66%)** with ToF is at 1550 mMD (165 mMD below major feedzone of 1385mMD). After fishing, flow test MTB A-02 with FCV 100% to atmospheric silencer shows the well can maintain wellhead pressure of 3.3 barg, wellhead temperature 133°C, and measured brine flow to pond at rate ~90 m^3/h. MTB A-02 newly installed capillary tubing and nozzle is set at depth 946mMD. A-02 restored downhole pH modification facility allowed the well for restored production to Unit-1 Sokoria binary power plant.

REFERENCES

Pradipta, R., and Hidayat, R.: Fluid Chemistry Evolution after one year production at Sokoria Geothermal Field, *Proceedings*, The 9th Indonesia International Geothermal Convention & Exhibition (IIGCE), (2023).

Sarmiento, Z., Sagala, Birean, S., and Siagian, H.: The Sokoria Geothermal System, Flores Island, Indonesia, *Geothermics*, (2019).

This page is intentionally left blank

Part 4:
Social, Politics, Economics, and Community

Integrated Geothermal Operational Dashboard using Business Intelligence Platform as a Digital Transformation

Fajar Khamim Mustofa, M. Vito Hamza, Hanifah Nur Azizah, Fransisco Simamora,
R. Fuad Satrio Ajie, Muhammad Thasril, and Efrata P. Meliala

PT GEO DIPA

fajar.khamim@geodipa.co.id, vito.hamza@geodipa.co.id, hanifah@geodipa.co.id, fransisco@geodipa.co.id, fuad.satrio@geodipa.co.id, thasril@geodipa.co.id, efrata@geodipa.co.id

Keywords: Business Intelligence, Operational Improvement, Digital Transformation

ABSTRACT

In order to fulfill its commitments as a signatory to the Paris Agreement on climate change and for economic reasons, Indonesia's government is dedicated to utilizing the country's significant geothermal potential. One of the key forces behind improving geothermal operational production is a digital transformation. It has been implemented in Dieng and Patuha geothermal fields by changing manual paper-based into an integrated digital sheet.

A previous method to collect the operational data was handled by the operator using manual log sheet, then transferred to the Head Quarter using corporate mail. This conventional method was obviously time consuming, it triggered to enlarge the engineer's non-productive time. In the 4th quarter of 2023, there was a digital initiative to make its method to be a full paperless system. By utilizing digital app sheet and business intelligence platforms, it successfully cut the total time length of operational processes 2 time faster.

An Integrated operational production dashboard has been well visualized using a business intelligence platform. It consists of steam field and power plant operational parameters trending which are inputted by the local operator using digital app sheet into the share point server. The centralized data in the share point, then transferred into power BI server to be visualized using a scheduled refresh scheme. This initiative offered great opportunity for geothermal operational monitoring optimization and improvement. This paper performed a business intelligence deployment success story, compiling operational data gathering, monitoring, and study case of operational optimization.

1. INTRODUCTION

According to the Paris Agreement in 2015, with incentives offered for renewable and clean energy sources, the use of geothermal energy has increased. Geothermal energy is a clean and reliable source of heat and electricity, will play a significant role in the clean energy transition alongside other renewable energy sources. Geothermal resources are abundant in volcanically active locations as well as sedimentary basins. The region which has many volcanic eruptions and earthquakes occurred in the rim of the Pacific Ocean is called as ring of fire. Most of the regions in Indonesia are included in ring of fire path (Figure 1), it impacted on the abundance of geothermal resources in Indonesia. Indonesia has the biggest geothermal potential in the world, and has developed geothermal power plants faster in terms of capacities in the last 5 years. Indonesia has developed 2356 MW or about 8.1 percent of 29,000 MW of geothermal potential through the year 2023.

Geo Dipa Energi as Ministry of Finance Special Mission Vehicle (SMV) were tasked to operate two Geothermal Field: Dieng with current capacity of 72,5 MW Gross (60 MW Gross Dieng Unit 1 and 12,5 MW Small Scale Unit) and Patuha with Capacity of 60 MW Gross. Dieng field comprised of three sub-unit or working units: Steam Field, Power Plant Unit 1, and Small-Scale Power Plant. While Patuha comprised of two sub-unit of Steam Field and Power Plant Unit 1. Operating whole stream of Geothermal from sub-surface into electricity, Geo Dipa faced with multiple challenges to maintain strong production and revenues.

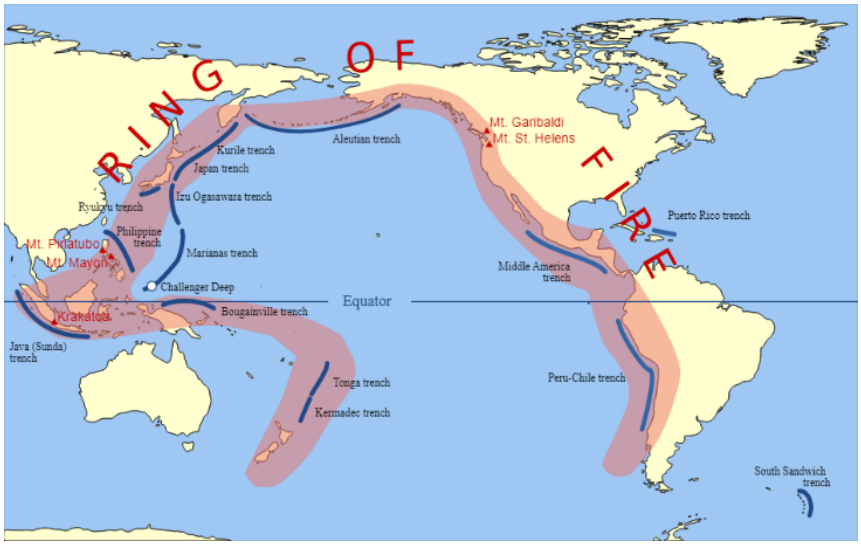


Figure 1: Ring of Fire Geothermal Path.

Figure 2: Geo Dipa Energi Operating Geothermal Field.

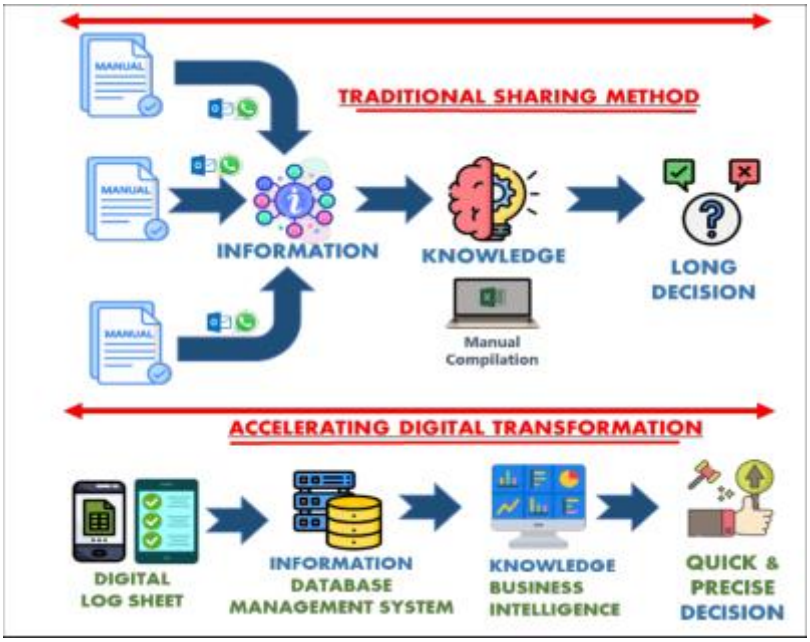


Figure 3: Process Workflow of Data Transformation.

Because of the operation responsibility, there were numerous parties involved when it comes to analyzing and making sound decision to improve or sustain production. From operators which were directly responsible to maintaining the field production 24/7 to engineers at the head office which processes the information gathered by operators in the field and stakeholders which created executive decision by the knowledge of engineers. This executive decision sometimes came immediate after knowing the condition of the field. Since a loss production in a day could resulted in a loss of revenue up to $254.000 (equivalent to 3,8 Billion IDR).

The process of this transformation of data to information, information to knowledge, and knowledge into decision faced with hidden losses of time which came from multiple sources. Prior to the deployment of the digital initiative, communication protocol between local operators and headquarter engineers was extremely complex, with frequent miss-data alignment. Paper-based Operation Log Sheet created redundant yet a mandatory work. Traditional file sharing methods caused lagging time to increased, resulted in late report submission. Table 1 shows the average duration spend of processing data into reports that were used as a knowledge to create a decision for stakeholders for a daily report.

Table 1: Total duration a cycle of operational daily report using traditional sharing method.

No.	Activity	Working Unit	Tools	Average Duration (hours)
1	Patrol Check from Operation	**Plant 1** SF, U1, SS **Plant 2** SF, U1	Paper-based	1:00 / Working Unit
2	Data Entry and Approval	**Plant 1** SF, U1, SS **Plant 2** SF, U1	**Plant 1** Entry Platform **Plant 2** Excel	0:30 / Working Unit
Duration Spend for Patrol Data Entry / Working Unit				1:30
Total Duration Spend for Patrol Data Entry **(5 Working Unit: 3 Power Plant Unit & 2 Steam Field Unit)**				**7:30**
3	Reporting, includes: - Re-Entry Critical Parameter Record - Entry of Operation Activity	**Plant 1** SF, U1, SS **Plant 2** SF, U1	Manual based	0:45 / Working Unit
4	Reporting Approval / Revision	**Plant 1** SF, U1, SS **Plant 2** SF, U1	Corporate Mail	0:15 / Working Unit
Duration Spend for Reporting / Working Unit				1:00
Total Duration Spend for Reporting **(5 Working Unit: 3 Power Plant Unit & 2 Steam Field Unit)**				**5:00**

5	Compiling Reports	Head Office	Manual based	0:45
6	Updating Charts and Graphs	Head Office	Manual based	0:45
7	Creating Presentation for Stakeholders	Head Office	Manual presentation platform	0:20
8	Publishing Presentations to Stakeholders	Head Office	E-Mail, WhatsApp	00:10
Duration Spend for Publishing Reports				**02:00**
Grand Total Duration of Daily Operation Reporting (Plant 1 + Plant 2)				**14:30** **14 Hours 30 Mins**

The entire process workflow consumed about 14.5 hours for two geothermal plants each of day. The local operators need to entry paper-based log sheet on their local PC, then performed internal routing approval by their supervisor. The process of Data Entry took around 30% of time during Operation Patrol. After reviewing the reports, the Person in Charge (PIC) of operators submitted it to the head quarter office via email and communication apps. Each Working Unit had to spent 75% of their time to re-entry same Parameter to Report. As a result, headquarter engineers undoubtedly need more allocation time to compile its disorganized reports for two geothermal plants. This process of Compiling and Updating Charts took 75% of duration spend for publishing reports.

Identifying these non-productive losses, Geo Dipa spearheaded a digital initiative to cut non-productive task by utilizing several tools for each process. Digital log sheet enabled local operators to send operation data directly on the field. The data then stored into a data management system which will be visualized in business intelligence platform automatically. Stakeholders only needed to monitor its dashboard and engineers could perform analysis and optimizations efficiently.

2. UTILIZATION OF DIGITAL TOOLS FOR GEOTHERMAL OPERATION

2.1 Accelerating Digital Transformation Journey

Achieving operational excellence through digital transformation is a transformation process that enables the organization to increase operational effectiveness and acquire a competitive edge at the corporate level. By the end of 2022, the project team initiated to create a digital transformation in terms of operational data processing in the integrated business intelligence platform that called as embryo of GEOREC (Geo Dipa Energi Optimization, Reliability, and Efficiency Center). The project team successfully accelerated this digital endeavor in just around two months for two working plants.

For similar result in the past, it took almost 2 years of developing integrated geothermal operation dashboard from scratch. This procedure included digitizing the operational log sheet, gathering the data, and creating an interactive dashboard. The acceleration process was emerged with a bottom-up strategy deployment surely without sacrificing the company's objective and vision. Its process includes five phases: defining the problem, measuring the baseline and improving the activity, identifying the opportunities for improvement, setting project goals, and meeting the needs of the business added value.

On the define phase, engineers made a project charter to create common understanding of issues and benefits for project. After earning point of view of this project, the project team leveraged to measure the baseline of current process by compiling historical data and information. Then, opportunity for improvement from the baseline process was analyzed by the project team. It was summarized in an updated guideline or Standard Operational Procedure (SOP) that to be proposed to the top management level. After getting the approval from top management level, its updated guideline would be socialized to the working level and parties to be implemented as soon as possible. Meanwhile, the project team needs to commit to accelerate this improvement and controlling phase. With a fully-support from the top management level, this digital initiative was successfully implemented in tight timeline.

2.2 Leveraging No-Code Mobile Apps for Data Gathering

The pipeline of Data has always come from data sources which gathered with various methods. The process of data gathering from operator daily monitoring was emphasized as one of the conventional yet effective methods to verify plant and equipment conditions. The challenge of operator daily monitoring comes from its paper worksheet which data entry is needed in terms of data collection. Mobile apps often come as a solution for this challenge. However, Plant Managers are forced with dilemmas of developing their own hard-coded mobile apps or outsourcing the development while both takes price, time, and people resources in mind.

The emergence of No-Code App Development came as a solution for subject matter experts (SMEs) in respected fields to tailor their own solution of mobile apps. In the current approach, Geo Dipa used Digital AppSheet for its mobile operation monitoring sheet (dubbed as *Mobile Operation Logsheet*). Digital AppSheet deployed apps comes in three forms: Web App, Mobile App, and Handheld (Tab) App which suited to almost every device available. Making it a versatile data and information gathering app.

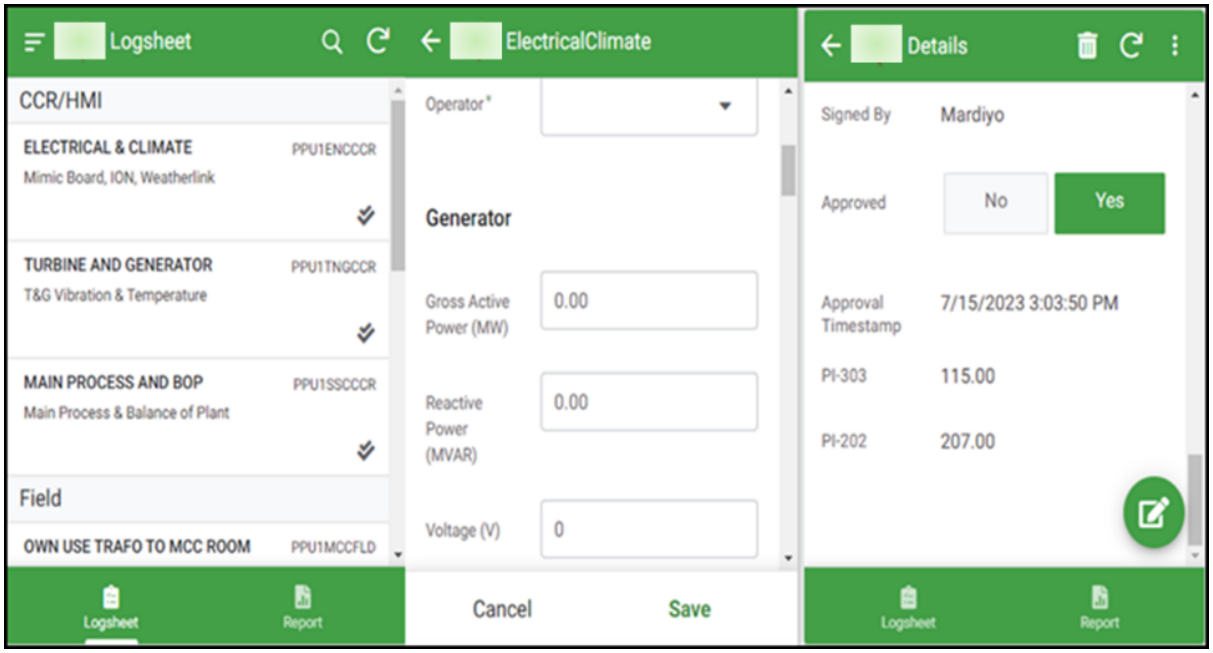


Figure 4: Digital App Sheet User Interface.

The development of working prototype was done in 1 week with minimum viable product (MVP) which are usable for storing data directly from mobile app for every paper sheet into data management sheet was done in 3 weeks. The next per-2 weeks (sprint) were used to develop a working automation. One of them enables operators to approve Operation Logsheet via App directly and giving a condition where rejected Logsheet could not be sent into the report database on Data Management Platform. While approved Logsheet automatically sent into the database.

2.3 Centralized Data Management Platform for Reporting

Data gathering is an essential part of reporting. Yet gathered data could not be utilized directly simply because it was stored in other platforms or on a bad shape. Prior to digital initiative deployment, some reports both Dieng and Patuha had delivered separately and disorganized. As represent in figure 5 below, there were several manual daily operational data which divided into 3 sections: steam field, power plant, other reports. All of reports have been sent manually to the head quarter office by using communicator apps or e-mail. It obviously led to enlarge non-productive time for some engineers to compile the data in the head quarter office.

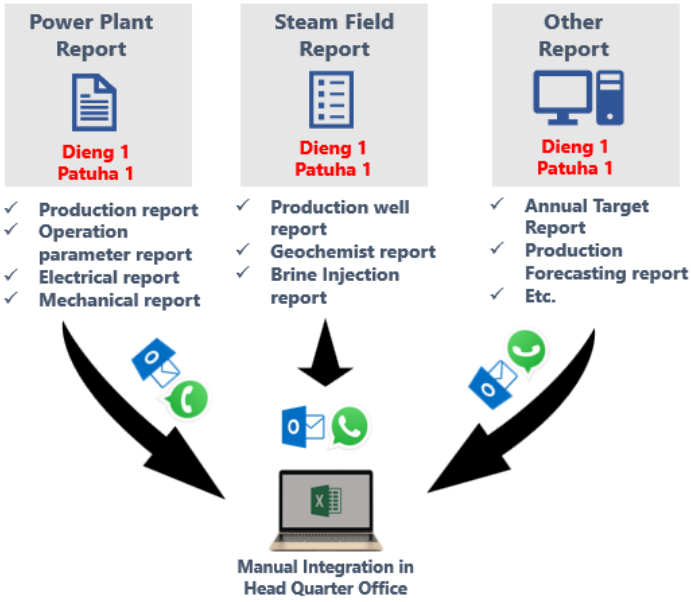


Figure 5: Traditional file sharing methods.

In order to clear its challenges, a centralized database management system is a requirement that must to be provided in this process. Centralizing the data that were used as a reporting had numerous benefits, with some of the most notable were able to integrate data into report directly and ensuring its accuracy and consistency. While data management platform is the foundational system for collecting and analyzing large volumes of data across an organization. As initial initiation, data management platform was fully-utilized to placing some reports above and as an integration platform of operational data.

Data management system can resolve issues in traditional file shares. The local operators only controlled the data which they inputted on their *Digital Operation Logsheet*. Since this implementation, operators were no longer needed to re-entry data into Excel and sent reports using corporate mail.

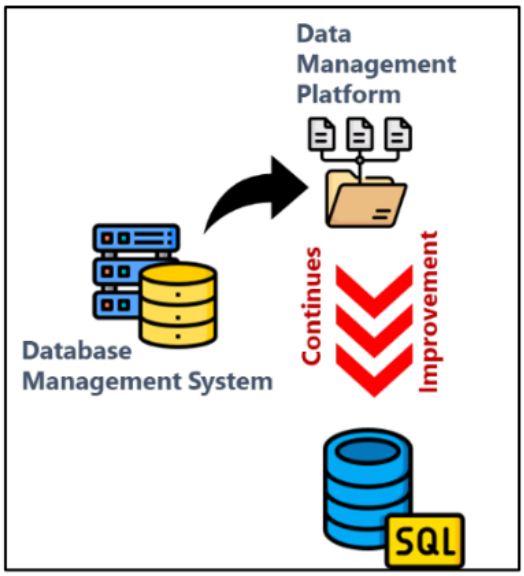


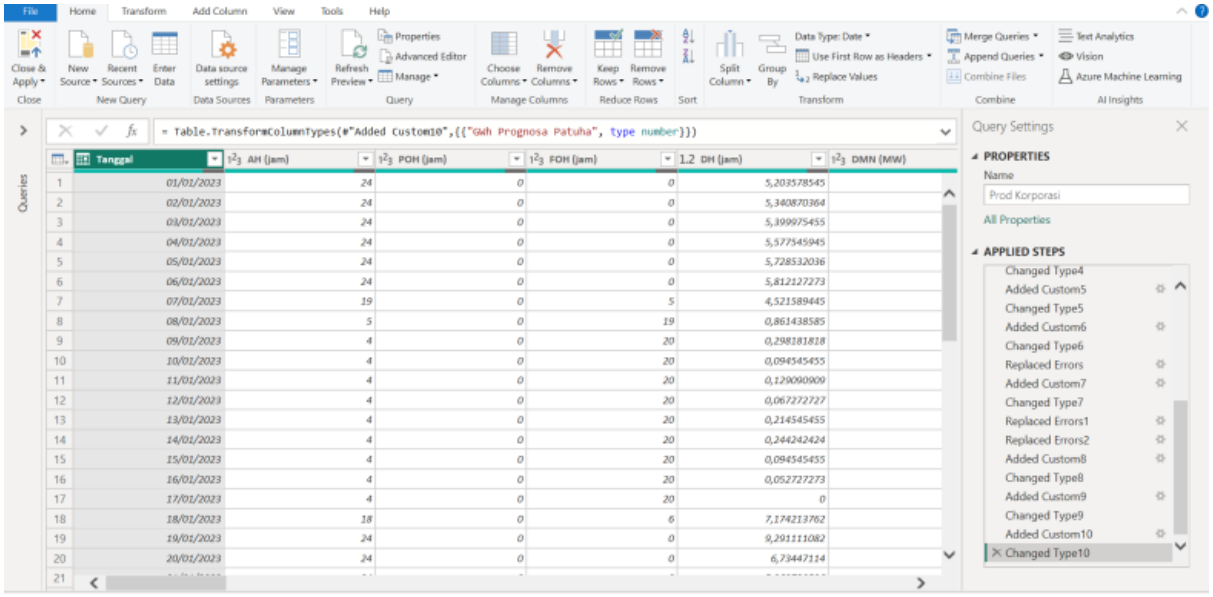
Figure 6: DBMS Platform.

Utilization of the temporary data management platform to storing the operational data might be a major issue in the future. As time goes by, the data will continue to grow that called as big data. Big data refers to data that is so large, fast or complex that it's difficult or impossible to process using traditional methods or non-robust DBMS platform. The act of accessing and storing large amounts of information

for analytics has been around for a long time. A SQL server will be a future aim in order to record operational data from both the Dieng and Patuha geothermal fields

2.4 Business Intelligence (BI) Platform Visualization

A Database is an intelligent way of organization, but may provide a limited number of operations over data. In the last decade we have witnessed an increasing use of BI solutions, which allow to query, understand and analyze data in more detail (Renewable Energy Journal, 2015). Business intelligence (BI) is a technology-driven process for analyzing data and delivering actionable information that helps executives, managers and workers make informed business decisions.



	Tanggal	AH (jam)	POH (jam)	FOH (jam)	DH (jam)	DMN (MW)
1	01/01/2023	24	0	0	5,203578545	
2	02/01/2023	24	0	0	5,340870364	
3	03/01/2023	24	0	0	5,399975455	
4	04/01/2023	24	0	0	5,577545945	
5	05/01/2023	24	0	0	5,728532036	
6	06/01/2023	24	0	0	5,812127273	
7	07/01/2023	19	0	5	4,521589445	
8	08/01/2023	5	0	19	0,861438585	
9	09/01/2023	4	0	20	0,298181818	
10	10/01/2023	4	0	20	0,094545455	
11	11/01/2023	4	0	20	0,129090909	
12	12/01/2023	4	0	20	0,067272727	
13	13/01/2023	4	0	20	0,214545455	
14	14/01/2023	4	0	20	0,244242424	
15	15/01/2023	4	0	20	0,094545455	
16	16/01/2023	4	0	20	0,052727273	
17	17/01/2023	4	0	20	0	
18	18/01/2023	18	0	6	7,174213762	
19	19/01/2023	24	0	0	9,291111082	
20	20/01/2023	24	0	0	6,73447114	
21						

Figure 7: Power Query Editor Interface.

The operational data that has already been placed in the data management platform was then transferred into Power BI desktop by connecting the web API URL. Figure 7 depicts the power query editor visualization, in which the user can change and edit the data as desired. After configuring the data in power query editor, it was ready to get started creating not only graphical charts, but also forecasting analysis on the home page of Power BI desktop. Integrated operation daily report dashboard was well-developed in this part that gathered the operational parameters from Dieng and Patuha. Prior to the completion, its local dashboard was uploaded into Geo Dipa's power BI server to create an automation scheduling refresh. Last but not least, all the stakeholders, including engineers, operators, and managements level could access anytime of the dashboard, via a mobile-app or web-browser.

In Figure 8, it was inferred that the power of the transformation process from scratch data to knowledge, which can boost quick and more precise decision-making. Data visualization with Power BI enables anyone to collect, prepare, analyze, and visualize data in minutes and help make better business decisions. Dashboards are an important visualization format that provides 360-degree-view and helps quickly gain insights.

3. RESULT AND DISCUSSION

The project team examined the present implementation of the first step of digitalization in operational Geo Dipa in terms of soft or hard benefits. Soft-benefit, defined as advantages in terms of boosting productive time and reducing the cycle time. Its matrix measurement commonly referred to time and person. Meanwhile, hard-benefit, defined as delivering added value in terms of increasing or optimizing the electricity generation (MWh). By combining a digital app sheet and a business intelligence platform, the cycle time of delivering a daily report to the management was successfully decreased by 5 times compared to using traditional file shares method. Furthermore, production optimization has been carried out in Plant 2 by Q4 2022 using a business intelligence platform.

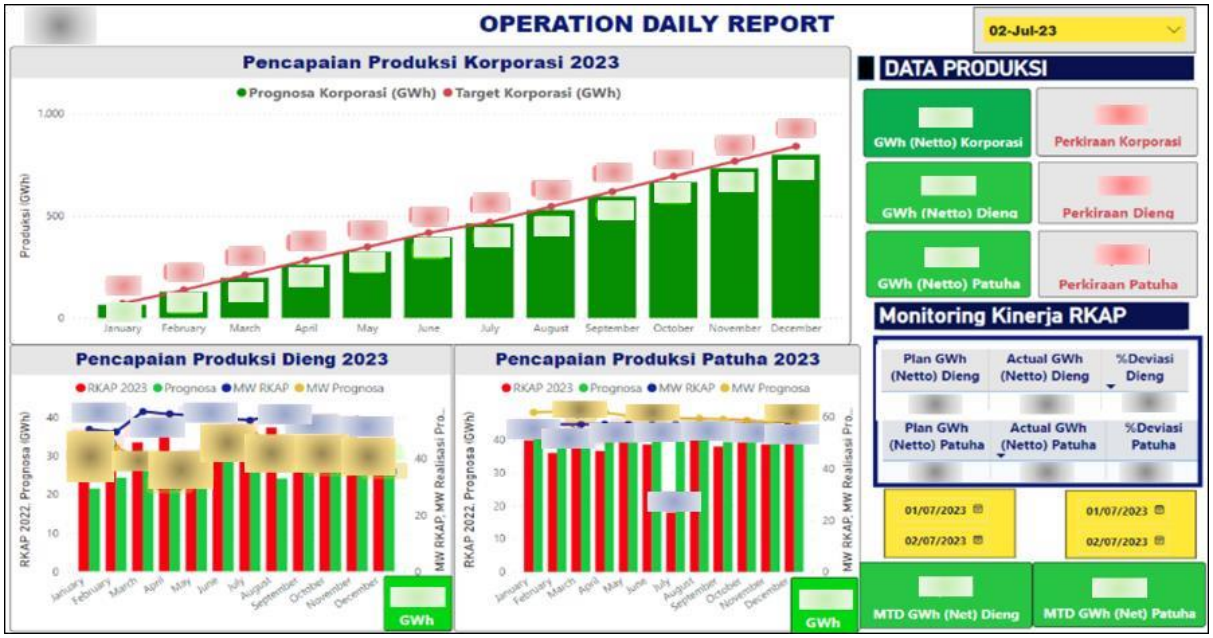


Figure 8: Integrated Operational Daily Report Dieng Patuha.

3.1 Soft-benefit Improvement

Non-Productive Time Decrease

Utilizing these digitalization tools, there were significant cut in 50% of duration spend for daily operation report process as shown in table 2. The transformation from paper-based to *Mobile Operation Logsheet* were not meant to replace the duration spend on the field, rather to cut the process of data entry entirely. While during reporting process, operators only needed to input daily operational activity. Since the process of operation parameter approval already done in Mobile Operation Logsheet, field supervisors only needed to approve the entry of operational activity in the data management platform. The most significant decrease of duration was shown by the integration of data management platform report into Power BI dashboard which decrease 90% time for Daily Operation Dashboard ready to be used by the Stakeholders.

From the Table 2, it can be shown that a 50% cycle time reduction for the entire process was accomplished. Once its improvement will be converted into another measurement i.e. soft-benefit employees cost saving, it will be equal up to $ 2,245 per month (equivalent to 33.2 million IDR per month) soft-benefit cost saving. The estimated yearly financial soft-benefit would be around $ 26,943 or equivalent to 398.7 million IDR.

Application Functionality & Usability

As Operation Logsheet deployed for both Dieng Unit 1 and Small-Scale Plants, a system usability scale (SUS) study is conducted to determine the app user interface and experience (UI/UX) from the perspective of user. The app reaches 77 of 100 score which tops 80% percentile in SUS score Benchmark (Brooke, 2013).

In the most positive interpretation of the study, the app reached 4.73 of 5 in retention (higher better). But this result was debatable since the operators were regulated to use the app. The second most positive interpretation was its functionality with a result of 4.47. While in the most negative interpretation, the app reached 2.5 of 5 on inadaptability (lower better). This result induced the management response to deploy the app into Patuha Geothermal Field while also improving its deployment process with proper procedures and knowledge bank.

In the future improvement, similar study such as Net Promotor Score (NPS) would be implemented for Centralized Data Management Platform and Business Intelligence Platform to promote continuous improvement in the business process.

Table 2: Total duration a cycle of operational daily report after improvement.

No.	Activity	Working Unit	Tools	Average Duration (h)
1	Patrol Check from Operation	**Plant 1** SF, U1, SS **Plant 2** SF, U1	App Sheet	1:00 / Working Unit
2	Approval	**Plant 1** SF, U1, SS **Plant 2** SF, U1	App Sheet	0:05 / Working Unit
Duration Spend for Patrol Data Entry / Working Unit				1:05
Total Duration Spend for Patrol Data Entry (5 Working Unit)				**5:25**
3	Reporting, includes: - Entry of Operation Activity	**Plant 1** SF, U1, SS **Plant 2** SF, U1	Data Management Platform	0:15 / Working Unit
4	Reporting Approval / Revision	**Plant 1** SF, U1, SS **Plant 2** SF, U1	Data Management Platform	0:05 / Working Unit
Duration Spend for Reporting / Working Unit				0:20
Total Duration Spend for Reporting (5 Working Unit)				**1:40**
5	Publishing Dashboard to Stakeholders	Head Office	Power BI, Corporate Mail	00:10
Grand Total Duration of Daily Operation Reporting (Plant 1 + Plant 2)				**7:15** **7 Hours 15 Mins**

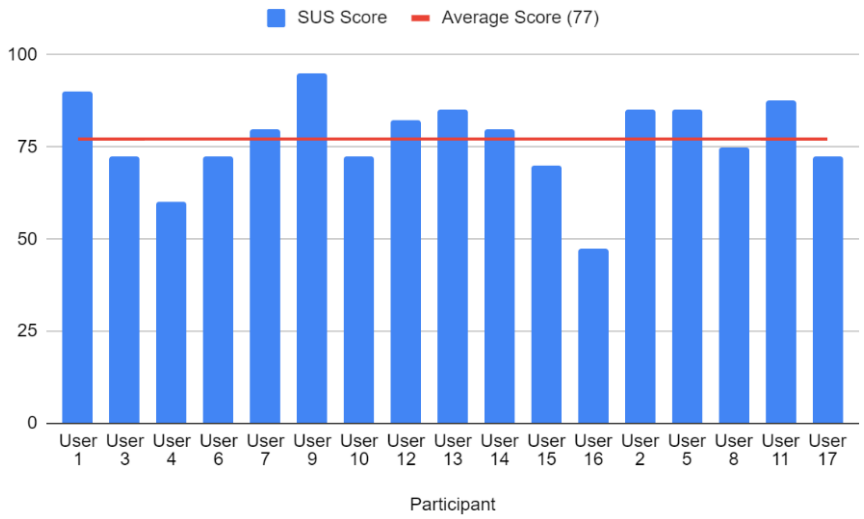


Figure 9: System Usability Scale (SUS) Study.

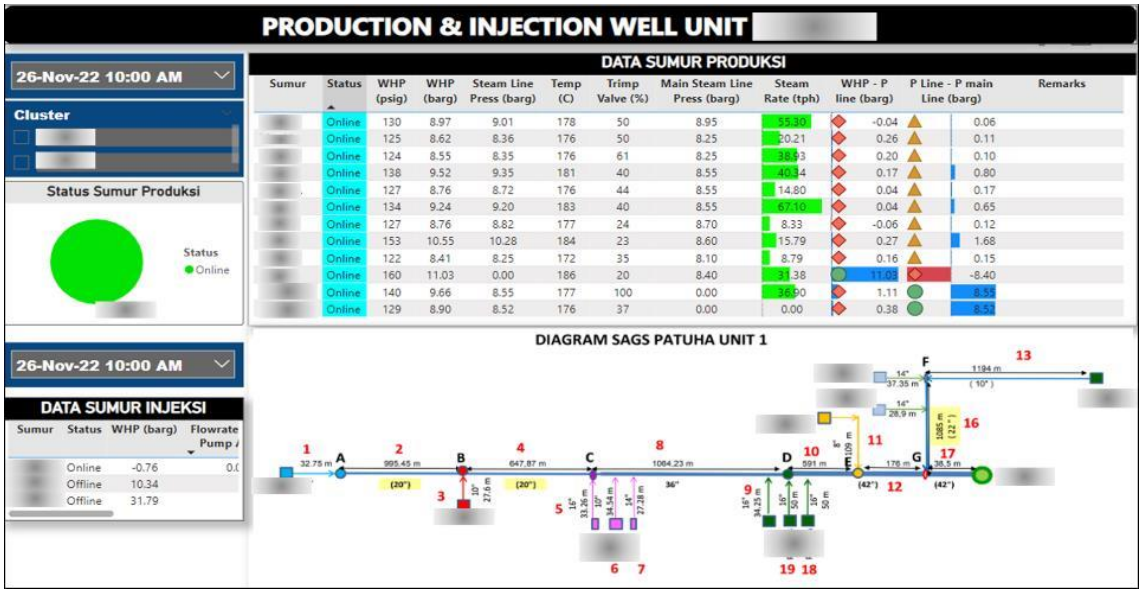


Figure 10: Production & Injection Well on Plant 2 Dashboard.

3.2 Hard-benefit Improvement

Performing Production Optimization through Business Intelligence Platform In addition, other benefits that earned by utilizing business intelligence platform was opportunity to conduct production optimization. It was such a hard-benefit improvement that increased business value by optimizing electricity output. Case study that was carried out in Plant 2, optimizing steam supply from the production wells by analyzing pressure drop among well head pressure, pressure line, and main line pressure.

After visualizing all operational steam field parameters in one integrated dashboard, managements challenged the project team to optimize the electricity production of Plant 2 by up to 60 MWh from the baseline of 58.8 MWh. To address the challenge, pressure drop analysis was performed in BI platform by gathering pressure, temperature, and steam rate data as an initialization step. Then, simplified nodal analysis was deployed in power query editor to create automatic calculating pressure drop each of steam line. A number of decisions to move some production wells emerged after grouping production wells by highest pressure drop and comparing main line pressure. After dealing with quick-win analysis, project team elaborated in deep dive with reservoir team to attempt the proposed scenario to maneuver

some production wells. The ultimate result was an increase in electricity production of more than 60 MWh, making it the largest production in the company's history. This amazing accomplishment resulted in a gain of about 2 MWh for around two months in Patuha Unit 1 towards the end of 2022, or equivalent with revenue gain up to $233,280 (equivalent to 3,4 Billion IDR).

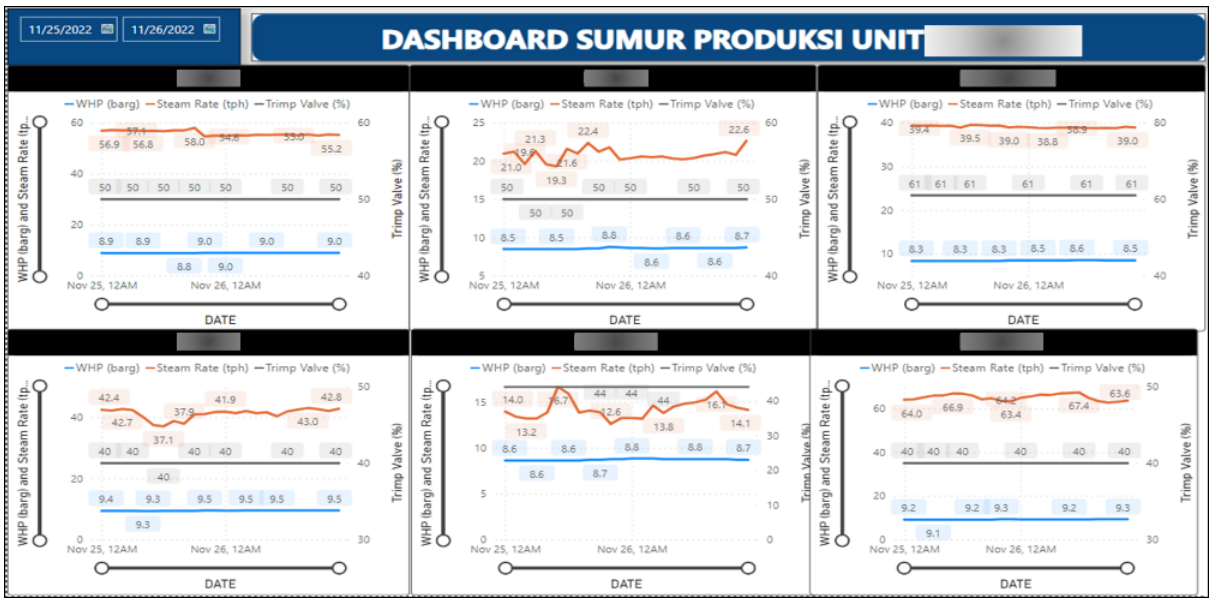


Figure 11: Trending of Production Well on Plant 2.

4. CONCLUSION

Following are the conclusions of the digital initiative for integrating operational geothermal parameters using business intelligence platform:

a. Traditional file sharing methods was the common practice of delivering all operational reports to the head quarter office. It was time consuming and still not effective yet, triggered to enlarge non-productive time both local operators and head quarter engineers.
b. Accelerating a digital initiative was performed to cut the length of cycle time of operational daily report as a main improvement metrics. Digital app sheet and business intelligence platform were the key success of the first step of digital transformation in Geo Dipa Energi which called as embryo GEOREC (Geo Dipa Energi Optimization Reliability and Efficiency Center).
c. By implementing digital app sheet and business intelligence platform, the cycle time of entire process was successfully reduced by 50% and 90% cycle time reduction for publishing report in the head quarter office.

ACKNOWLEDGMENT

The authors would like to thank the local operators and supervisor levels of working plant 1 and plant 2 for regularly inputting operational parameters into the data management platform. A special thanks was also expressed to the top management level of Geo Dipa Energi for fully supporting of this tremendous digital initiative.

REFERENCES

Argotte L. et al.: Business Intelligence and Energy Markets: A Survey, Research Institute Cuernavaca, Mexico (2009).

Bertani R.: Geothermal Power Generation in the World 2005 – 2010 Update Report, Geothermic Journal, Rome, Italy (2012).

Brennan M., and loustau P. et al: The Use of Business Intelligence Tools to Drive Asset Performance Management Improvement, Gas Machinery Conference, Pittsburgh (2017).

Brooke J.: SUS: a retrospective, Research gate conference (2013).

Hakki A., and Cenk T.: Application of Machine Learning Techniques in Geothermal Industry: A Case Study of Power Generation from a Combined Geothermal Power Plant, Research gate conference (2022).

Trumpy E. et al.: The Web-Oriented Framework of the World Geothermal Production Database: A business Intelligence Platform for Wide Data Distribution and Analysis, Renewable Energy Journal (2014).

A Remote-Diagnostics and Predictive Maintenance Solution for Geothermal Power Plants

Renato Papale[1], Roberto Parri[1], Luca Giancarlo Xodo[1], Doriano Pesenti[2], Giorgio Tori[2], Roberto Brogi[1], and Luca Giannecchini[1]

[1]Steam S.r.l. – Via Ponte a Piglieri, 8 – 56122 Pisa, PI, Italy
[2]ABB S.p.A. – Via Luciano Lama, 33 – 20099 Sesto San Giovanni, MI, Italy

info@steam-group.net, contact.center@it.abb.com

Keywords: Power Plant, Diagnostics, Maintenance, Operations, Remote Control

ABSTRACT

Converting geothermal energy into electricity is a complex process that involves a lot of skills and disciplines, from geology to thermodynamics. Consequently, the optimal operation and maintenance of a power plant requires the collection and management of a considerable amount of information.

In order to manage the information collected within the power plant, ABB and STEAM developed a solution that performs remote diagnostic and predictive maintenance of any geothermal power plant. This software is a platform able to offer utilities having a wide range of geothermal power plants, an instrument for analyzing the operating conditions that goes beyond pure control and automation logics, based on the principles of the Standardization of the measured data and the Formalization of the know-how.

"*Standardization*" means that the database generated in real time in each system is collected in a storage system (Historian), where similar engineered quantities from different sources have the same symbolic representation (TAG) within a "Library" of "Functional Units" which can describe each major component. Additionally, the behavior of such components is predicted on the basis of mathematical, thermodynamic, statistical and graphic "rules", combined with trends and algorithms. This method also allows the comparison of similar events that occurred at different times on same or different plants, providing diagnostic tools and increasing the staff's ability to recognize future warning symptoms.

"*Formalization*" means that every single “rule” is based both on physical laws, as on the construction characteristics and guaranteed performance of each component and, last but not least, on experience. The “knowledge” embedded in the system, represents the technical know-how coming from the human factor, historically matured on field during site operation. Formalization is the key to invest in capacity building of the O&M staff, to keep the worth of their experience, to transmit it to the future operators of the power plant.

1. INTRODUCTION

Geothermal power plants are considered the most reliable base-load among the renewable energy conversion facilities. The investment in geothermal energy is extremely capital intensive as compared to wind and solar photovoltaic, and the return of investment is highly dependent on the operational efficiency and effectiveness. In order to improve the average efficiency of a power plant, it needs to operate under optimum conditions at the maximum extent, and that the unavailability and/or underperformance rates due to unplanned events are reduced to a minimum. It is clear that operation and maintenance of a complex system such as a geothermal power plant requires the collection and management of a considerable amount of information.

Control and management of such a large amount of raw data pertaining the specific disciplines would be impossible for the operational staff which, for this reason, usually limit themselves to the analysis of a small subset of all the available parameters. This way of conducting supervision allows them to guarantee, at least, the safety and the continuity of the operation of the whole power plant, while the maximization of the energy produced over the time is rarely accomplished. It must be clear that the

main operating parameters generally utilized as indicators of efficiency, such as net power generated, vacuum at the condenser, and cold water temperature, are naturally variable at the same efficiency "setting" of the equipment, because they are affected by weather conditions.

Considering the challenges described hereabove, STEAM and ABB cooperated in the creation of a system, based on the principles of the *standardization* of the measured data and the *formalization* of the know-how, that can perform remote diagnostic and predictive maintenance of any geothermal power plant, with the aim of managing all the systems related to the geothermal field and power plant, obtaining maximum performance in the full range of climatic and geothermal reservoir conditions and interpreting every small symptom of degradation of the machinery to plan maintenance interventions and promptly avoid unexpected failures and damages.

This system was designed and created targeting a centralized remote supervision of any type of geothermal power plant by "decomposing" it in various systems and then in functional units, each of them having its own physical representation and a characteristic "*signature diagram*", created by correlating two characteristic quantities (measured or calculated parameters and variables), and through which its monitoring is possible. The above-mentioned "*standardization*" of each "*functional unit*" then allows to compose the actual plant connecting the different components like they were pieces of a puzzle, as shown in Figure 1. This way it is possible to pass from a general overview of the plant to the view of a system (group of equipment connected to form a section of the plant handling a specific fluid), up to the analysis of the single equipment ("*functional unit*").

The analysis (both visual and analytical) of the behavior of each single "*functional unit*" allows to support the operator in the evaluation of both its correct actual operation and the trend of a parameter leading to an alert situation much earlier than a "real" alarm. Moreover, the *alert* allows the operator to schedule the relevant maintenance work in the same period of a planned shutdown, avoiding urgent and dedicated interventions and reducing the plant downtime. The system here described, built over thirty years of experience of STEAM in the geothermal environment, is, indeed, based on both physical laws and data actually collected on field, guaranteeing a constant update on the component characteristics, and thus ensuring an actualized description.

This software is the best solution for utilities-scale companies and for geothermal plant operators that require tools to help their staff to discriminate through the high amount of data, in order to deepen their understanding in how their assets work and, finally, to track and store their experience and to transfer it through generations description by applying the above-mentioned criterion of "*formalization*".

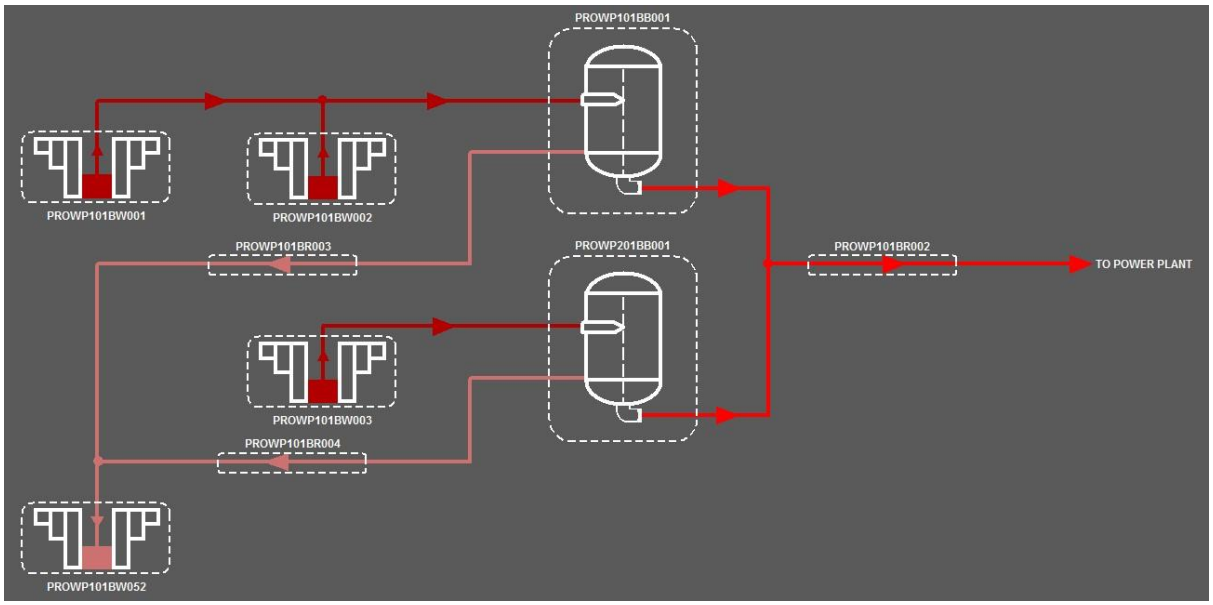


Figure 1: Example of a steamfield system.

2. DIAGNOSTIC RULES: PLANT DESCRIPTION VIA "FUNCTIONAL UNIT"

Aiming at assessing the actual operation of a plant in the project conditions, the ratio between the operating hours and the total hours in a year may not represent the correct parameter, as it is preferable to evaluate the actual production compared to the maximum energy producible in the environmental conditions experienced over the time, which is a parameter that takes into account the seasonality of a geothermal power plant process.

However, the definition of the maximum producible power is not immediate, as there are fluctuations in the key operating parameters due to the different weather conditions that influence the performance of the plant. Those key parameters are different case by case according to the characteristic of the equipment installed in the power plant. For example, if wet cooling towers are used, the operating parameters will be linked to the wet bulb temperature, while with dry coolers depend on dry bulb ambient temperature. The variations of the above-mentioned parameters will lead to different cold-water outlet temperature and, therefore, to consequent variations in the pressure of the condenser with a different resulting efficiency.

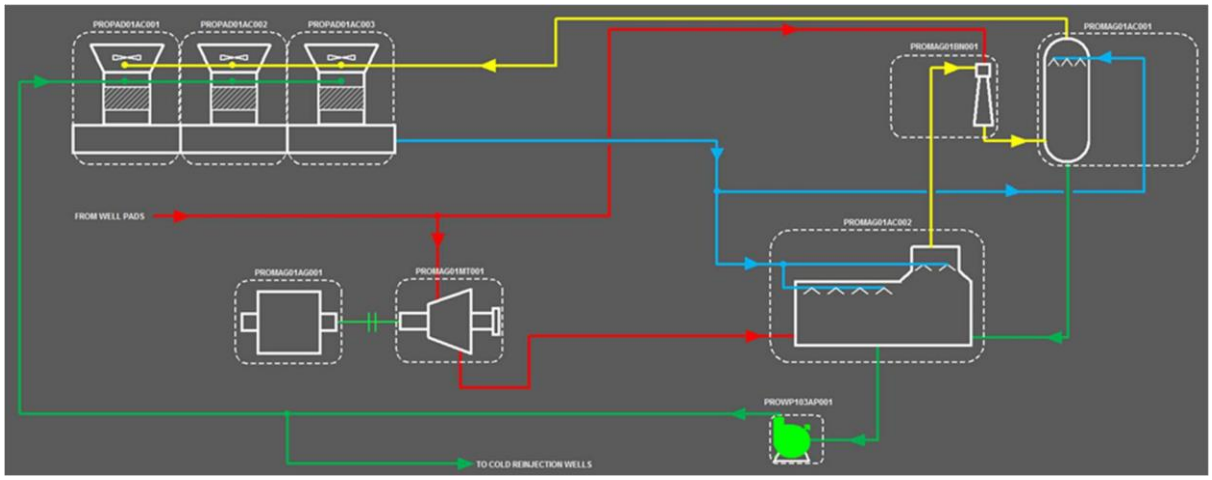


Figure 2: Example of Power Plant overall view.

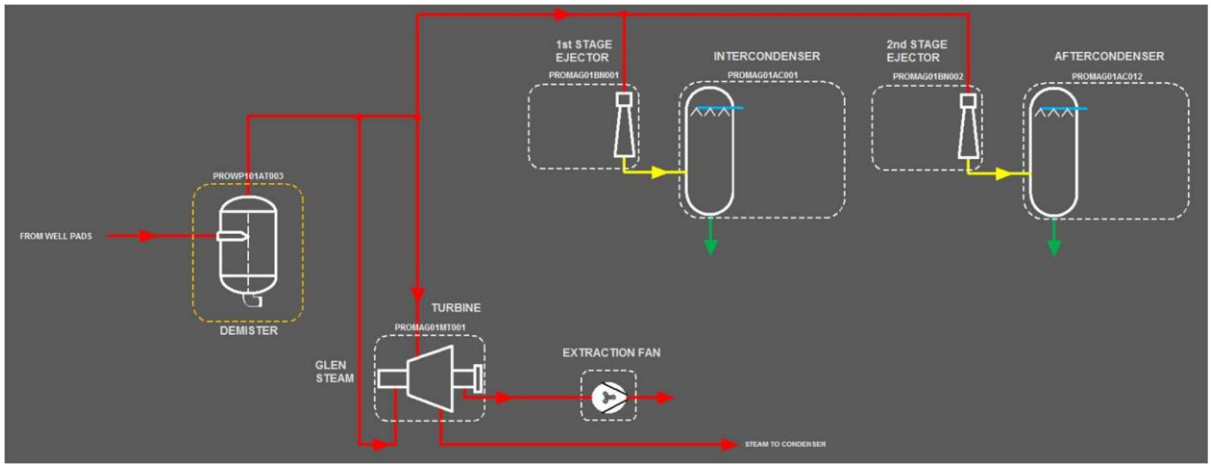


Figure 3: Example of a Power Plant system: steam system.

In order to be able to say whether the operation of the machinery is aligned to the maximum achievable performance or not, it is therefore necessary to de-seasonalize these data discriminating the differences of the production resulting from seasonality with respect to the ones due to a real loss of plant performance or to different availability. This deviation, however, is not always appreciable analyzing the system in its entirety: for example, a 10% loss of efficiency of a component that affects the production of the overall system for 15%, produces a loss of efficiency on the entire system of 1.5%; a difference that is not easy to detect since its value it is really near to the uncertainty of the various

measurements. On the contrary, detecting a 10% variation on a single component is quite easy. For this reason, it is clear that analyzing the plant just checking only the input and output parameters is not effective as the examination of each single component of which the plant is composed.

In the described diagnostic system, for the above-mentioned reasons, the decision was so to have a detailed analysis for each individual component through the creation of "*functional units*", i.e. simple blocks in which the input and output quantities are measured and in which some parameters will be selected (and calculated, if necessary) for carrying out predictive diagnostics according to two philosophies:

- Analysis of the temporal trend of each single quantity of interest and verification of any anomalous behaviors through the application of predictive algorithms that can calculate the onset time of a possible fault situation and, on this basis, trigger an alert to the operator;
- Creation of characteristic curves named "*signature diagrams*" that relate two parameters (mainly, input vs. output) of the functional unit to be examined and its analysis to verify if the points representing the more recent operating condition lay within the limits of acceptability of the graph and/or not denotate, in the latter case, that an anomalous situation is occurring.

In addition, the system allows to pass from a general overview to a more detailed one (system) in which all the equipment is shown, as noticed when comparing Figure 2 and Figure 3. As an example, in the latter demister and extraction fan can be monitored while on the general one those are omitted.

2.1 Description of a Functional Unit

As reported in the previous paragraph, the approach by functional units allows a subdivision of the analysis focused into simple units, which are individually described in general and standardized terms, and which can be composed to create any type of desired system.

Generally speaking, a functional unit is an "object" with defined inlets and outlets (characteristic of the specific unit) and which can store all the measured and calculated quantities that can completely describe the functionality of the Unit. The desired behavior, in a specific component, is often not just determined by mathematic relationships or via a physical model, but it is instead established by the user combining the data provided by the manufacturer, the experience that he has on similar components and, last but not least, from the history of the measurements carried out after each maintenance. In this way, the system can calibrate itself according to a Bayesian approach: in fact, subsequent calibrations are carried out with which, based on prior knowledge, the correct operational range of a component can be established. An example of a functional unit (condenser unit) with its characterization is reported in Figure 4.

Figure 4: Example of the characterization of a condenser functional unit.

This unit is general, and it can be used for every type of condenser: a complete set of measurements is foreseen, in addition to some parameters than can be either manually inserted or calculated (like, if needed, enthalpy, NCG fraction, two-phase flow, etc.), to fully describe the item.

In practice, in a specific project, after the decision on the type of condenser to be used is made and after deciding which measures are to be detected in the field, the parameters required for the monitoring of the specific component are selected among the complete set.

This unit will be, in fact, together with all the other functional units, a piece of a bigger and complete "mosaic", which is the plant, as shown before in Figures 1, 2 and 3.

The functional units can be arranged into groups that can compose a system, for example, a wellpad (wells, separators, pipelines, etc.), as well as the actual power plant configuration (turbine, generator, condenser, cooling towers), in order to ensure the highest possible modularity of the system.

The functional units are also structured in a way that, if there is the need to replace an equipment with another one with different characteristics or if, more generally, one equipment has to be added or removed, it can be easily done in fact the addition/removal of the unit takes with itself all the stored parameter, graph and calculation to use it in the system.

2.2 Temporal Trend Analysis

As stated in paragraph 2, one of the two diagnostic philosophies implemented in this system is the analysis of the temporal trend of a quantity, which aims to prevent any malfunctioning and plan an early intervention: this is made possible by the division in functional units of the power plant.

Unlike the analysis of the signature diagrams (which will be discussed in the next paragraph), this prediction is made on quantities featuring anomalous increasing or decreasing tendency that can lead to a damage of an equipment or to a plant shutdown, i.e. quantities which should be constant or fluctuating around a constant average value (e.g., turbine gearing vibration level, brine level in a separator, pressure drop across a valve, etc.).

The predictive algorithm will therefore take the form shown in the following Figure 5 (as an example, the algorithm for "*high value*" alert is shown).

The algorithm is based on the analysis of the linear growth that can be deducted from the study of the so-called "*moving average*", i.e., the calculation of the average value between a set of n measured variables. This value is re-calculated after every measurement.

At first, the system calculates the moving average of a fixed amount of measured variables, in order to eliminate or reduce any external disturbances in the measurement: this is done for the previous n values of two consecutive time steps, here named as t_n and t_{n+1}, to create the two couples $(t_n; y_n)$ and $(t_{n+1}; y_{n+1})$. With these two couples, the control system first calculates the incremental ratio and compares the sign of this angular coefficient as shown in the diagram. Next, with the linear growth equation, the threshold achievement time is first calculated and then compared with the threshold time limit previously fixed by the user: if the calculated one is too short for a defined number of occurrences, it means that the component is gradually going into a dangerous situation, so the alert signal triggers.

The algorithm can consider also another situation: as can be seen from Figure 5, if the angular coefficient of the linear approximation stays as zero for a certain time, the alarm triggers too. This happens because a persistent constant value could indicate a malfunction of the instrument so, the alert warns the operator that should check it and, eventually, perform the required maintenance work to the instrument.

This "alert algorithm" can prevent lots of common situations of loss of productivity by simply highlighting the trend that the moving average of a given quantity assumes over time: for example, the presence of a drift that can lead to deviations from the standard values can provide an indication of progressive scaling, or the increase in fluctuations with respect to the average value can be the beginning

of cases of instability that can lead to overstressing of the machinery, and so on. In addition, other rules can be created based on operational experience.

A system like this allows therefore to have signals at the minimum deviation of the operating parameters: this gives immediate indications of loss of efficiency or degradation of the machinery. The advance signaling compared to traditional threshold alarm systems allows the operator to be able to program targeted checks and any corrective and maintenance interventions with greater promptness and therefore with reduced interruptions and less production losses.

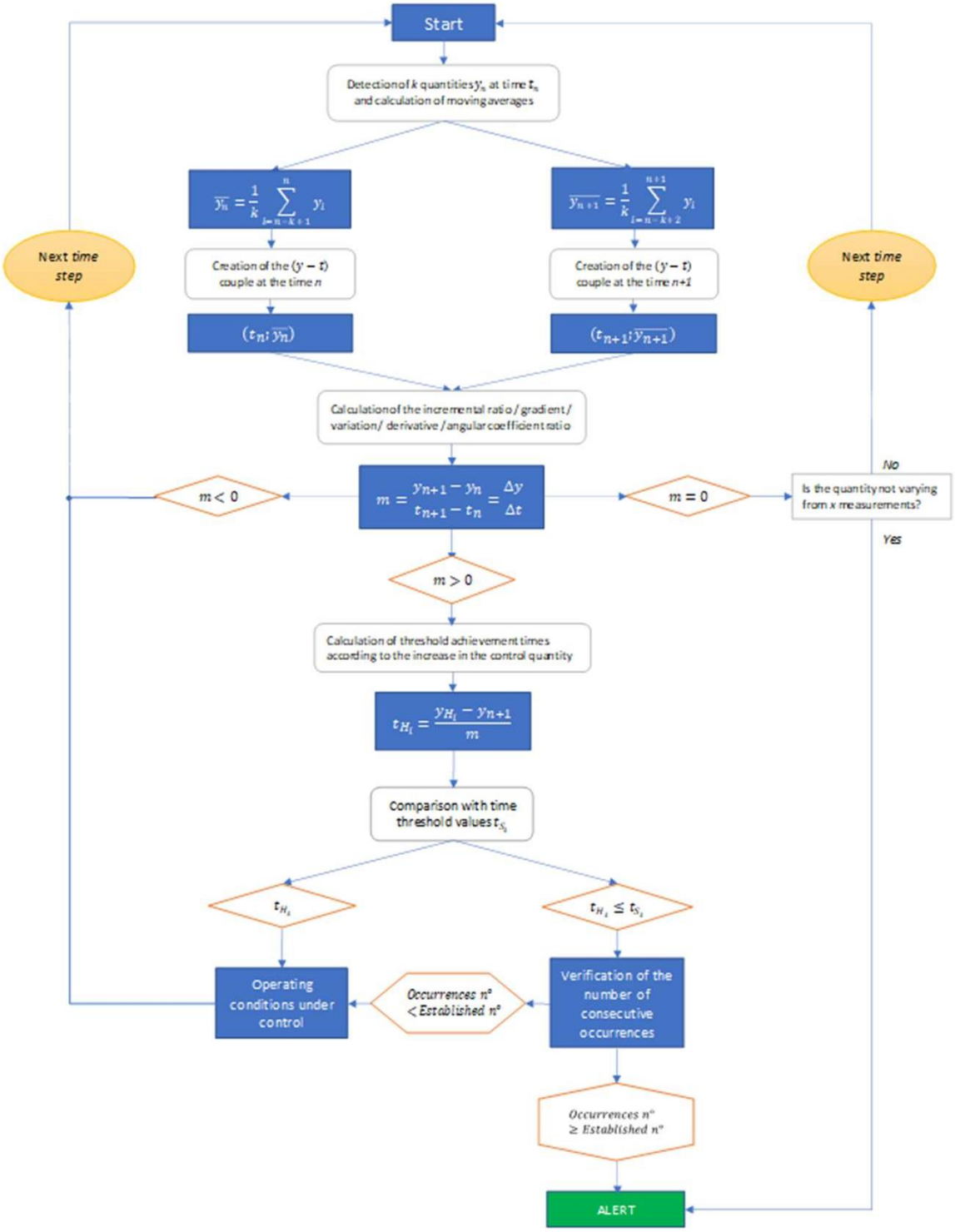


Figure 5: Predictive algorithm for "high value" alert.

For example, the measurement of vibration on a rotating machine gradually increasing can be an index of progressive scaling and is processed and treated as an indication of increasing trend. It is quite different to intervene when the vibrations are at the threshold limit, which generally requires urgent interventions with longer and more onerous machine stops, compared to making an analysis at the beginning of an anomalous vibration level that may perhaps highlight the presence of malfunctions which, if corrected, let to block the growth of the scale; alternatively, washing operations can be carried out in operation: this can be programmed and therefore efficiently performed.

Figure 6: Example of increasing level in a separator.

From this example it is therefore evident that the operation control activity focuses on some cases of true anomaly and does not disperse in routine generic controls. In this way, corrective maintenance activities can be directed. The purpose would be to have no more urgent interventions that cause production losses and additional costs but only scheduled and predictive maintenance, driven by the indications of the system.

3. DIAGNOSTIC RULES: COMPONENT DESCRIPTION VIA "SIGNATURE DIAGRAMS"

The second type of plots that will be used in this predictive maintenance system is the "signature diagrams". The operation of a single equipment can be simulated developing a mathematical model that represents it and that allows to establish the relationships between different characteristic quantities of that equipment. Those calculated quantities will be compared, during the test at the start-up of the plant, to the actual values using the actual measured parameters.

In this phase, the behavior of all the components are analyzed and correction actions are implemented to set all the units at their optimized conditions and in such a way that the system performs at his best.

The actual parameters measured in that optimal working status are not, in general, exactly the ones calculated during the design phase, but some differences are registered because each equipment is incorporated in a specific plant and has its particular behavior. This means that each plant, even if it is of the same type of another, cannot be treated such as an identical one, and that the equipment composing it, in the same way, works according to a specific and unique behavior due to the fact that there are interactions between different components that are not easily predictable or simple to be modeled.

Once this setting has been completed, it means that all the equipment is working according to its optimized conditions and that status will be taken as reference for the subsequent diagnostic analysis.

In order to do that, it is necessary to memorize those conditions in order to be able to verify that during the life of the plant each component and the plant as a whole are working at their best performances, so following its characteristic way or signature.

The ability to record it is reached by creating the so-called "*signature diagrams*" that are graph correlating two quantities following a specific trend.

During the operation, the actual points positioned using the measured or calculated quantities, are be displayed on the diagram in the form of a point cloud, with the last ones viewed in a different color to highlight the evolution of the operation of the equipment and to check if it is departing from its signature.

In fact, the relation of those quantities shall maintain the same rule i.e. each point representing, time by time, its condition shall stay on the curve over time. If this does not happen, it means that there is something wrong, as the comparison is between the performance of the equipment with the actually tested conditions and not with the ones resulting from a theorical model.

Using a medical parallelism, this graph could be compared to an electrocardiogram: as everyone has its personal electrocardiogram, each equipment has its own signature graph that represents its behavior in this specific plant.

The selection of those two quantities is a key choice because it shall represent clearly the most important characteristic of the working of the equipment under investigation in a way that, if the actual point does not lay on the curve, it will be possible to suppose the reasons of its anomalous operation.

The adoption of those diagrams allows to de-seasonalize the behavior of some components. In fact, as explained before, the geothermal power plants performance is affected by the weather conditions and there are some quantities that cannot be fixed all over the year, but the evaluation of the optimal condition cannot be done comparing this quantity to a unique set point.

The analysis foresees a comparison between this parameter and the value calculated in the same weather conditions. For example, the change of the outlet cooled water in a wet tower is connected to the wet bulb temperature, so the evaluation of the performance of the cooling tower cannot be done just checking that outlet temperature but verifying, according the relevant signature graph, if that outlet temperature is the one corresponding to the actual wet bulb temperature.

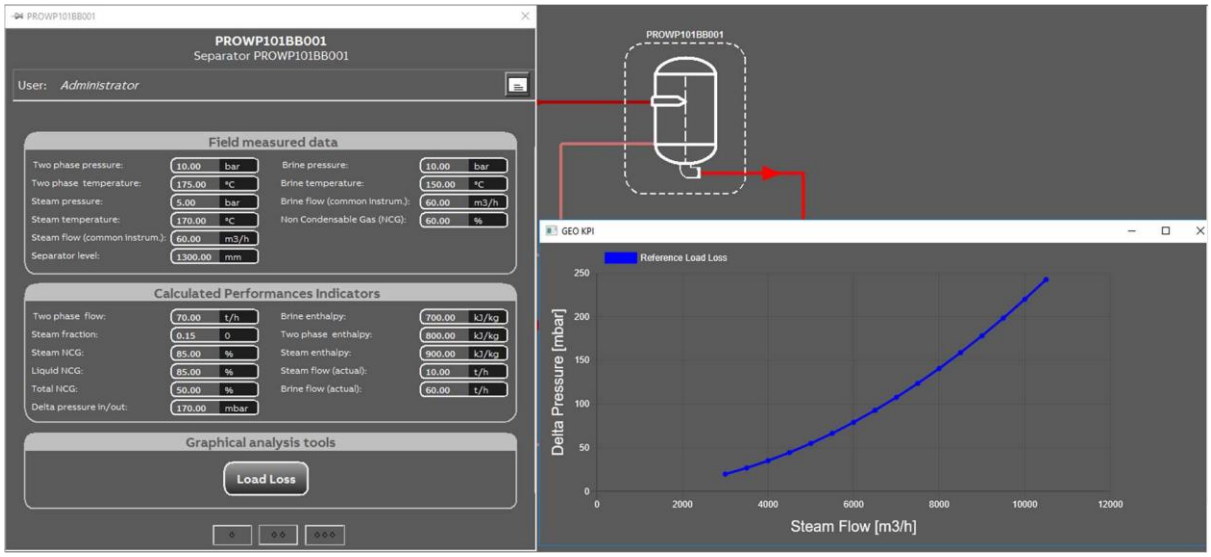


Figure 7: Separator functional unit with signature diagram.

As example, a steam-liquid separator can be taken: one of the possible signature diagrams is the relation between the steam flow rate and the pressure drop across it. It is clear that, for a separator with given geometry and with a defined flowrate, the pressure drop will result consequently. In case, for the same

flow rate, the pressure drop rises, means that an obstruction is building up, like for example the one caused by a growing scaling in a valve.

This simple example can give an idea of another important feature of this diagnostic tool, that is to detect an anomaly that will, later, cause a real problem or, in the worst case, a shutdown of the plant. In fact, the pressure drop rise due to a scaling phenomenon is a slow process and having the information of this deviation in time, much earlier that it will cause an alarm, it allows to understand which corrective action has to be taken and to plan a maintenance work, maximizing the availability of the whole system. In this sense, it is the key tool of the predictive maintenance.

According to the importance or the complexity of the equipment, more than one signature diagram can be created. For example, for the main condenser, that for the geothermal power plant is usually a direct contact type, different signature diagrams can be created, i.e. temperature difference between outlet gas and cold water inlet as function of the cold water flow, or exhaust turbine pressure as function of non-condensable gas flow rate, and so on. The first of them, allows to verify if the water distribution on the nozzle is homogeneous so that the gas is enough cooled down or not while the second can alert if the enthalpy drop in the turbine is far from expected.

Up to now, the analysis of a single equipment has been considered but, on the other hand, its performances are connected to the presence of the other equipment composing the plant. In this regard, it can be found a system to monitor simultaneously the operation of the main equipment present in the power plant by comparing their signature diagrams. For example, it is possible to read consecutively two specific signature diagrams of cooling tower (temperature of the cooled water temperature vs. wet bulb temperature) and gas extraction systems (non-condensable gases temperature vs. condenser pressure): cooled water temperature and non-condensable gases temperature are indeed related by the *condenser approach* parameter, therefore by comparing these measured values read by these diagrams it is possible to verify if the design approach is satisfied or not.

Another example is a heat exchanger: this component is prone to scaling, and, for that reason, it is crucial to monitor its operating conditions to verify if its efficiency is kept constant or not.

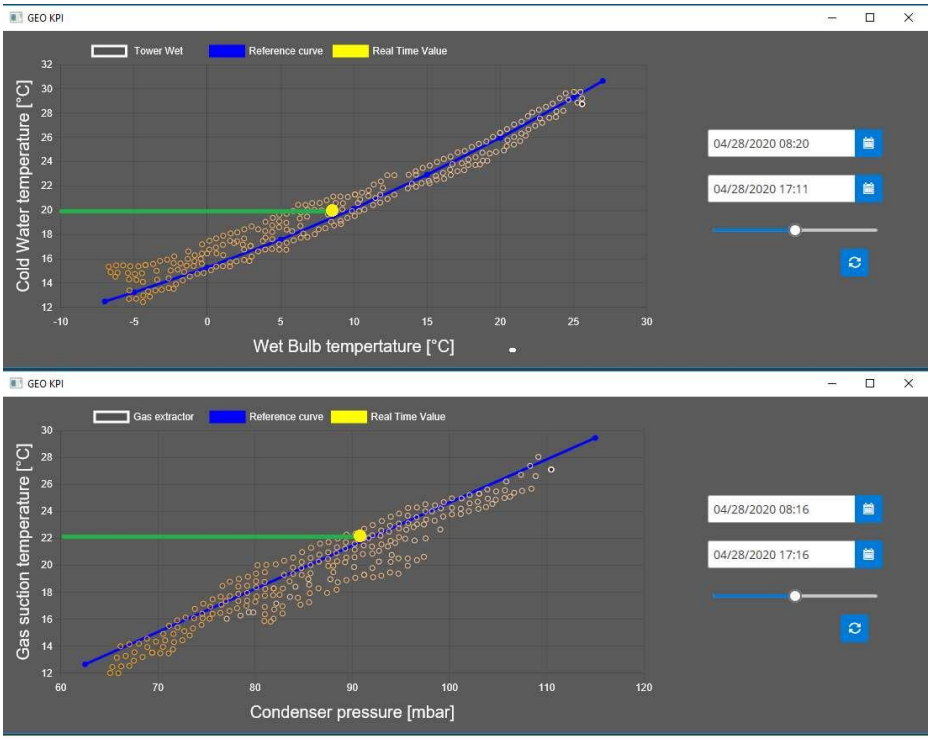


Figure 8: Cooling tower and gas extraction systems signature diagrams comparison for the "condenser approach" evaluation.

The operation of this kind of equipment is, mainly, function of 6 parameters: the inlet and outlet temperature of the fluids and their flowrates.

If, in the plant, all the temperature sensors are available, the diagnostic system is able to calculate the *logarithmic mean temperature difference* (also known as LMTD) and, if there is also a flow meter on, at least, one of the two fluids, it is possible to calculate the heat exchanged:

$$Q = M \cdot c_p \cdot \Delta T \tag{1}$$

where Q is the exchanged heat, M is the mass flow rate, c_p is the specific heat and ΔT is the difference between the inlet and outlet temperature of one of the two fluids.

It is, in addition, possible to calculate the global heat exchange coefficient U of the equipment, using the well-known heat exchange equation:

$$Q = U \cdot A \cdot LMTD \tag{2}$$

where

A is the exchange area, that is a knew and constant datum.

Rearranging the two equations above, it is possible to find the expression of the global heat exchange coefficient as function of the flow rate M:

$$U = \frac{M \cdot c_p \cdot \Delta T}{A \cdot LMTD} \tag{3}$$

The graph for U as a function of the M built using the data measured when the heat exchanger is new (i.e., clean, so working at its best conditions) shows a curve that is almost linear (it is not exactly a straight line because the heat exchange coefficient is not constant for the different conditions tested). This is one of the possible signature diagrams for this equipment.

In Figure 9 this graph is shown for a liquid-liquid shell and tube heat exchanger. In order to make this analysis feasible, it is important to choose correctly the flow to be analyzed: in this case it is the one flowing in the shell because it has the lower velocity so changing it, the influence in the U is detectable. Using the same data and taking as reference the flow of the fluid in the tubes, the data are scattered in the plane and not aligned.

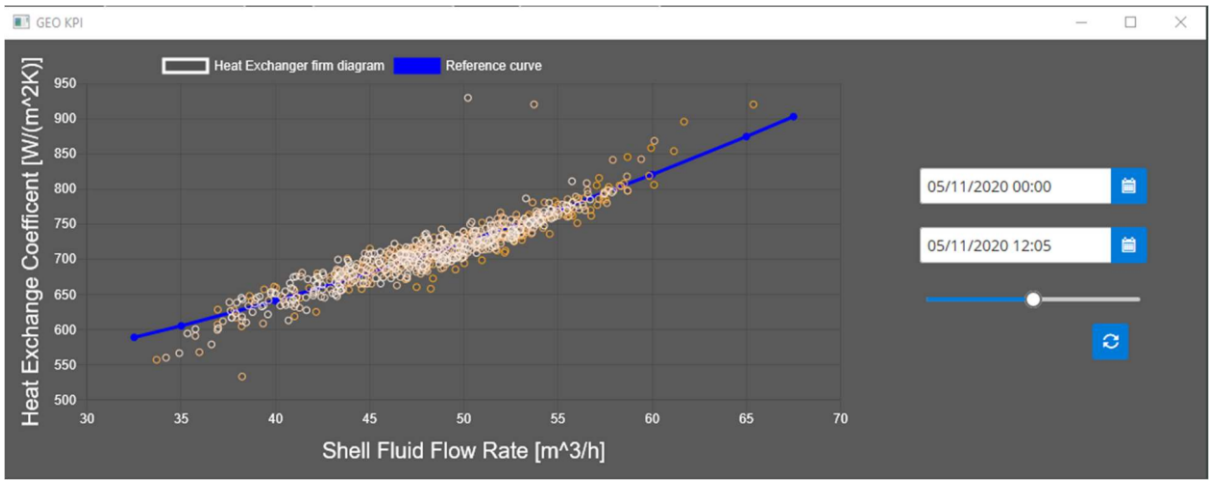


Figure 9: Heat exchanger signature diagram.

In general, it is important to select the limiting parameter that affect significantly the heat exchange coefficient.

If, during the equipment operation, the registered data proceed far from the point indicated by the described signature diagram, it means that that heat exchanger is no more working at its optimal conditions. The most probable cause of it, as previously written, is that scaling is forming in the heat exchanger, so the heat transfer coefficient is decreasing. The monitoring of that kind of plot allows to detect this phenomenon earlier than it can be perceived by a normal supervision control systems and so it allows to plan a maintenance work prior than the equipment performance will create problems for the plant process best Operation.

It is important to remark that the power of this method is that those rules are not fixed but taking advantage of the experience of the operator on the specific plant, it will be possible to add some signature diagrams to put under control particular parameters that over time have proven to be critical.

4. PLATFORM DESCRIPTION

The Geothermal Power Plants solution for remote-diagnostic and predictive maintenance is based on ABB Ability Symphony Plus (S+) platform composed of S+ Operations HMI and S+ Engineering workbench.

The platform boasts a consolidated history with over 4000 installations worldwide, mainly as DCS in the production of conventional electricity but also as SCADA in the world of renewable energy and remote control of plants distributed over vast geographical areas with critical telecommunication situations such as satellite which highlights the strong reliability.

Its high flexibility and scalability added to all the native and integrated components make it adaptable to the most different applications that benefit from all the embedded features.

The platform can be implemented in different configurations from a single server, serverless, standard client-server, multi-level with fault tolerant redundancy *1...n* at every level with standalone, composite, or aggregate database. Therefore, it can easily interface with existing systems for the sole acquisition of data useful for its purpose or be integrated as a plug-in that allows the addition of plant control.

In addition, its centralized object oriented, multi-user workbench engineering for applications deployment and management simplifies design and maintenance.

The centralized long-term Historian aggregates all data in a unique database for analysis and exposure via all common connectors and dedicated web interfaces, based on latest technologies, without software installation in any desktops or tablets just by browser.

Platform natively offers wide range of proprietary and standard drivers to collect data from existing systems with store & forward capabilities; API for any type of communications, data acquisition and synchronization between sites are also available with full capabilities and secure access at all levels and components.

Seamless integration of thousands of intelligent devices, instruments, remote sites with inherent system security ensures plant integrity and confidentiality directly to the platform or via edge computing, remotely configurable, for data treatment close to the source.

High performance graphics customizable HMI with advanced alarm management and integrated GIS, maps vendor independent, allows for cross-platform and spatial navigation and direct object aspect link to any controlled or monitored device. All displays are automatically available via full web-based interfaces multiplatform, also mobile smartphone apps available with secure protocol encryption and user access control, and also allows high user management with distributed control & monitoring privileges for applications areas jurisdiction assignment.

The platform integrates the calculation package and the information management system to optimize business decisions with drag and drop trends configuration, intuitive data navigation and advanced trending capabilities for immediate analysis, automatic reports generation, IT corporate applications links, advanced alarms & events management.

Seamless integration of wide range of digital solutions, available on prem or cloud, for performance monitoring, integrated assets health platform, advanced process control at plant level, helps to improve plants optimization for asset lifecycles and energy efficiencies, reliability, and productivity enhancement.

The Geothermal Power Plants solution is object oriented designed: a library of functional units is available for all plant components (turbine, alternator, tower, condenser, pump, etc..), each of them composed by standard database and related graphic symbol and faceplate objects to be instanced based on site layout, and populated thanks to the platform high connectivity capabilities.

A set of specific trends for the digital signatures representation of the various plant devices automatically retrieve data from the long-term historian and visualize the working status deviation from configurable linear curve.

The integration of standard thermodynamic functions in the powerful calculation platform C# environment lets the engineering add any kind of algorithm to the available base.

All graphics objects have been designed following the high-performance standards in terms of shapes, colors, navigations, etc. to improve the user experience; colors are one click configurable with logical colors implementation.

5. CONCLUSION

This Geothermal Power Plants solution is meant for Operators and Utilities active in geothermal power generation, regardless the number of production wells: the principles of the system and the achievable benefits are applicable for a single plant as well as for a fleet of plants.

Thanks to the openness and flexibility of ABB S+ platform, the system can be on-premise, distributed through remote connection in a large geography, cloud-deployed or a mix of all these techniques to accommodate the optimal architecture.

Any type of plant and any type of automation, unmanned or totally manually operated, even built in very different times and very dis-homogeneous can be integrated into the system thanks to a wide variety of communication protocols and IoT connectivity.

Main advantages delivered by the system:

- Considering average MWh cost, even with a small yearly production improvement of e.g. 1%, ROI can be achieved in short time (between 6 months to 1 year).
- The “standardization” of components allows easy modelling of complex plants and simple comparison among their different behaviors, in different times and de-seasonalized.
- The “formalization” of process-rules allows embedding of know-how into the system for historical memory and transfer to new generations of operators.
- Huge amount of data acquired by the system from multiple sources are aggregated and consolidated into digital information, thus providing operators with focus on important events.
- Fault prediction increases plant availability by means of early detection of possible failure, thus allowing to schedule maintenance activities during normal plant shutdown.
- Failure can be monitored at the level of single functional unit or as the result of interaction of multiple units, with the possibility of identifying early deviations in slow processes.

The adoption of the state-of-the-art ABB Symphony Plus platform delivers further value:

- S+ platform can be extended vertically, with its DCS hardware components, providing full automation for any type of geothermal plant.
- Various “digital” add-ons are available, including Vibration Monitoring system for rotating machine equipment (e.g. turbine, generator), complete “asset management” for BOP equipment (e.g. pumps, valves, motors, switchgears, transformers etc.).

- Possibility to perform remote diagnostic, anytime, anywhere, thanks to the platform data publishing capabilities, virtual control room view, with less physical intervention on sites.
- Multi-utility customers, having plants in other renewable / conventional power generation areas (i.e. hydro, solar PV, solar CSP, wind, fossil power, W2E, biomass), can extend the geothermal Predictive-Maintenance solution to cover the entire spectrum of their production fleet, with similar "predictive/asset maintenance" solution in each power generation sector.

REFERENCES

ABB "ABB Ability™ Symphony® Plus – SIMPLE, SCALABLE, SEAMLESS, SECURE™, https://new.abb.com/control-systems/symphony-plus.Coulson, L.M., and Richardson, K.F. "Coulson and Richardson's Chemical Engineering – Volume 1: Fluid Flow, Heat Transfer and Mass Transfer", *Butterworth – Heinemann* (6th ed. 1999), Chapter 9.

Dengo, J., Papale, R. "Remote Control of Geothermal Plants", *Geothermal Resource Council* (2001).

Di Pippo, R. "Geothermal Power Plants: Principles, Applications and Case Studies", Elsevier (2005).

Parri, R., Magrini, M., Montomoli, S. "Geothermal power plants in Italy: increasing the technological performance", *European Geothermal Congress* (2013).

Application of Drone Technology in Topography Mapping – Case Study at Star Energy Wayang Windu

Adityaputera W., Fajar H., Toto J., and Mochamad R.

Star Energy

adityaputera.wirawan@starenergy.co.id, fajar.hartanto@starenergy.co.id, tjey@starenergy.co.id, wwfac.civilinspector@starenergy.co.id

Keywords: Drone, Photogrammetry, Topography, Geothermal, Surface Infrastructure and Facilities

ABSTRACT

Drone technology has been used in Star Energy Geothermal Working Area (WKP) for the past 10 years, however its use is more often used to document operation and construction activities through photos and videos. Alternatively, with photogrammetry techniques, aerial images captured by drones can be used to produce topographic maps. To support the wider use of drone mapping, the accuracy of the topographic maps produced by drones must meet the criteria for large-scale maps. This paper has the purpose of testing the accuracy of a topographic map produced by processing aerial images taken with a drone regarding its application for planning construction projects.

In the development of surface infrastructure and facilities in WKP, topographic maps serve as the basic data for the Department of Engineering to able to plan the technical and capital requirements of site locations, such as power plants, wells, roads, and pipelines. Large-scale topographic maps from 1:50,000 and larger are required to allow for detailed site measurements.

Topographic maps are generally produced through terrestrial or land survey by contractors. Although land surveys can produce large-scale topographic maps with high accuracy, it usually takes about 1 month to collect and process field data for 10 hectares at a cost of between Rp 5 million and Rp 10 million per hectare depending on the survey location. It takes a company's financial resources that are quite large to carry out a land survey that covers the entire geothermal working area which can reach thousands of hectares. Thus, the need for topographic maps tends to follow the number of projects undertaken during the geothermal working areas contract period.

The aerial survey with drone DJI Phantom 4 Pro V2.0 and Post Processing Kinematic (PPK) method was carried out by utilizing the Company's internal resources which include personnel and equipment. It took less than 1 weeks to collect 199 aerial images and process them into a topographic map that covers an area of 34 ha within Wayang Windu Power Plan. Then, a geometric accuracy test was computed referring to the Regulation of Geospatial Information Agency of Republic of Indonesia No. 15 Year 2014 and No. 6 Year 2018 concerning Technical Guidelines for Basic Map Accuracy. The test results show that the resulting topographic map meets the large-scale category with standard accuracy for map 1:10,000.

Drone mapping enables the Company to produce large-scale topographic maps in a shorter time at a potentially lower cost than land surveys. However, due to weather and vegetation constraints, the drone interpretation images result may not be accurate as land survey. Therefore, it is not intended to completely replace land surveying for detail design.

1. INTRODUCTION

A drone or known as Utilization of Unmanned Aerial Vehicle (UAV) is a vehicle that is equipped with a flight control system through waves, precision navigation (Ground Positioning System (GPS)), and electronic flight control so that it can fly according to the flight plan both of manual or autopilot. This drone makes it possible to track the position and orientation of sensors implemented in local or global coordinate systems.

Drones has begun to be used within the past 10 years at Star Energy Geothermal Working Area (WKP). However, drones more often used to obtain aerial documentation photos or videos to support operations and construction activities. Drones also use for visual monitoring of area that potentially have geohazard risky, because drones can fly over challenging terrains and reach areas that are otherwise inaccessible, traditional methods of visual monitoring, such as ground surveys can be time-consuming and dangerous.

Drones, on the other hand, can cover large areas quickly and provide high-resolution images completed with GPS (Global Positioning System) information, with photogrammetry techniques, aerial images captured by drones can be used to produce topographic maps. By utilizing Company's drones and personnel, some topographic map was produced serve as basic data for the Department of Engineering to be able to plan the technical and capital requirements in the development of surface infrastructure and facilities in WKP, such as power plants, wells, roads, and pipelines. Large-scale topographic maps from 1:50,000 and larger are required to allow for detailed site measurements.

Topographic maps are generally produced through terrestrial or land survey by contractors. Although land surveys can produce large-scale topographic maps with high accuracy, it usually takes about 1 month to collect and process field data for 10 hectares at a cost of between Rp 5 million and Rp 10 million per hectare depending on the survey location. It takes a company's financial resources that are quite large to carry out a land survey that covers the entire geothermal working area which can reach thousands of hectares. Thus, the need for topographic maps tends to follow the number of projects undertaken during the geothermal working areas contract period.

To know accuracy level of the topographic map produced by this drone, we will make a test by compare the topographic map from drone survey with existing topographic map obtained by conducting a terrestrial survey in the same area of case study locations as the baseline. By knowing the accuracy level of the topographic map, we can determine how far we can use this map in applications for planning construction projects.

2. METODOLOGY

2.1 Aerial Survey

The aerial survey with drone DJI Phantom 4 Pro V2.0 and Post Processing Kinematic (PPK) method. PPK is GPS correction data technology conducted after the data collection of aerial photos is completed, the correction process must be applied with appropriate software. The PPK drone will fly together with the PPK GNSS receiver which functions to collect data from satellites and record them for data retrieval needs after the flight.

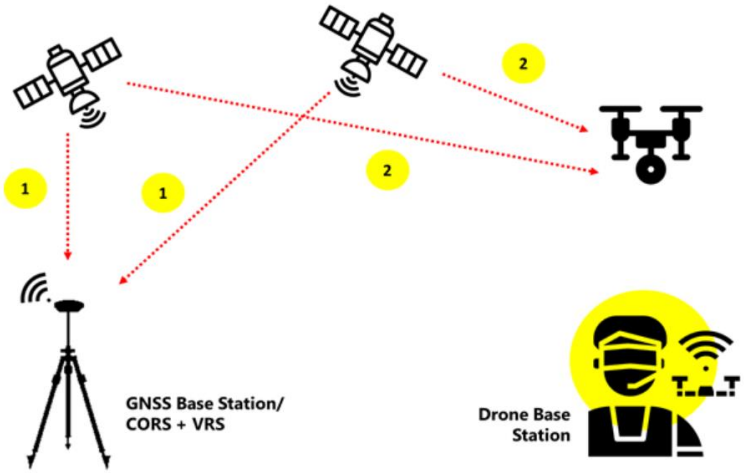


Figure 1: Post Processing Kinematic (PPK) process.

Information:
1. The line between the satellite and the GNSS base or CORS network
2. The line between satellites and drones

In this paper the data used is aerial photo data obtained from trials with flight height 150 meters. One coordinate benchmark as a GCP (Ground Control Point) for reference point and some ICP (Independent Check Point) as a test point.

2.2 Geometry Accuracy Test

Geometric accuracy test was computed referring to the Regulation of Geospatial Information Agency of Republic of Indonesia No. 15 Year 2014 and No. 6 Year 2018 concerning Technical Guidelines for Basic Map Accuracy. To classify geometric accuracy of produced map, refer to geometric accuracy standards of the RBI Map (Topographical Map of Indonesia) shown in the table below.

No	Skala	Interval Kontur (m)	Ketelitian Peta RBI					
			Kelas 1		Kelas 2		Kelas 3	
			Horisontal (CE90 dalam m)	Vertikal (LE90 dalam m)	Horisontal (CE90 dalam m)	Vertikal (LE90 dalam m)	Horisontal (CE90 dalam m)	Vertikal (LE90 dalam m)
1	1:1.000.000	400	300	200	600	300	900,0	400
2	1:500.000	200	150	100	300	150	450,0	200
3	1:250.000	100	75	50	150	75	225,0	100
4	1:100.000	40	30	20	60	30	90,0	40
5	1:50.000	20	15	10	30	15	45,0	20
6	1:25.000	10	7,5	5	15	7,5	22,5	10
7	1:10.000	4	3	2	6	3	9,0	4
8	1:5.000	2	1,5	1	3	1,5	4,5	2
9	1:2.500	1	0,75	0,5	1,5	0,75	2,3	1
10	1:1.000	0,4	0,3	0,2	0,6	0,3	0,9	0,4

Figure 2: RBI map geometry accuracy.

The accuracy value in each class is obtained from as shown in the table below.

Ketelitian	Kelas 1	Kelas 2	Kelas 3
Horisontal	0,3 x bilangan skala	0,6 x bilangan skala	0,9 x bilangan skala
Vertikal	0,5 x interval kontur	1,5 x ketelitian kelas 1	2 x ketelitian kelas 1

Figure 3: RBI map geometry accuracy provisions by class.

RBI map geometric accuracy values in Figure 2 are the CE90 for horizontal accuracy and LE90 for vertical accuracy, which means that the position errors do not exceed these accuracy values with a 90% confidence level. CE90 and LE90 values can be obtained by using formula referring to United States National Map Accuracy Standards as follows:

$CE90 = 1.5175 \times RMSE_r$
$LE90 = 1.6499 \times RMSE_z$

With:
$RMSE_r$ = Root Mean Square Error on x and y axis (horizontal)
$RMSE_z$ = Root Mean Square Error on z (vertical)

Positional accuracy testing refers to the difference in coordinates (X, Y, Z) between the test points on the image or drone map and the location from the test point on the ground surface (terrestrial survey map). Measurement accuracy using root mean square error (RMSE) or circular error. RMSE is used to describe position quality including both of random and systematic errors. The RMSE value is obtained through the equation:

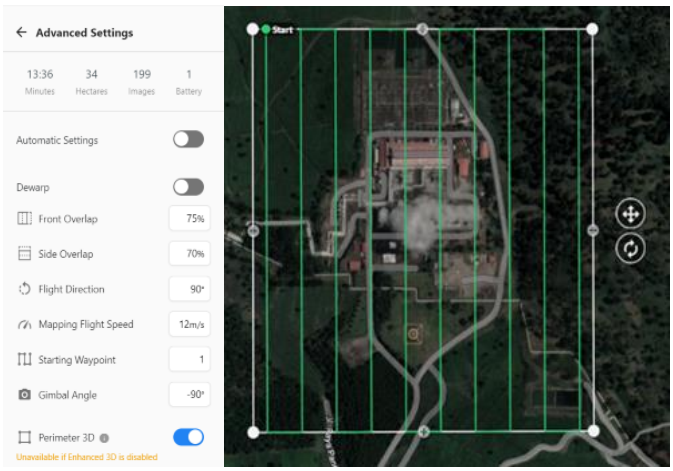
$$\text{RMSE}_r = \sqrt{\frac{\sum((\Delta_r)^2)}{n}}$$

$$(\Delta_r)^2 = \sqrt{\Delta x^2 + \Delta y^2}$$

$$\text{RMSE}_z = \sqrt{\frac{\sum((z_{data} - z_{cek})^2)}{n}}$$

Information:
n = total number of test point on the map
Δ_r = deviation value between field coordinates and orthophoto map coordinates
Δx = deviation value on x axis coordinates
Δy = deviation value on y axis coordinates
z = z coordinates value

3. DATA ACQUISITION AND PROCESSING



Flight plan

Drone Equipment & PPK

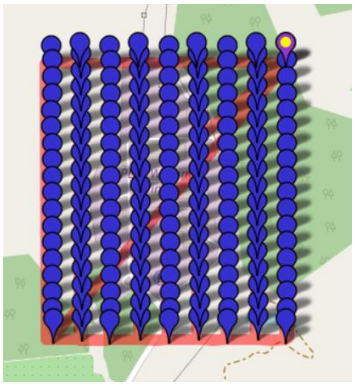
Independent Check Point (ICP) & Ground Control Point (GCP)

Drone flight operations activity

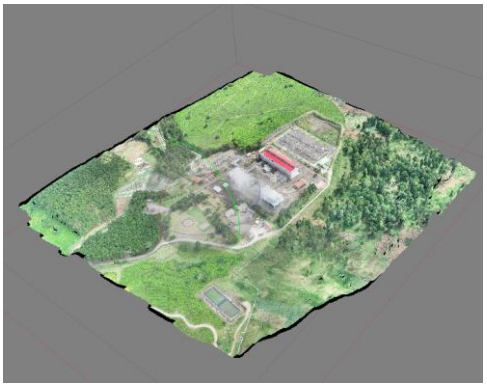
Figure 4: Flight plan and data acquisition at the field.

The aerial survey with drone DJI Phantom 4 Pro V2.0 and Post Processing Kinematic (PPK) method was carried out by utilizing the Company's internal resources which include personnel and equipment. The first step of data acquisition is to determine the target area depending on the need of the project, after that the flight plan shall be developed to cover all target areas. Other important things during determining a flight plan are to set up the number of photos, flight height, flight time, battery requirement, and route. After the flight plan is ready the second step is operating the drone and the PPK tools i.e., GPS at the base and GPS at the drone. Before the flight, need to make sure the drone battery

is enough to complete the flight plan and the PPK tools are ready to record the flight plan. The PPK base needs to be installed at the identified benchmark as a GCP. The benchmark coordinate value will be used at the post-processing stage to do corrections for drone photos data. To check the accuracy of the drone image result, some ground control points were installed at the site. When the drone is ready to fly, the operator must keep watching the drone operation even if the drone becomes autopilot while taking the photo data using the flight plan. Sometimes the connection between the drone and the remote become lost due to frequency issue. Figure 4 shows Flight plan, tools, Equipment, and data acquisition at the field.

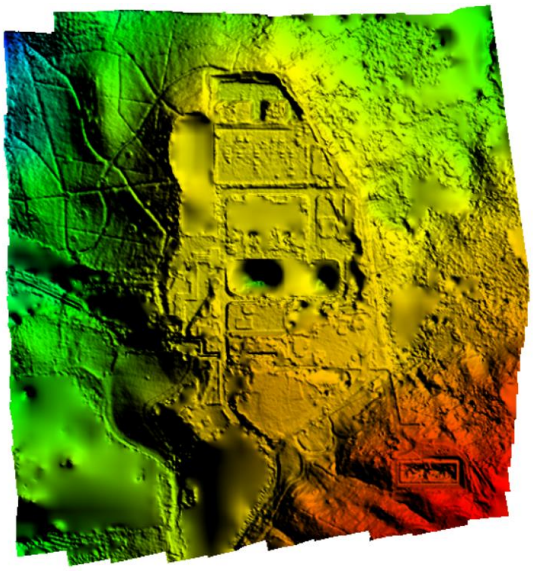


Synchronizing Photos & PPK data



Combining Photos become 3D Model

Orthophoto



Digital Elevation Model

Figure 5: Synchronizing and Processing Photos Data.

In the third step, after the drone completed the flight plan, the photo data, GPS tracking record data from the drone, and GPS tracking record data from the base shall be moved to the computer for post-processing purposes. The post-processing needs to be done to synchronize geotagging between photo data from drones, and GPS data records from PPK tools. The synchronizing geotagging purpose is to coordinate correction to the photo taken by drone to become more accurate based on GPS installed at the existing benchmark. Usually, time correction between drone photos and GPS base needs to be checked. After synchronize completed the photos may have new coordinates which more accurate compared to global coordinates and position. After that, the last or fourth step is to process the Photos data to become a map image or orthophoto. From the orthophoto data, the Digital Elevation Model (DEM) and contour map can be processed and developed together. There is many software in the market that can be used to do processing photos and becomes orthophotos, usually, the software can do processing until contour map. All these processes from the first step to the fourth step can be done

within one week. Figure 5 shows Synchronizing and Processing Photos Data until the orthophoto and DEM result.

The final output from processing using software is an orthophoto map completed with contour line (topography map) that shows on Figure 6.

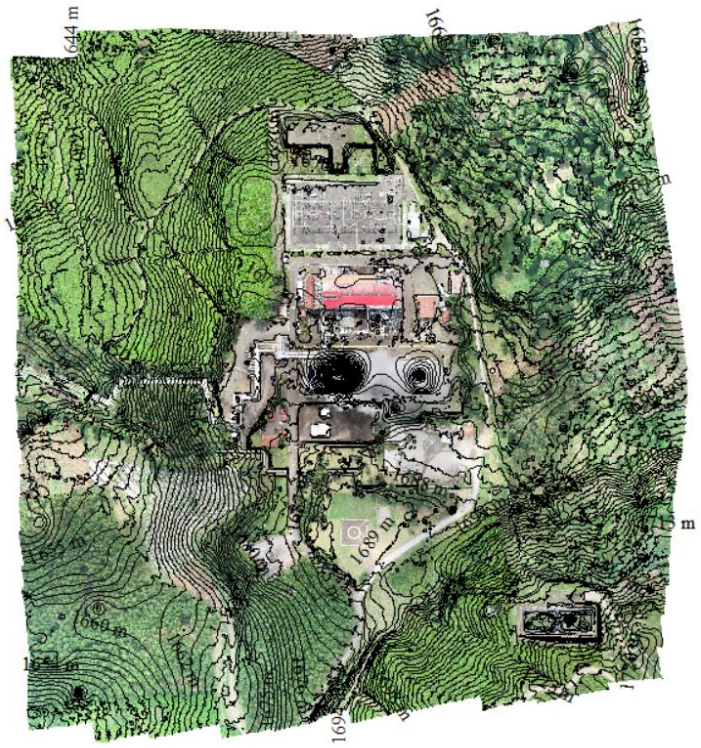


Figure 6: Topography map from aerial survey.

It took less than 1 weeks to collect 199 aerial images and process them into a topographic map that covers an area of 34 ha within Wayang Windu WKP Power Plan. Because of weather, vegetation and building constraints, the drone interpretation images result may not be accurate, is seem contour line it shows from the pattern of contour lines on constraint area. Furthermore, situation maps of existing buildings and infrastructure e.g. road, pipeline, building, etc. cannot be generated directly with software.

4. GEOMETRY ACCURACY TEST PROCESSING & RESULT

To know the geometric accuracy of the drone topographic map, it is necessary to compare with accurate data, in this paper we use existing topographic map from the terrestrial surveys as the baseline. 6 benchmark coordinate points are taken as a comparation in calculating the geometric accuracy of the topographic map produced by the drone. BM PS-02 as a GCP, while 5 other points function as an ICP. The location of these points show on Figure 7 as follows.

There is deviation in average of 10 m between elevation coordinate at test point of topographic drone map and the baseline. From the cross sections that made to compare, the deviation values are consistent in both the A-A' and B-B' cross-sections. With that consideration, we localize the elevation of the topographic drone map with GCP BM PS-02 as the baseline. The elevation deviation show on Figure 8 as follows.

Figure 7: GCP & ICP from baseline map and drone topographic map.

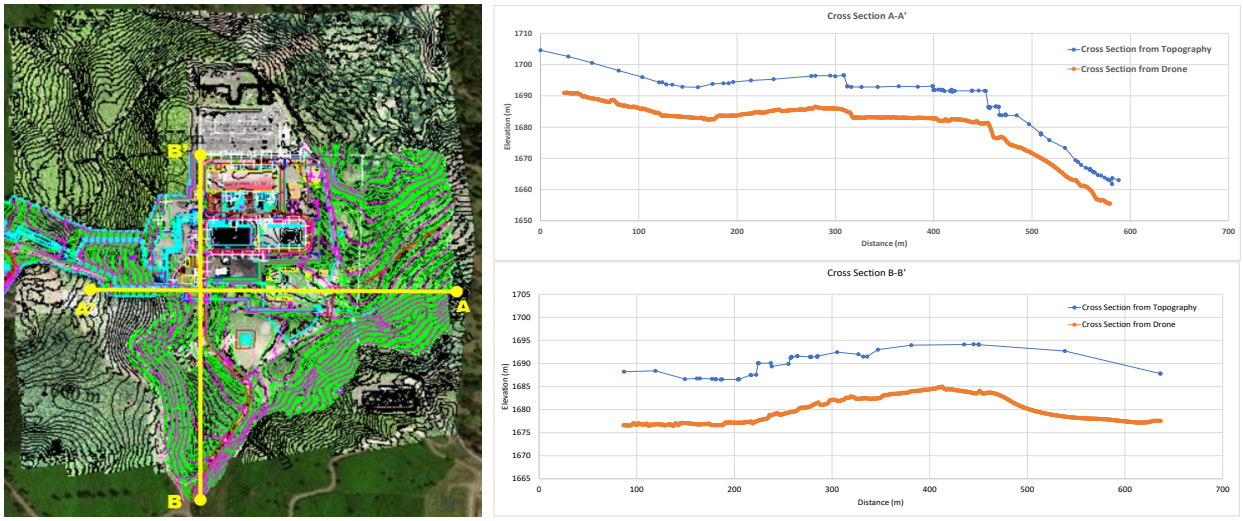


Figure 8: Cross-section for elevation comparation.

The results of horizontal geometric accuracy test are shown in the calculation table on Figure 9, while the results of vertical geometric accuracy test are shown in the calculation table in Figure 10 bellows.

Number	Point	X Map	X Baseline	dx	dx^2	Y Map	Y Baseline	dy	dy^2	dx^2+dy^2
A	*B*	*C*	*D*	*E*	*F*	*G*	*H*	*I*	*J*	*K*
1	PS-01	789881.034	789882.644	1.610	2.592	9203566.295	9203565.484	-0.811	0.658	3.250
2	PS-02	790105.314	790106.057	0.743	0.552	9203645.208	9203644.243	-0.965	0.931	1.483
3	NSE-01	790071.555	790072.725	1.170	1.369	9203643.852	9203646.532	2.680	7.182	8.551
4	NSE-02	790000.442	790001.992	1.550	2.402	9203229.724	9203228.684	-1.040	1.082	3.484
5	NSE-03	789868.920	789871.588	2.668	7.118	9203535.349	9203534.850	-0.499	0.249	7.367
6	HP-01	789985.438	789987.019	1.581	2.500	9203330.421	9203329.788	-0.633	0.401	2.900
									Jumlah	27.036
									Rata-rata	4.506
									RMSE	**2.123**
									CE 90	**3.221**

Figure 9: Calculation table of horizontal geometric accuracy test.

Number	Point	Z Map	Z Baseline	dz	dz^2
A	*B*	*C*	*D*	*E*	*F*
1	PS-01	1686.743	1686.220	-0.523	0.274
2	PS-02	1686.886	1686.886	0.000	0.000
3	NSE-01	1686.979	1686.521	-0.458	0.210
4	NSE-02	1701.064	1699.008	-2.056	4.227
5	NSE-03	1686.135	1685.751	-0.384	0.147
6	HP-01	1700.641	1699.536	-1.105	1.221
				Jumlah	6.079
				Rata-rata	1.013
				RMSE	**1.007**
				LE 90	**1.656**

Figure 10: Calculation table of vertical geometric accuracy test.

Referring to the Regulation of Geospatial Information Agency of Republic of Indonesia No. 15 Year 2014 and No. 6 Year 2018 concerning Technical Guidelines for Basic Map Accuracy, the result of topographic map from drone meets the scale category with standard accuracy for map 1:10,000, with horizontal accuracy class 2 and vertical accuracy class 1 as shown on Figure 11.

	Test Result	Map Accuracy Scale		1:10.000
Accuracy	CE 90 dan LE 90	Kelas 1	Kelas 2	Kelas 3
Horizontal	3.221	3	6	9
Vertical	1.656	2	3	4

Figure 11: Resume of geometric accuracy test.

5. CONCLUSION

Topographic maps generated from aerial survey data with drone DJI Phantom 4 Pro V2.0 and Post Processing Kinematic (PPK) method can meet the standard for map scale 1:10,000, with horizontal accuracy class 2 and vertical accuracy class 1.

Topographic map with this scale and accuracy very fulfilling to use as data when doing to plan the technical and capital requirements of site locations such as power plants, wells, roads, and pipelines.

Drone mapping enables the Company to produce large-scale topographic maps in a shorter time at a potentially lower cost than land surveys. However, due to weather and vegetation constraints, the drone interpretation images result may not be accurate as terrestrial survey. Furthermore, situation maps of existing buildings and infrastructure e.g. road, pipeline, building, etc. cannot be generated directly with software. Therefore, it is not intended to completely replace terrestrial surveying for detail design.

REFERENCES

Annabel, N.A.: What's the Difference Between PPK and RTK Drones, and Which One is Better? Handal Selaras, (2020)

Eko, B.W., and Bambang, S.: Applied Photogrammetry Subject Modules, STPN, Yogyakarta (2017)

Geospatial Information Agency of Republic of Indonesia: Head of Geospatial Information Agency Regulation No. 15, concerning Technical Guidelines for Basic Map Accuracy, (2014)

Geospatial Information Agency of Republic of Indonesia: Head of Geospatial Information Agency Regulation No. 6, concerning Revision of Head of Geospatial Information Agency Regulation No. 15 year 2014, (2018)

Verma, A., and Pruess, K.: Enhancement of Steam Phase Relative Permeability Due to Phase Transformation Effects in Porous Media, *Proceedings,* 11th Workshop on Geothermal Reservoir Engineering, Stanford University, Stanford, CA (1986).

Critical Stress Analysis Based on 3D MEM in Geothermal Field Study Case: Utah FORGE, USA

Mulyani S., Wisnubroto B., Aulia A.B., Widiatmoko W.,
Pradana A., Trikukuh J.S., and Puspa M.A.

Schlumberger, Wisma Mulia Building 45th floor, Jl. Gatot Subroto kav. 43, Jakarta Selatan, Indonesia

SMulyani@slb.com, BWisnubroto@slb.com, AAulia@slb.com, WWidiatmoko@slb.com,
APradana2@slb.com, JTrikukuh@slb.com, MPuspa@slb.com

Keywords: Critical Stress, Fracture Permeability, Mechanical Earth Model

ABSTRACT

Fracture permeability is one of the most important parameters for reservoir characterization and well targeting in Geothermal field. This value can be obtained from fracture modeling process based on fractures well data and conceptual model, however the uncertainty is very high due to dependency on the fracture data and limited subsurface information. Most of the time, fracture permeability parameters from fracture modeling results created by using all of fracture planes, without any further analysis or consideration on the geomechanics condition of the field to filter out the non-effective fracture planes. It will make the result of fracture permeability model will be not very optimal. To address the challenge, this study was done by doing critical stress analysis process that will give more detail results on identifying the critically stressed fractures to be used for creating fracture permeability process, instead of using all fractures planes. Main objective of this study is to show the workflow to do critical stress analysis for the fracture model. All data used for this study is published data from Utah FORGE, USA. It is an Enhanced Geothermal System (EGS) field, however the method can be applied for other geothermal systems. Input data for the workflow consist of lithological 3D model, fracture model, well data, fracture data and well logs (sonic & density). The workflow starts with loading all wells data and lithological model into the software, followed by creating 1D MEM (Mechanical Earth Model), build 3D MEM, and critical stress analysis. The result of this study is critically stressed fractures data defined as effective fractures based on geomechanic analysis. Having more accurate effective fractures data will give us information on which fractured area really has effect on the fluid flow and will lead us to better result of fracture modeling for entire field. Finally, this study can be utilized optimally for subsurface reservoir characterization and well targeting.

1. INTRODUCTION

In the development of geothermal fields, understanding the importance of fracture permeability is a must because not all fractures that are formed will contribute to fluid flow. Investigation of the slip potential of fractures is a great interest because there is strong evidence showing that when planar discontinuities are mechanically active, the fractures are also hydraulically conductive and will allow fluid migration. This becomes especially interesting when dealing with subsurface conditions in geothermal fields where fractures are generally the main source for permeability in the rock.

In many cases, the fracture model used to obtain fracture permeability is used directly with the assumption that all these fractures are geomechanically effective fractures. This assumption will cause the identified fracture permeability to have a higher value than it should. Research on fracture permeability at this study area has been carried out previously with those workflows and obtained the results of a fracture permeability model which has a trend of high permeability values in the southeastern part of the study area and is related to the Mineral Mountain West Fault System (Mulyani & Aulia, 2022).

For the new study, additional step was done by doing critical stress analysis process that will give more accurate result on the fracture permeability. The concept of critically stressed fractures showed that in many settings with stiff or hard crystalline rocks that fractures and faults that experienced high induced shear stresses appeared to be more permeable. Due to the rough nature of fracture surfaces in some

lithologies, when fractures experience small amounts of shear, they ride up resulting in increasing permeability (Rogers et al., 2014; McLellan et al., 2013; Barton et al., 1995). The analysis can identify the critical stressed fractures and filter the existing fracture model as selected fractures that will be used to extract the new fracture permeability. Overall, the objective of this study is to show the workflow of critical stress analysis process by using data from the Utah Frontier Observatory for Research in Geothermal Energy (FORGE) site near Milford, Utah.

2. REFERENCE FIELD

The study area located in the Utah Renewable Energy Corridor, around 350km south of Salt Lake City, Utah, USA. The Utah FORGE site classified as Enhance Geothermal System with relatively high temperatures (around 200deg C at depth 2.5 km). The lithology in study area can be classified into two units, they are crystalline plutonic rocks forming the basement of the basin and younger overlying simple-bedded alluvium and volcanic deposits (Simmons et al., 2019). The stratigraphy of this area consists of Tertiary igneous plutons, Paleozoic to Mesozoic sedimentary strata, Tertiary to Recent volcanic deposits, and Tertiary to Recent basin-fill sediments (Nielson et al., 1986, Coleman et al., 1997, Kirby, 2019). Based on XRD analysis data from the well cutting sample of well 58-32, the geothermal reservoir interval where the temperature exceeds the threshold of 175deg C located at depth around 6,500 ft with lithology of plutonic rock that rich of quartz (Jones et al., 2019).

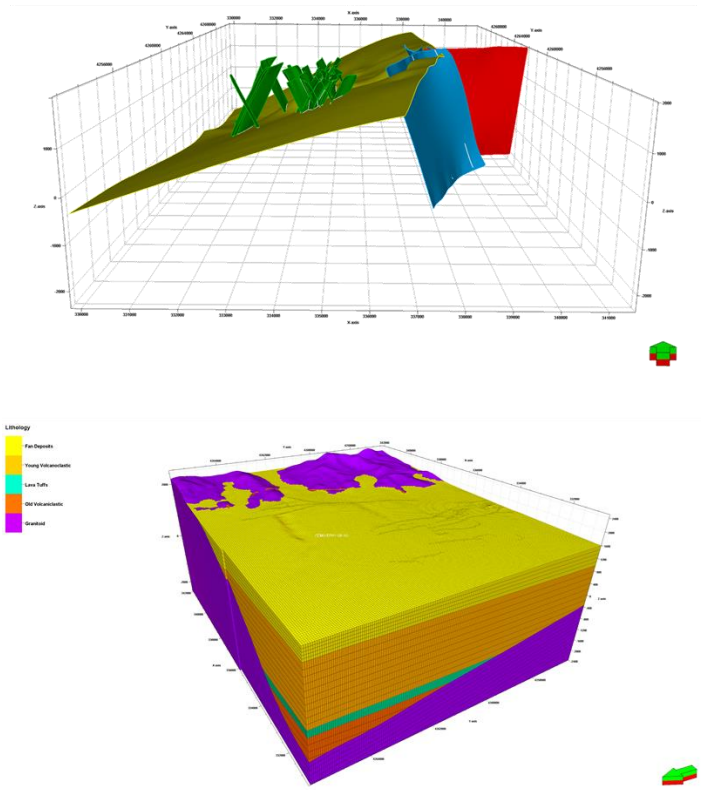


Figure 1: The upper image showing fault model in the reference field consist of Basin-Bounding fault unconformity (yellow), Opal mound fault (blue), Negro Mag (red) and Opal Mineral Mountain West (green). The lower image summarizes the lithologies in the study area consisting of granitoid as basement rock and sediment filling inside the basin (modified from Mulyani & Aulia, 2022).

In this case, the lithology of study area will focus on the basement of the basin which is made of granitoid and part of the Mineral Mountains batholith that intruded by some intrusion of rhyolitic-basaltic magma (Lipman et al., 1978; Coleman and Walker, 1994; and Jones et al., 2019).

Structural geology in the study area can be classified into four faults systems as result of extension event in Late Miocene. The oldest fault system is Basin-Bounding fault unconformity where the footwall has

dip around 30 degrees to the West of study area. The next fault system is Opal Mound fault which is a steep east-dipping fault located east of the Utah FORGE site. This fault is the hydrological barrier that prevents the westward hydrothermal flow of the Roosevelt Hydrothermal System (Allis and Larsen, 2012; Allis et al.; 2016, and Simmons et al., 2019). Negro Mag fault is an East-West structure that steeply dips to the north of the study area and forms an intersection with the Opal Mound fault. There is possibly that Negro mag fault was driven by Pleistocene rhyolitic magmatism. The youngest fault system is Mineral Mountains West that consists of parallel north-south trending. This normal fault was interpreted as faut that rooted in and caused by the downdip slip of the basin-bounding fault unconformity (Bartley, 2019). The lithological model and the position of fault systems can be seen by Figure 1.

3. DATA

The main input data for the workflow are the existing discrete fracture model and well logs such as density and sonic. The well logs were retrieved from publicly available data of FORGE which dedicated underground field laboratory sponsored by the US Department of Energy's Geothermal Technologies Office for developing EGS technologies (Energy and Geoscience Institute at the University of Utah, 2021).

3.1 Existing Fracture Model

The fracture model was obtained from previous study based on fracture intensity model as result of Natural Fracture Prediction (NFP) fracture driver. The intensity and fracture model from one of the fracture sets shown by Figure 2.

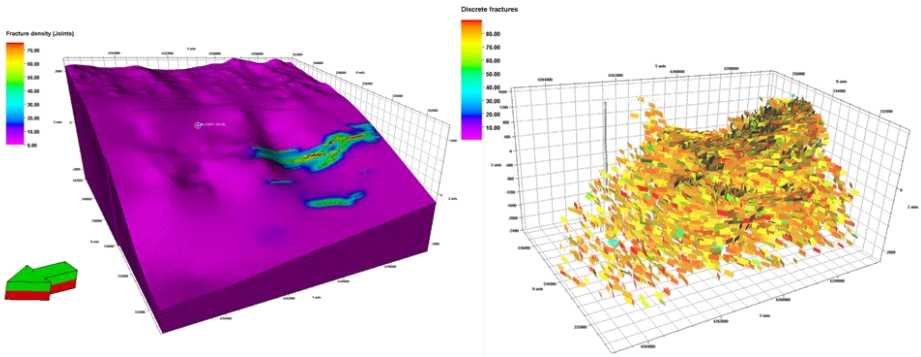


Figure 2: The fracture intensity model (left) and the fracture model (right) of discrete fracture model from fracture set related with Mineral Mountain fault system (modified from Mulyani & Aulia, 2022).

3.2 Well Logs

Well logs data is the most important input used for geomechanic process especially at 1D MEM stage. The well logs used in this study coming from four wells: 58-32, 9-1, 52-21 and 14-2. Well 58-32 or MU-ESW1 is the only well with fracture point data used as input for the existing fracture model. In this case, the new additional logs consist of density and sonic logs.

3.2.1 Density

Density log data obtained in the study area have mean value around 2.6 gram/cc, with maximum value 4.09 gram/cc at well 58-32 and minimum 1.35 gram/cc at well 52-21. The density log available at digital format and raster format that have been digitized into digital data and being loaded into the software. The density log data from all available wells at study area shown by figure 3.

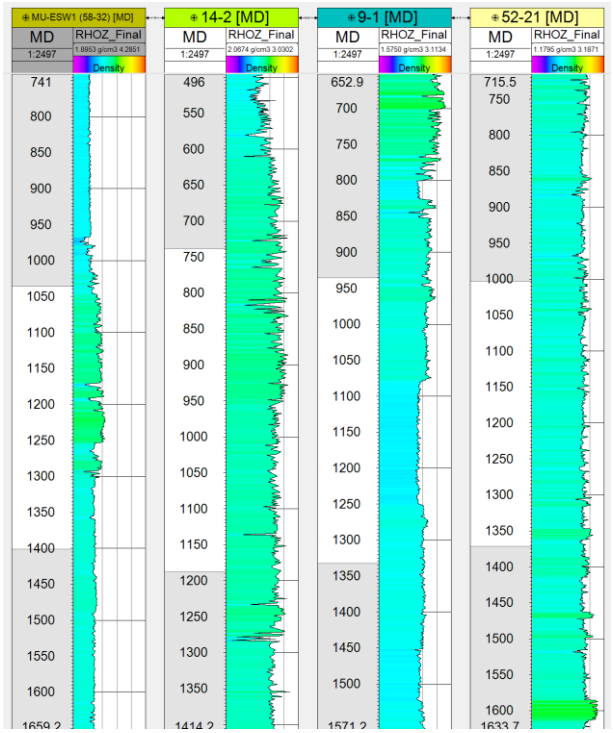


Figure 3: The density logs data from well 58-32, 14-2, 9-1 and 52-21.

3.2.2 Sonic

Sonic log is one of the important inputs for the workflow. For well 58-32 and 9-1, this log available in raster format. These logs then being loaded into software and digitized into digital log. The example of sonic log with raster format at Well 52-21 shown by figure 4. The sonic log in that well has minimum value 38.92 us/ft and maximum value 107.89 us/ft with mean value around 54 us/ft. All sonic logs from available wells were prepared and loaded into a borehole software.

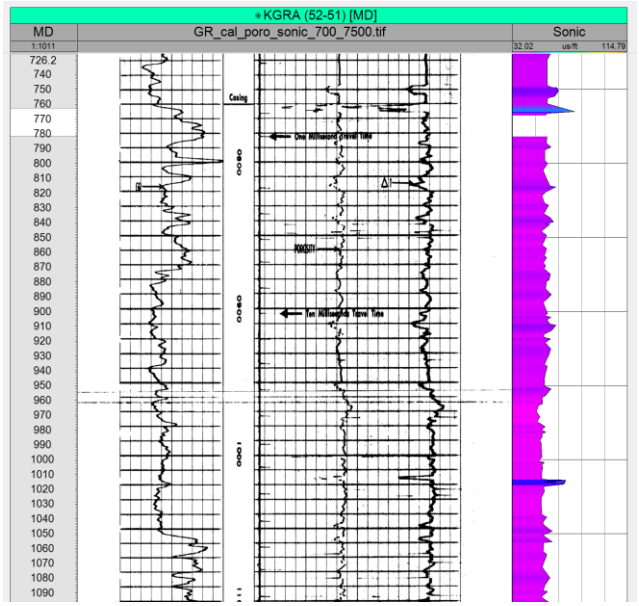


Figure 4: The sonic log data from well 52-21 with raster format (2nd track) and digital format (3rd track).

4. WORKFLOW

The workflow in this study started with preparing all data and load them into the software. For the geomechanical analysis, the first stage is constructing 1D MEM (Mechanical Earth Model). The next process is building 3D MEM with stress simulation, and finally a discontinuity stability analysis can be done to identify critically stressed fractures in study area.

4.1 1D MEM (Mechanical Earth Model)

The 1D MEM process was done by using Techlog software © to get pore pressure, rock mechanic properties, and in-situ stresses at wells that will be upscaled into 3D grid model. The main well logs data required in this process are:

1. Compressional Sonic (DTCO)
2. Density (RHOZ)
3. Shear Sonic (DTSM)

In this case, compressional sonic and density have been loaded from data source while the shear sonic (shear slowness) need to be estimated. To obtain the shear sonic log, neural network method was done with the available well logs data. Neural network process was selected to solve the condition when the value of output properties is out of the trend. Moreover, this method can combine several variables instead of relying on one variable in linear correlation. The cross plot between DTSM and DTCO from well MU-ESW1 (58-32) can be seen at figure 5. The correlation has R^2 value around 0.9 for data at depth 2150-7569 ft.

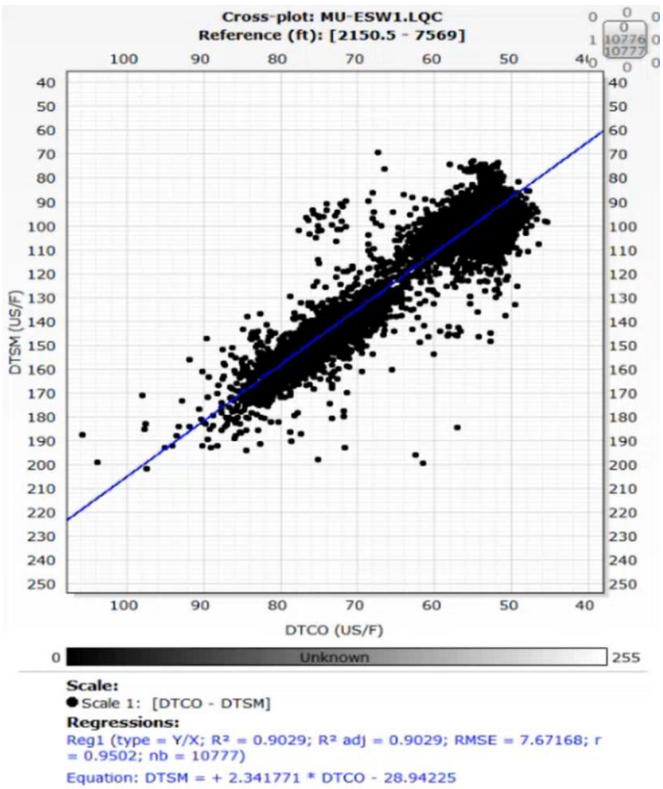


Figure 5: The cross plot of DTCO and DTSM at well MU-ESW(58-32).

Once the main well logs inputs are ready, the isotropic mechanic properties such as Young's Modulus, Poisson ratio, Unconfined Compressive Strength (UCS) and Friction Angel (FANG) were derived as dynamic log. To convert those properties into static log, calibration process was done based on rock mechanic test result obtained from previous study. The value of rock mechanic test results by McLennan (2018) was used as reference to calibrate the value of mechanic properties for all of the wells.

To complete the 1D MEM, an In-situ stresses was modeled by using poroelastic method by honoring the overburden (vertical aspect) and tectonic process (horizontal). In this study, the minimum horizontal stress was calibrated with DFIT interpretation report data from previous study done by Xing, McLennan and Moore (2020) with the average value of 0.76 psi/ft. For the stress azimuth value was obtained from drilling induced failure data of FMI (image log) in well MU-ESW1 (58-32). In this case, the stress regime in study area is normal stress regime with the maximum horizontal stress direction N 30° E. The complete 1D MEM for well 58-32 at measured depth 3000-7500ft can be seen at figure 6.

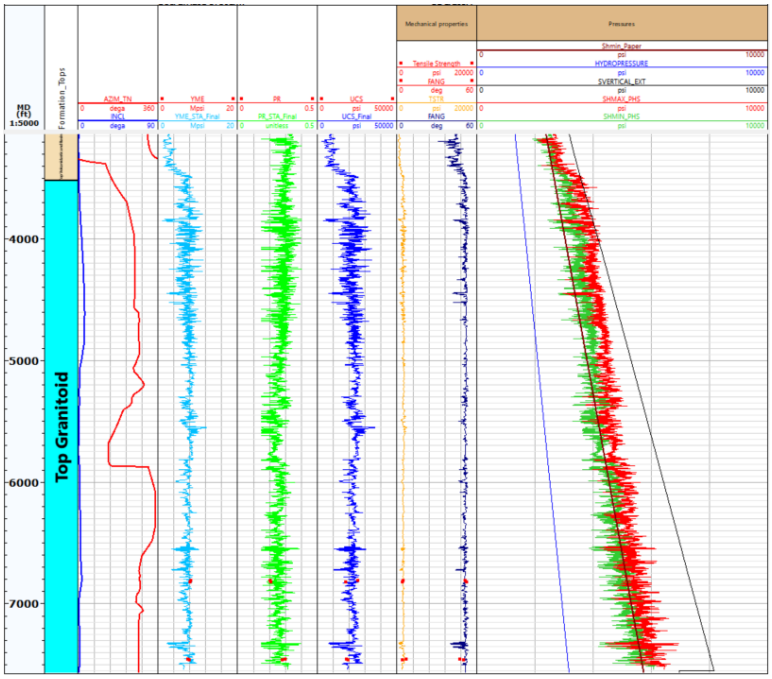


Figure 6: The 1D MEM at Well MU-ESW1 (58-32) based on rock mechanics test results (red points in track 4-7) from McLennan (2018) and average minimum horizontal stress value 0.76 psi/ft (dark brown line in track 8) from McLennan and Moore (2020).

4.2 3D MEM (Mechanical Earth Model)

The result of 1D MEM along the well trajectories then being transferred into Petrel software © and upscaled into 3D grid for 3D MEM. The 3D grid for geomechanic process should be embedded first by adding the side and under burden. Once the grid is ready with properties data along the wells, the next process is distributing those properties into 3D grid and run the stress simulation. Following are detail steps for 3D MEM.

4.2.1 Embedment Process

The embedment process created by using the existing 3D static model as the center of entire geomechanic grid. The objective of this process is to create a new 3D grid with geometrical ratio that close to a cube. To get this new grid, under burden and side burden were added to the existing 3D static grid. For under burden, surfaces with depth -5,000 and -10,000 m were added with proportional variation. For the side burden, additional cells were added in the IJ direction with factor 1.5 for the geometric factor. Overburden was not added since the existing static grid has region to the topography covering the interest area already. The settings for embedment process are shown by figure 7.

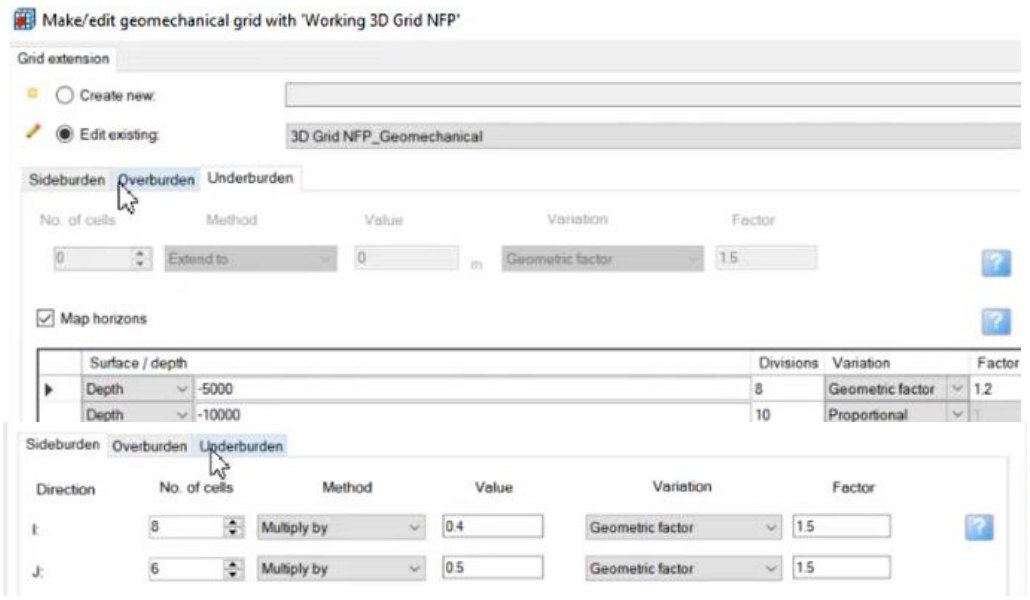


Figure 7: The settings for embedment process for 3D MEM.

By having this kind of geometry, the noise of stress in area of interest can be minimized when the stress boundaries were applied during the finite element process (geomechanical simulation). Moreover, with geometrical ratio maximum 1:3, it will properly transferring the constant stress/strain boundary load applied at the face into a material dependent stress/strain. As the comparison, the existing static 3D grid has around 2.9 million cells while total number of cells after embedment is almost twice from it, which is around 4.3 million of cell grid (Figure 8).

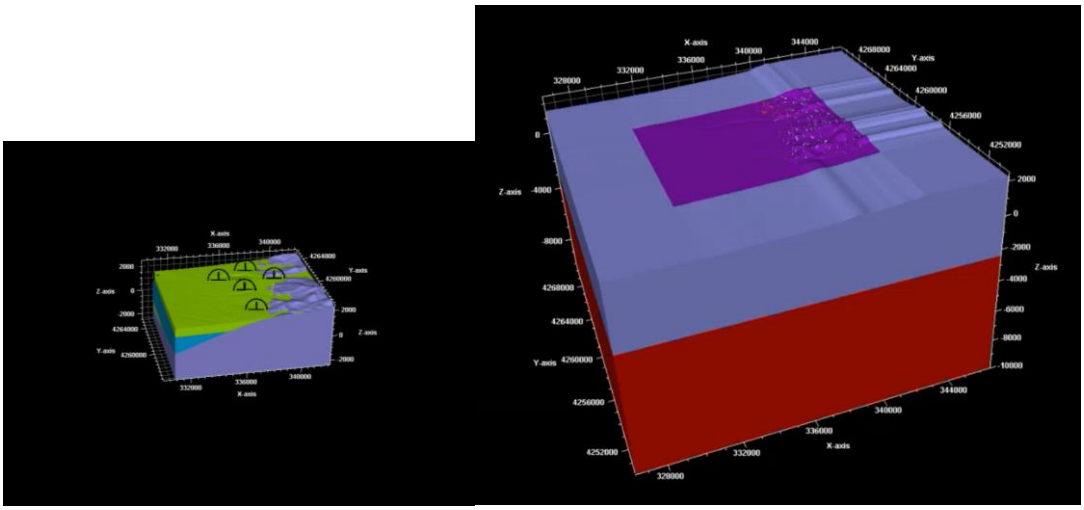


Figure 8: The comparison of existing 3D grid (left) and geomechanic grid as result of embedment process (right).

4.2.2 The 3D Mechanical Properties

All properties of 1D MEM were loaded into the new geomechanical grid. To distribute those properties for entire grid, machine learning algorithm EMBER (Embedded Model Estimator) was used to do property modeling by embedding geostatistical prior models of spatial continuity and correlation into a decision forest-based model. This algorithm not explicitly depending on the geostatistics but embedding them into something between the geostatistics compared to 3D magnetotelluric data. This method was selected instead of common algorithms such as Gaussian Random Function Simulation (GRFS) because it can incorporate more secondary variables and do variogram analysis automatically for each zone. The result of 3D mechanical properties such as Young's Modulus and UCS shown by Figure 9.

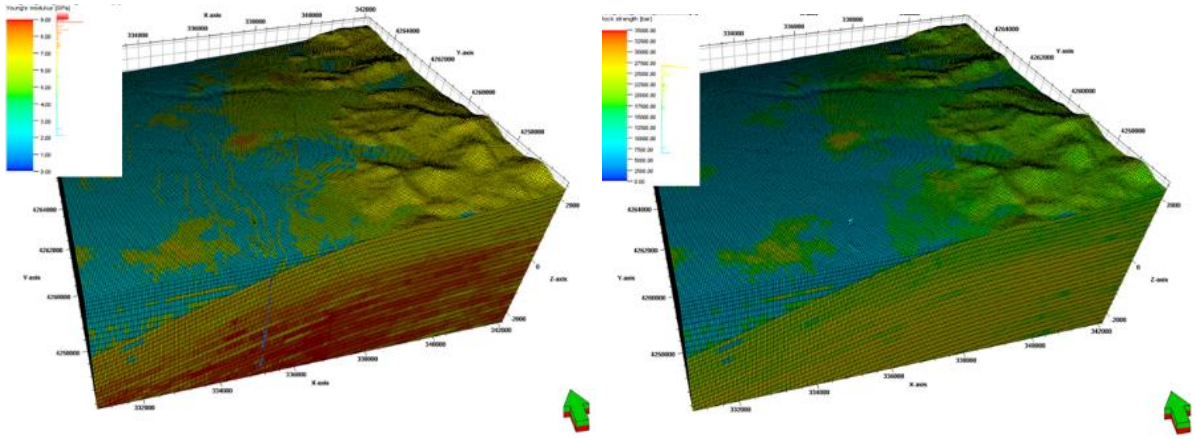


Figure 9: The 3D mechanical properties of Young's Modulus (left) and UCS (right).

The next process is blind well test to the original well data. In this process, well 14-2 was selected for blind well test process. Based on that analysis, most of the mechanical properties such as Young's Modulus and Shear slowness (DTCO) have good match. While density model showing relatively not good match with the original well data, which assumed caused by thick cell grid on area of interest due to coarse layering which could not captured the trend from density information (Figure 10).

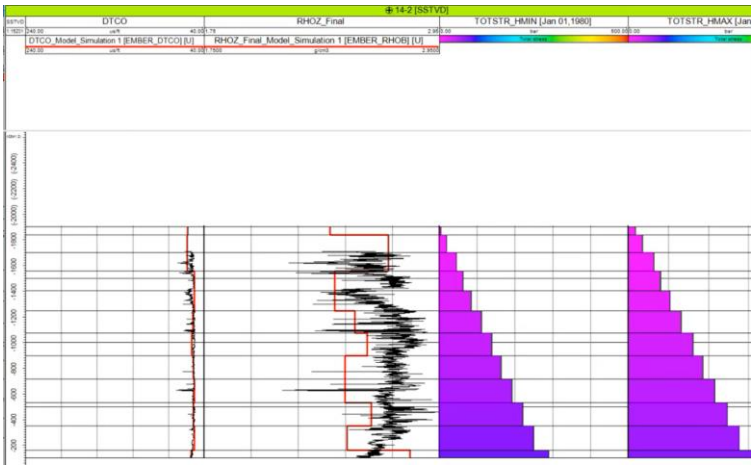


Figure 10: The result of mechanical properties model at blind well test (14-2).

4.2.3 The Stress Simulation

To run the stress simulation, discontinuity modeling of faults and fractures were done by using the existing model. In this study, the faults used as inputs are Opal Mountain fault system and Negro Mountain Faults only. All fracture sets from existing fracture model were selected (Figure 11).

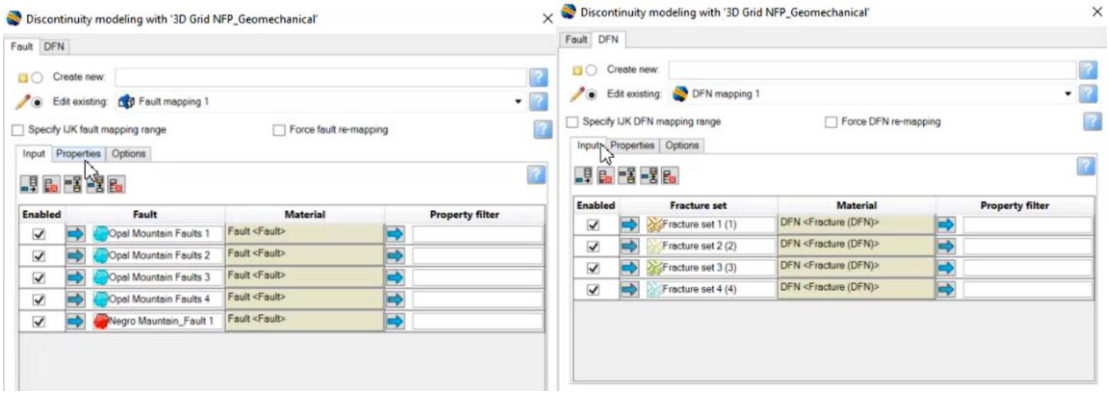


Figure 11: The discontinuity modeling of study area by using selected faults and fracture sets.

After that, the simulation case was defined based on geomechanic 3D properties and discontinuity data from previous process. The 3D stress simulation was performed with strain parameters from 1D MEM analysis to get the 3D stress that validated against 1D MEM stress profiles. In this case the 3D geomechanical model was subjected to external far-field stresses with internal vertical gravitational and pore pressure loads, including a sea-weight surcharge load acting on the top boundary of the model. An equilibrium stress condition was calculated by using VISAGE© simulator finite element. The variation of minimum horizontal stress (Shmin) and maximum horizontal stress (SHMax) with their tensor at Granitoid zone is shown by Figure 12. The result of this process will be carried out to do critical stress analysis in the next step.

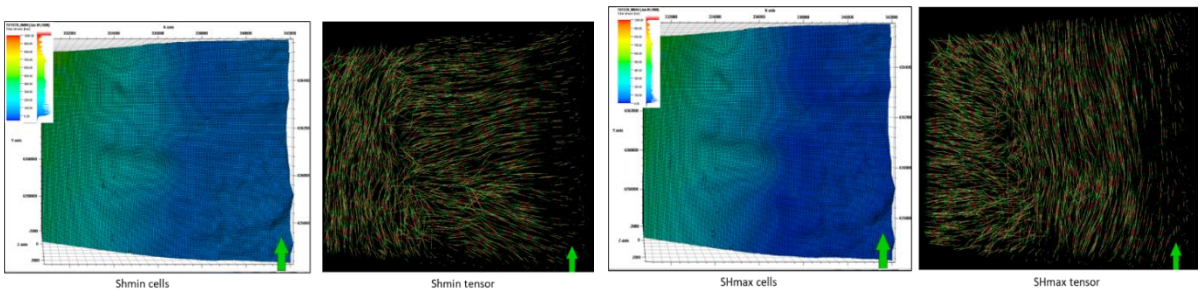


Figure 12: Variation of 3D horizontal stresses for Shmin (left) and SHmax (right) in the Granitoid zone.

4.3 Discontinuity Stability Analysis

The critical stress analysis in this study was done by using the Discontinuity Stability Analysis module with effective stress in the study area obtained from VISAGE ©. The other input required for this step is the existing discrete fracture network (DFN) and the value of friction angle and cohesion.

Fracture stability was analyzed based on the Mohr-Coulomb criterion considering the friction angle and cohesion of the discontinuity, its dip angle and dip azimuth, also the 3D stress field provided by VISAGE ©. There is no data about the friction angle in the reference study, so this parameter used as uncertainty variable with range 20, 30 and 45 deg. The friction angle 30 means the coefficient of friction is 0.6, etc. The cohesion value for all of three scenarios are the same which is 0. The settings critically stressed analysis was shown by figure 13. The result then being analyzed to select the case which will be used to identify the critically stressed fractures.

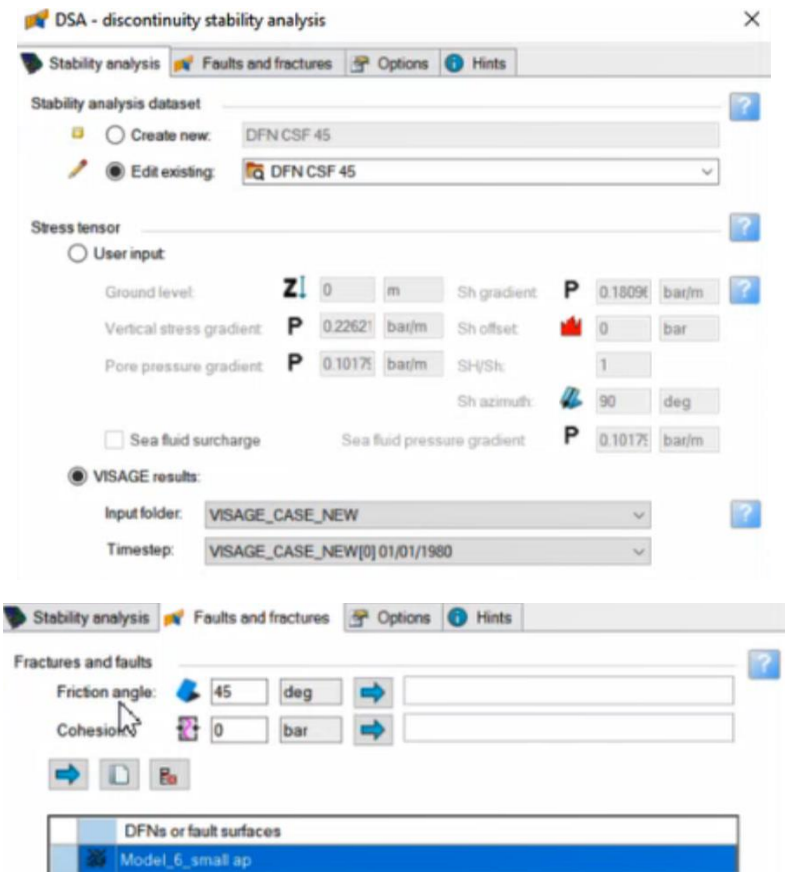


Figure 13: The setting of critically stressed analysis with friction angle 45deg and cohesion 0 for the existing fracture model (Model_6_small ap).

5. RESULT

To get the result of this study, three cases on discontinuity stability analysis (DSA) were analyzed. The case with fraction able 20deg showing critically stressed fractures have dip around 30-60deg with dip azimuth appeared for all of direction (no specific trend). The coulomb failure function showing relatively large number of fractures identified as critically stressed fractures shown by red points at Figure 14. The total of critically stressed fractures for this case is 56,100 fractures or around 53.7% from the existing fracture model.

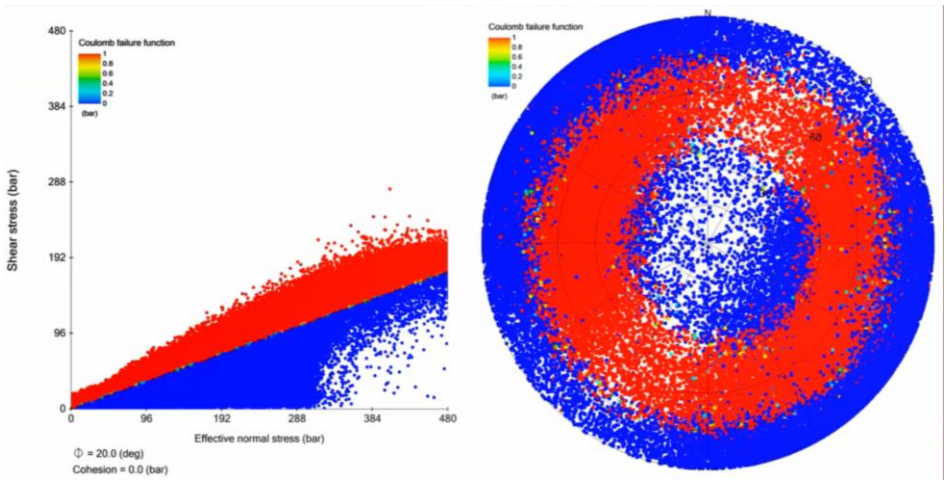


Figure 14: The distribution of critically stressed fractures with friction angle 20deg.

The case with friction angle 30deg showing less amount of critically stressed fractures, with characteristic dip angle around 35deg-55deg and dip azimuth concentrated at relatively East-West direction (around N 210 E - N 270 E). The total of critically stressed fractures for this case is 2,857 fractures or around 2.7% from the existing fracture model. The distribution of critically stressed fracture for this case is shown in Figure 15 with red points.

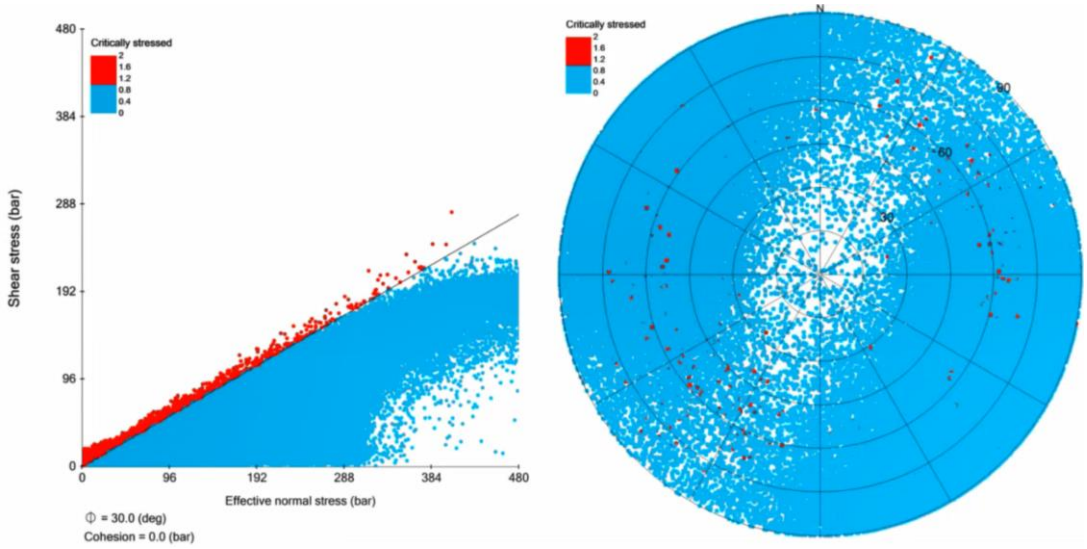


Figure 15: The distribution of critically stressed fractures with friction angle 30deg.

The case with friction angle 45deg showing the least amount of critically stressed fractures which is 481 fractures or around 0.5% from the original fracture model. The characteristic of these critically stressed fractures relatively similar with case friction angle 30deg which have dip angle around 35deg-55deg, and dip azimuth concentrated at relatively East-West direction.

6. DISCUSSION

Based on the result of this study, case of DSA with friction angle 30deg was selected due to the total of identified critically stressed fractures, dip angle and the trend of dip azimuth. The comparison of three cases can be seen in figure 16. For all cases, fracture set 3 shown by dark green points is the most common for the critically stressed fractures. This fracture set related to Opal Mound Fault's tectonic event.

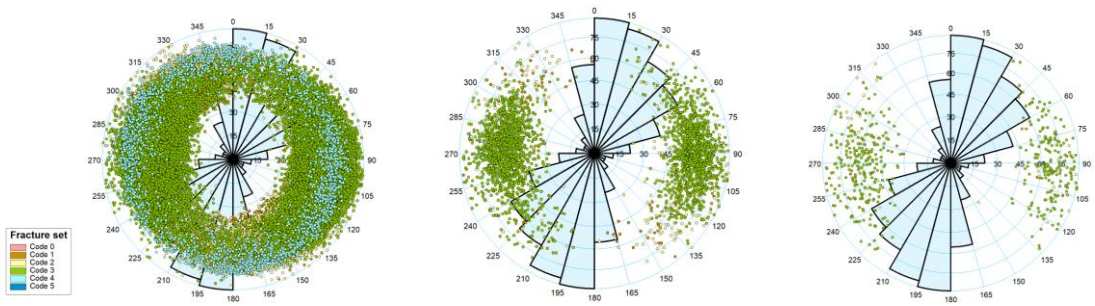


Figure 16: The comparison of critically stressed fractures created by using friction angle 20deg (left), 30deg (middle) and 45deg (right) with colors of fracture sets.

The critically stressed fractures for case 30deg mainly located in the center and eastern part of the study area (Figure 17). There are a lot of critically stressed fractures near well 82-33 in the North and 52-21 in the South. Moreover, the critically stressed fractures were identified in the southeastern part of the study area. This particular area has no faults that could be related with these fractures, nor the well data to check the findings. The current assumption is that the fractures in that area related with the big fault of Basin-Bounding fault unconformity which cover that area.

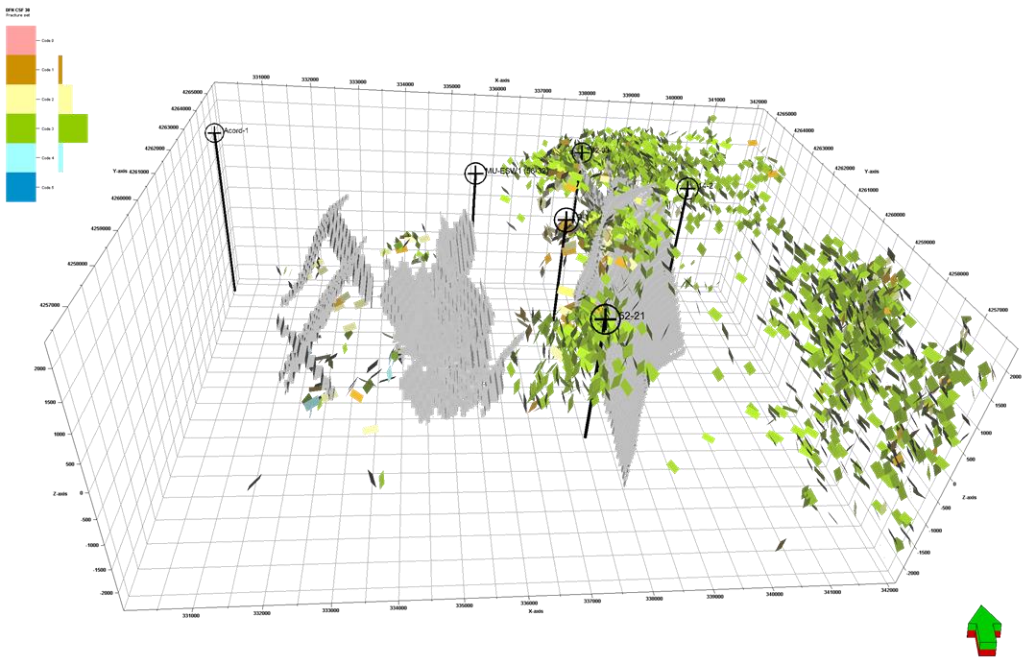


Figure 17: The location of critically stressed fractures created by using friction angle 30deg that located in the center part (near Opal Mound fault) and in the southeastern part of study area.

Those selected fractures can also be extracted into fracture permeability for Granitoid zone to get more detail information than the fracture permeability from the existing fracture model. The comparison of fracture permeability on I direction (Ki) between the existing fracture model and the critically stressed fractures only shown by figure 18. Overall, the new fracture permeability (mean 0.0036 mD) has less value than the existing one (mean 0.061 mD) and different distribution of high permeability area.

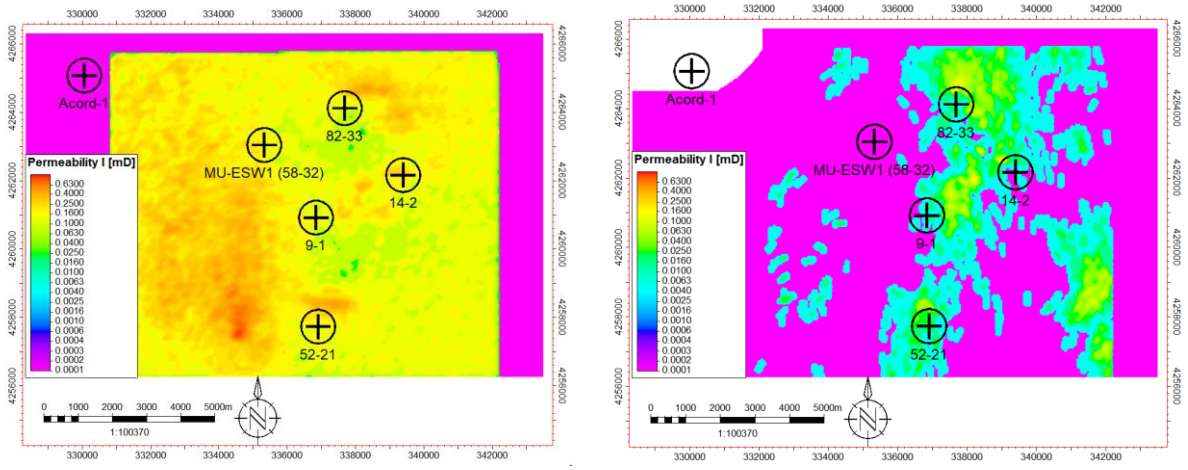


Figure 18: The comparison of facture permeability (Ki) maps extracted from the existing fracture model (left) and the critically stressed fractures only (right).

By having more accurate fractures permeability information, subsurface reservoir characterization and well targeting in field area can be more optimized. However, there are some notes about the limitation of this study that should be aware of and improved for the next study.

Geomechanic study in geothermal area should consider the temperature effect on mechanical properties. Li et al (2021) conducted the experimental test on the effects of thermal on mechanical properties of Granite rock which shows that the mechanical properties (Young's Modulus, UCS, Tensile) do not change significantly until temperature reach 300°C. For this study, the temperature measurement in

well MU-ESW1 (58-32) has maximum value of 266°F or 130°C, hence the temperature effects on mechanical properties calculation in this study are negligible.

Due to limited data and information, most of discontinuity properties parameter of fault and fractures such as Normal stiffness and shear stiffness used in this study was not the actual value from the field. The values for those parameters defined based on common value in geothermal field which is 8,000,000 bar/m for the normal stiffness and 4,000,0000 bar/m of shear stiffness. Those parameters are very significant during geomechanic calculation. So, having accurate value for those parameters based on analysis in the reference field or using uncertainty analysis with those parameters as variables will surely improve the results. The other improvement that can be done is by using more detail layering, with small vertical scale of cell grid, so the value from log data can be captured with more accurate. Detail layering or thin cell grid can minimize the potential of un-match histogram between the well log and the upscaled cell value. The last one is regarding the faults selected for discontinuity analysis, the biggest fault (Basin-Bounding fault unconformity) which included as lithology boundary can be added to the process as fault to get more comprehensive results by considering all faults model.

7. CONCLUSION

The critical stress analysis has been done to the existing fracture model. A new set of selected fractures has been identified based on critical stress analysis by using friction angle 30deg. The critical stress fractures have dip angle 35-55 deg and dip azimuth around 270deg with trend direction relatively East – West. Those fractures located near the existing wells (82-33 & 52-21) and correlate with geological structure of Opal Mountain. This result can be used as to define the high permeability area in the reference study which is one of the key parameters on the reservoir characterization in geothermal field.

ACKNOWLEDGEMENT

Authors would like to thank the Energy and Geoscience Institute at the University of Utah for the main data source, and the management of SLB who provided the software to complete the study and this manuscript.

REFERENCES

Allis R.G., and Larsen, G. (2012). Roosevelt Hot Springs Geothermal field, Utah – reservoir response after more than 25 years of power production. Proceedings, 37th Workshop on Geothermal Reservoir Engineering, Stanford University, Stanford, California, 30 January – 1 February 2012.

Allis, R.G., Moore, J., Davatzes, N.C., Gwynn, M., Hardwick, C.L., Kirby, S.M., McLennan, J.D., Pankow, K.L., Potter, S., and Simmons, S.F. (2016). EGS Concept Testing and Development at the Milford, Utah FORGE Site. Proceedings, 41st Workshop on Geothermal Reservoir Engineering, Stanford University, Stanford, California, February 22 – 24, 2016.Barton, C.A., M.A. Zoback, and D. Moos. 1995. Fluid flow along potentially active faults in crystalline rock. Geology; v. 23; no. 8; p. 683–686.

Bartley, J.M. (2019). Joint patterns in the Mineral Mountains intrusive complex and their roles in subsequent deformation and magmatism. Utah Geological Survey Miscellaneous Publication, 169-C.Coleman, D.S., and Walker, J.D. (1994). Modes of tilting during extensional core complex development. Science, v. 263, no. 5144, p. 215–218.

Coleman, D. S., Bartley, J. M., Walker, J. D., Price, D. E., and Friedrich, A. M. (1997). Extensional faulting, footwall deformation and plutonism in the Mineral Mountains, southern Sevier Desert, in Link, P.K., and Kowallis, B.J., editors, Mesozoic to recent geology of Utah: Brigham Young University Geology Studies, 42, part 2, 203–233.

Energy and Geoscience Institute at the University of Utah (2021). Utah FORGE: Well 58-32 (MU-ESW1) FMI Log Fracture Results [data set*]. Retrieved from https://gdr.openei.org/submissions/1299*.

Jones, C.G., Moore, J.N., and Simmons, S. (2019). Petrography of the Utah FORGE site and environs, Beaver County, Utah. Utah Geological Survey Miscellaneous Publication, 169-K.

Kirby, S. M. (2019). Revised mapping of bedrock geology adjoining the Utah FORGE site. Utah Geological Survey Miscellaneous Publication, 169-A.

Li, N., H.B. Wang, S.C. Zhang, Y.S. Zou, Z.P. Zhang, and T. Zhou. 2021. Effect of Cyclic Thermal Shock on Mechanical Properties and Brittleness of Granite. American Rock Mechanics Association.

Lipman, P.W., Rowley, P.D., Mehnert, H.H.S., Evans, S.H.J., Nash, W.P., and Brown, F.H. (1978). Pleistocene rhyolite of the Mineral Range, Utah—Geothermal and archaeological significance. U.S. Geological Survey Journal of Research, v. 6 no. 1, p. 133–147.

McLellan, P., V. Mostifavi, and I. Anderson. 2013.Geomechanical Characterization of an Unconventional Montney reservoir: In-situ Stresses, Rock Properties and Natural Fractures. Presented at the Canadian Society of Petroleum Geologists Gussow Conference, Banff, Alberta, 15 – 17 October 2013.

Mulyani, S., and Aulia, A.B. (2022). Discrete Fracture Network Modelling Based on Natural Fracture Prediction Geomechanic Inversion Process. Proceedings, The 8th Indonesia International Geothermal Convention and Exhibition (IIGCE) 2022.

Nielson, D. L., Evans, S.H., and Sibbett, B.S. (1986). Magmatic, structural, and hydrothermal evolution of the Mineral Mountains intrusive complex, Utah. Geological Society of America Bulletin, 97(6), 765-777. Rogers, S., McLellan, P., Webb, G., 2014. Investigation of the Effects of Natural Fractures and Faults on Hydraulic Fracturing in the Montney Formation, Farrell Creek Gas Field, British Columbia. International Discrete Fracture Network Engineering Conference (DFNEC) 2014, Vancouver, Canada.

Simmons, S.F., Kirby, S.M., Bartley, J., Allis, R.G., Kleber, E.J., Knudsen, T.R., Miller, J.M., Hardwick, C.L., Rahilly, K., Fischer, T.P., Jones, C.G., and Moore, J.M. (2019). Update on the Geoscientific Understanding of the Utah FORGE Site. Proceedings, 44th Workshop on Geothermal Reservoir Engineering, Stanford University, Stanford, California, 11 – 13 February 2019.

Investigating the Performance of Ground Heat Exchangers with Nanoparticle-based Fluids using CFD

Muhammad Indjra Dije[1], Syaharussajali[2], and Fikrul Jihad[1]

[1]Pertamina Geothermal Energy
[2]Sepuluh Nopember Institute of Technology

Muhammad.dije@pertamina.com, Syaharussajali74@gmail.com, Fikrul.jihad@pertamina.com

Keywords: Nanofluid, horizontal ground source heat pump, and heat transfer

ABSTRACT

Horizontal ground source heat pump (HGSHP) is one of the technological solutions due to the high demand for energy for heating and cooling buildings. Unlike conventional air conditioners, which use outdoor air as heat dissipation. GSHP utilizes soil temperatures which are more stable than ambient temperatures throughout the year, GSHP thermal performance is better than conventional air conditioners. There are several types of GSHP using closed and open system, but one of the most commonly used is closed system with vertical heat exchangers. Vertical heat exchangers have high efficiency but have high costs, and drilling costs depend on soil composition. Horizontal ground heat exchanger is an alternative solution between efficiency and cost. To increase the efficiency of the heat exchanger system can be achieved by improving the thermal properties of the based fluid. The purpose of this research is to investigate the different material and concentration configurations between Al2O3, TiO2, and CuO nanoparticles on the performance of the horizontal ground source heat pump. The CFD approach developed to simulate a horizontal ground source heat pump. The proposed model verified with the previously reported numerical and analytical results. The model is used to predict the HGSHP performance using the fluid properties of nanoparticles in previous studies. Based on the simulation results, we found that nanofluid concentration of around 1% - 2% has a significant effect on the increase in HGSHP heat transfer of around 34% when compared to using water. With the highest heat transfer that is at a concentration variation of 1.5% CuO with a heat transfer of 35,578 kW.

1. INTRODUCTION

Climate change has significant impacts on natural systems and leads to a decline in environmental quality, disrupting the delicate balance of ecosystems (Malhi et al. 2020; Montoya and Raffaelli 2010). It is concerning to note that Southeast Asian countries have experienced a substantial increase in CO2 emissions, with levels rising from 711 MT in 2000 to 1288 MT in 2015, making them among the most rapidly developing regions in terms of electricity consumption (Widiatmojo et al., 2019). In response to the growing need for energy for heating and cooling buildings, ground source heat pumps (GSHP) have emerged as a viable technological alternative. Unlike conventional air conditioners that rely on outdoor air for heat dissipation, GSHP utilizes the stable temperatures found in the soil throughout the year, resulting in better thermal performance compared to traditional air conditioners.

This technology offers the opportunity to increase the efficiency of a traditional heat pump system by exploiting the heat storage capabilities of the soil. For this kind of heat pumps the soil is used as heat reservoir: heat source in winter and heat sink in summer (Lazzarin, 2001). There are several types of GSHP using closed and open system, but one of the most commonly used is closed system with vertical heat exchangers. Although vertical heat exchangers are expensive and efficient, the cost of drilling varies depending on the kind of soil. Horizontal ground heat exchanger is an alternative solution between efficiency and cost. The ground coupled horizontal heat exchangers are long pipes buried at a depth of 1- 2 m, by which a heat transfer fluid (usually water added with glycol) exchanges heat to or from the soil (Florides and Kalogirou, 2007).

The potential for using GSHP in tropical areas such as Indonesia continues to develop. Research conducted by Jalaluddin and Akio Miyara (Jalaluddin and Miyara, 2015) shows that GSHP buried at a depth of about 1 meter below the soil surface has an average temperature of 27-28 ºC. By comparing

parallel and series GSHP configurations, an average heat exchange rate of 86.2 W/m is obtained with an inlet temperature of 40 ºC and an outlet temperature of 35.6 ºC for a series configuration and a heat exchange rate of 122.4 W/m with an inlet temperature of 41 ºC and an outlet 37 ºC for parallel configuration. Overall, the authors say that GSHP has the potential to be applied as a cooling mode for tropical countries such as Indonesia (Widiatmojo et al., 2019; Ratchawang et al., 2022; Jalaluddin and Miyara, 2015).

Enhancing the heat exchanger system's efficiency can be accomplished by enhancing the thermal characteristics of the base fluid. Nanofluids are created by dispersing solid nanoparticles into base fluids like oil, water, or ethylene glycol (EG), with the primary goal being to augment thermal conductivity and, subsequently, heat transfer. The light mass, small size, and high performance of thermal systems are the main requirements of advances in device miniaturization (Chamkha et al., 2013).

There are four thermophysical properties for nanofluids that change with the addition of nanoparticle into the base fluid (Hajatzadeh Pordanjani et al., 2019). These modifications include increase of thermal conductivity; increase of density; decrease of heat capacity; increase in viscosity; and possible non-Newtonian behavior (Metz 1983). Both metallic and nonmetallic nanosized particles, with an average diameter of less than 100 nm, can be utilized in nanofluids, such as SiO2, Al2O3, Cu, CuO, Ag, and TiO2. It is crucial to note that the type, shape, and size of particles play a significant role in determining the thermal conductivity of nanofluids, thus impacting their overall performance (Menni, Chamkha, and Ameur 2020).

Using computer simulations to predict horizontal GSHP's performance is a way to reduce expensive and long experimental analysis and to have, at the same time, reliable results [8, 9, 10, 11]. In this work, the different configuration of nanoparticles analyzed were: Al2O3, TiO2, CuO. For each one, different concentration (1%, 1.5%, 2.5%, 3,5% and 5%) were varied in order to investigate the most important parameters to be considered in the evaluation of their performance.

2. METHODS

2.1 Nano fluid effect in base fluid properties

Nanofluids are an exciting category of heat transfer fluids that are based on nanotechnology and have attracted a lot of attention in recent years. The surge in interest in nanofluids is due to advancements in understanding and exploring their thermophysical properties. Thermophysical properties of the nanofluids can be computed using classical formulas derived for a two-phase mixture (Huminic and Huminic, 2012a). The effective density of the nanofluid is (Huminic and Huminic, 2012a; Xuan and Roetzel, 2000).

$$\rho_{NF} = (1 - \varphi)\rho_{BF} + \varphi\rho_{NP} \quad (1)$$

Specific heat of the nanofluid is calculated from (Huminic and Huminic, 2012a; Pak and Cho, 1998) as follows:

$$C_{pNF} = [(1-\varphi)(\rho_{Cp})_{BF}+\varphi(\rho_{Cp})_{NP}] \,/\, [(1-\varphi)\rho_{BF}+\varphi\rho_{NP}] \quad (2)$$

The density and specific heat of the nanofluids are assumed to be a linear function of volume fraction due to lack of experimental data on their temperature dependence (Huminic and Huminic, 2012b). While the effective thermal conductivity of nanofluids can be calculated from Maxwell's model (Farajollahi, Etemad, and Hojjat, 2010).

$$k_{NF} = k_{BF}\,[k_{NP}+2k_{BF}-2\varphi(k_{BF}-k_{NP})] \,/\, [k_{NP}+2k_{BF}+\varphi(k_{BF}-k_{NP})] \quad (3)$$

The addition of nanoparticles also affects the viscosity, this phenomenon is then formulated by the Einstein equation as follows (Breki and Nosonovsky, 2018).

$$\mu_{NF} = (1 + 2{,}5\varphi)\mu_{BF} \quad (4)$$

On nanofluid single-phase heat transfer, a number of theoretical and experimental studies have been published in the literature. One of the non-dimensional numbers that depends on the fluid properties is the Prandtl number. Prandtl number assesses the relation between momentum transport and thermal transport capacity of a fluid. Therefore, fluid's viscosity, thermal conductivity, and heat capacity all affect this number.

Namburu et al. (2009) finding that the Prandtl number decreases with the temperature due to the decrease of viscosity so that it rises as the Reynolds number rises. They proposed a relation based on the Reynolds number and the Prandtl number and showed that the effective Prandtl number increases by increasing the volume fraction of CuO, Al2O3 and SiO2 nano particles.

Besides the advantages already mentioned, another significant obstacle is the deposition of nanoparticles within the heat transfer fluid. The accumulation of unwanted materials on heat transfer surfaces, due to nanoparticle sedimentation, is defined as fouling (Awais and Bhuiyan 2019). The issue arises when base fluids with an excessively high concentration of suspended solid nanoparticles encounter sedimentation issues, resulting in the accumulation of particles on the heat transfer surfaces.

2.2 Nano particle comparison

In this study, three metallic oxides, aluminum oxide (Al2O3), titanium dioxide (TiO2), and Copper oxide (CuO) are considered to be dispersed in water as the base fluid. The properties of the base fluid and the nanoparticles are given in table below.

Table 1: Nanoparticles properties dispersed in base fluid.

Type of nanofluid	Density (kg/m3)	Thermal conductivity (W/m.K)	Specific heat (J/kg.K)	Reference
Al2O3	3700	46	880	(Farajollahi, Etemad, and Hojjat, 2010)
TiO2	3900	8.4	710	
CuO	6500	18	540	(Abu-Nada, 2010)

The additional nanoparticles were selected as the most researched Al2O3 and the least researched CuO and TiO2. In comparison to copper and titanium oxide nanofluids, multiple authors support the advantages of Al2O3-water nanofluids in the open literature (Timofeeva, Routbort, and Singh, 2009; Bianco et al. 2009; Murshed, Leong, and Yang 2008; Ho and Chen 2013; Delavari and Hashemabadi, 2014; Indikar et al., 2017). With regard to the other two nanofluids, Eiamsa-ard and Kiatkittipong (2014) showed experimentally that using water with TiO2 nanoparticle as a working fluid yielded a higher thermal performance (up to 9.8%) than using pure water.

2.3 Heat transfer

Heat exchanger in general is one of the components installed in industrial systems to transfer heat from one fluid to another with the aim of getting an increase in economic value. Nowadays, heat exchanger has become vital to many industrial processes, such as, manufacturing, transportation, electronics, etc. According to earlier research, the main problem of heat exchanger is its inefficiency. The use of nanofluids has been suggested as a way to improve their efficiency in order to address this issue. The use of nanofluids has been suggested as a way to improve their efficiency in order to deal with this issue. The use of nanofluids for this purpose has been investigated and explored in numerous earlier studies (Linnhoff, Mason, and Wardle, 1979; Ranga Babu, Kumar, and Srinivasa Rao, 2017). Heat transfer rate can be calculated with

$$Q = mC_{pNF}(T_{out} - T_{in}) \quad (5)$$

The rate of heat transfer to the tube wall is assumed to be totally dissipated to the fluid flowing through a circular tube.

2.4 Numerical simulation

This study uses a CFD numerical approach by simulating the interaction between two solids (pipes and soil GSHP) and fluid (nanofluid). Observation on the effect of variations of nanoparticles on heat transfer that occurs in the GSHP system. Following are the material properties used in the simulation.

Table 2: Material properties used in the HGSHP simulation for each variation in concentration and type of material.

Concentration (wt%)	Material	Viscosity (kg/m.s)	Specific heat (J/kg.K)	Thermal conductivity (W/m.K)	Density (kg/m3)
0.01	Al2O3	0.001028	4063.038	0.615	1027.000
0.01	TiO2	0.001028	4050.408	0.613	1029.000
0.01	CuO	0.001028	3957.611	0.614	1055.000
0.02	Al2O3	0.001041	4005.872	0.624	1040.500
0.02	TiO2	0.001041	3987.355	0.620	1043.500
0.02	CuO	0.001041	3853.968	0.623	1082.500
0.03	Al2O3	0.001066	3895.878	0.642	1067.500
0.03	TiO2	0.001066	3866.364	0.635	1072.500
0.03	CuO	0.001066	3661.714	0.640	1137.500
0.04	Al2O3	0.001091	3791.311	0.661	1094.500
0.04	TiO2	0.001091	3751.743	0.651	1101.500
0.04	CuO	0.001091	3487.195	0.657	1192.500
0.05	Al2O3	0.001128	3643.789	0.689	1135.000
0.05	TiO2	0.001128	3590.699	0.674	1145.000
0.05	CuO	0.001128	3253.647	0.683	1275.000
water		0.001003	4182.000	0.600	998.200

The CFD simulation process begins with constructing a geometry called the domain. This domain is used as the initialization location in the CFD simulation. The location of the domain used in the simulation can be seen in Figure 1. The properties of soil and pipe are shown in Table 3 (Tiwari and Rana 2023).

Table 3: Specification of the ground and helix pipe material.

Properties	Soil	Pipe
Specific heat capacity (J/kg K)	1200	502.48
Density (kg/m3)	1960	8030
Thermal conductivity (W/m K)	2.1	16.27

To start the simulation, it is necessary to define the boundary area, the boundary conditions used are velocity inlet, pressure outlet, and wall (surface upper soil & surface bottom soil), each of which is set as velocity inlet, pressure outlet, and wall. The inlet velocity and outlet pressure were set constant at 2 m/s and 1 atm to prevent the influence of flow velocity and outlet pressure on variations of nanoparticles and HGSHP geometries. Meanwhile, the upper and bottom wall surfaces are initialized as walls.

The geometric domain is then divided into small elements called meshes. Mesh is a discretization stage that converts integral equations into algebraic equations. The main mesh form used is the hexahedral mesh. This mesh has the advantage that it can be applied to complex geometries and produces a small number of elements compared to other shapes with quite good quality.

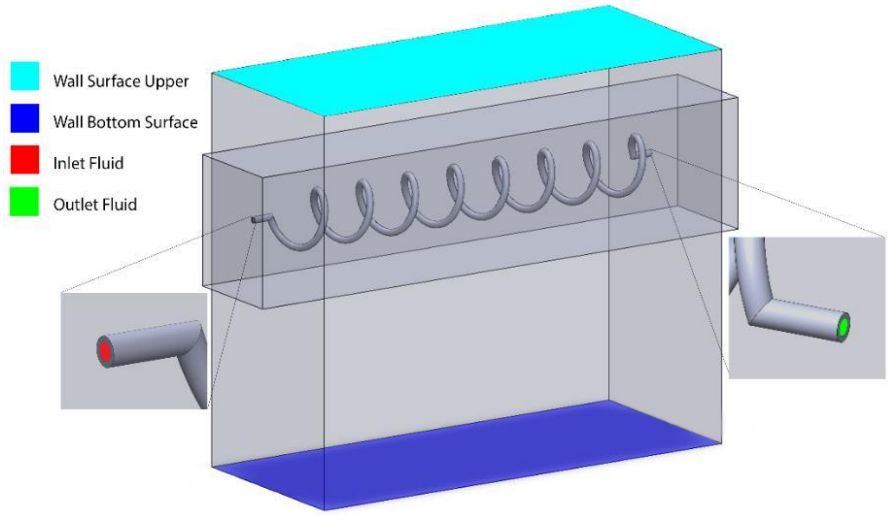


Figure 1: The location of the boundary conditions in the HGSHP simulation domain.

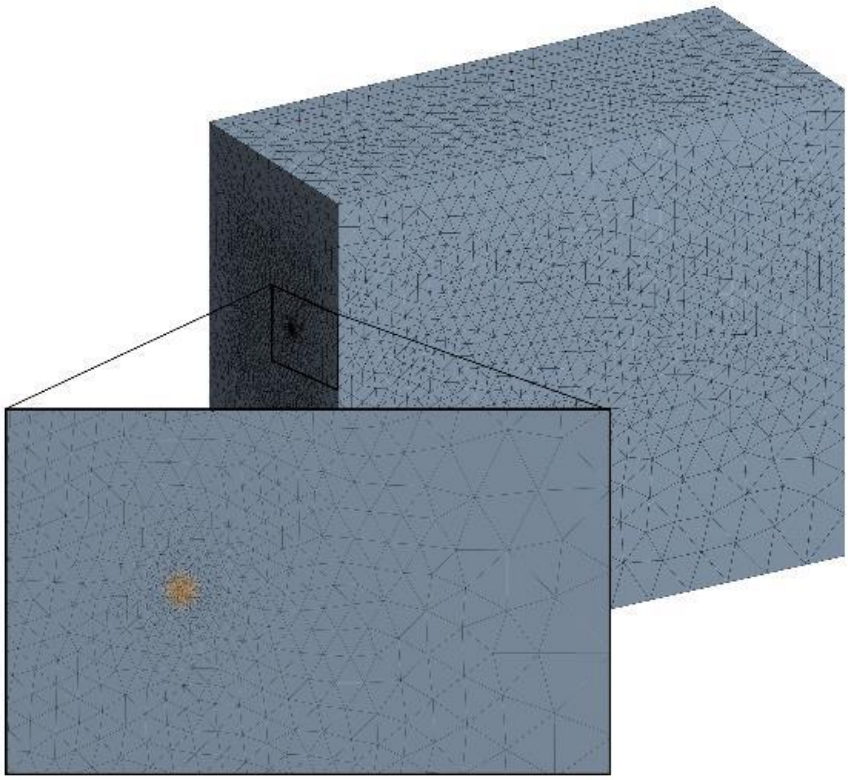


Figure 2: Hexahedral mesh shape for HGSHP simulation.

The quality of the mesh can be assessed based on the value of skewness and orthogonal quality. it is recommended that the skewness value is less than 0,94 and the orthogonal quality is at least greater than 0.01 so that the simulation is stable. The HGSHP mesh geometry has a skewness and orthogonal quality of 0.84 and 0.99. Before entering the simulation setup stage, the mesh needs to be tested for grid independence. The grid independence test was performed to test the effect of the number of mesh elements on the simulation results. In this simulation, the value used as a comparison is the average outlet temperature using the working fluid water. Table 3 shows the results of the independence grid analysis.

Table 4: Grid independence results.

Mesh type	Mesh size	Max skewness	Outlet temperature	Error
Mesh 1	0.03	0.84157	32.8956	-
Mesh 2	0.02	0.84281	32.8930	0.01%
Mesh 3	0.05	0.84895	32.9011	0.02%
Mesh 4	0.09	0.84632	32.9045	0.01%

Based on Table 3, mesh 1 to 4 the error values are relatively below 5% and there is no significant error spike in the outlet temperature results. Therefore, the mesh range 1 to 4 can be applied to the simulated geometry for various nanofluids and concentrations in the GSHP system. This simulation uses the Coupled algorithm with first order upwind settings for turbulent dissipation rate and kinetic energy and second order for energy and momentum with the initialization used is standard initialization with convergence criteria set at 1×10^{-3} for all simulation parameters. This simulation uses a steady state model because temperature changes in tropical areas are not too significant throughout the year so the soil temperature is considered constant (Ratchawang et al., 2022).

3. RESULT AND DISCUSSION

3.1 Fluid temperature

Fluid temperature is important to reflect the performance of the HGSHP system. The inlet temperature used is a constant 40 ºC for all variations of nanofluid and water (Ratchawang et al., 2022), in the initial simulation, the outlet temperature of HGSHP using water fluid is 32.8 ºC, then the graphic image below shows the results of the outlet temperature with variations in concentration and nanofluid material used.

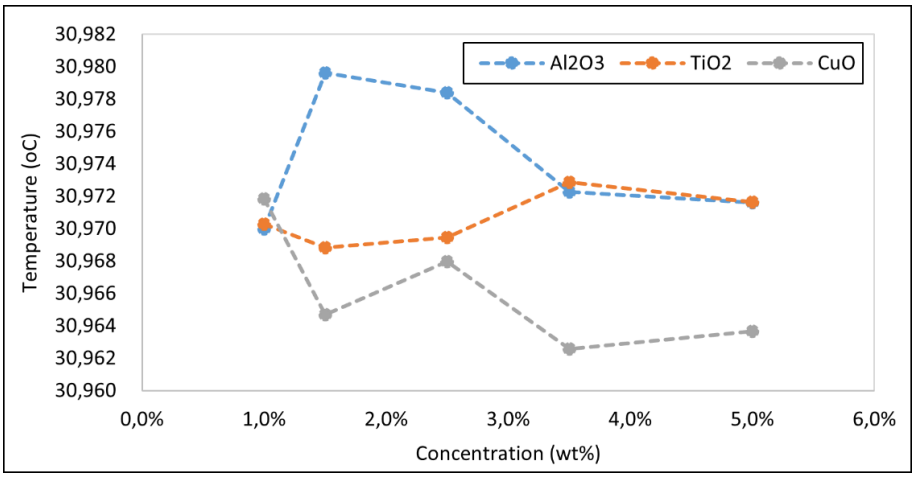


Figure 3: Outlet temperature results on the simulation of nanofluid variations and concentrations.

Based on figure 3, it shows the results of the HGSHP outlet temperature for each variation of the fluid nano material and the concentration used. In general, there is no significant temperature difference between the 3 variations of nanofluid materials, but the difference in concentration has a different effect on each nanofluid and the temperature difference between water and nanofluid has a significant difference, which is around 1.85 ºC. The lowest decrease in HGSHP outlet temperature for the addition of Al2O3 nanofluid occurred at concentrations of 1% and 5% wt with temperatures of 30.97 ºC and 30.972 ºC. Then for the addition of TiO2 nanofluid the lowest outlet temperature occurred at a concentration of 1.5 and 2.5% wt with a temperature of 30.969 ºC. then the addition of CuO nanofluid the lowest outlet temperature occurred at concentrations of 3.5% and 5% with temperatures of 30.963 ºC and 30.964 ºC.

The difference in the outlet temperature between the types of nanofluid can be caused by the different convection coefficient and thermal conductivity between the nanoparticles and the base fluid. When

these nanoparticles are added to water (base fluid), the nanoparticles can increase the thermal conductivity of the mixture (nanofluid). As a result, the outlet temperature of the ground source heat pump with nanofluid can be lower than that of ordinary base fluids. In addition, differences in outlet temperatures at different concentrations can also be caused by interactions between the nanometer particles and the liquid base. Higher concentrations may produce agglomeration or particle aggregation effects, which may affect the thermal conductivity of the mixture and fluid flow.

3.2 Thermophysical properties

There is a change in the convection coefficient based on the concentration of the nanofluid used. Convection coefficient is a parameter that describes the effectiveness of the phenomenon of heat transfer between the soil and the fluid flowing in the pipe. Changes in the convection coefficient can affect the efficiency and overall performance of the heat pump system.

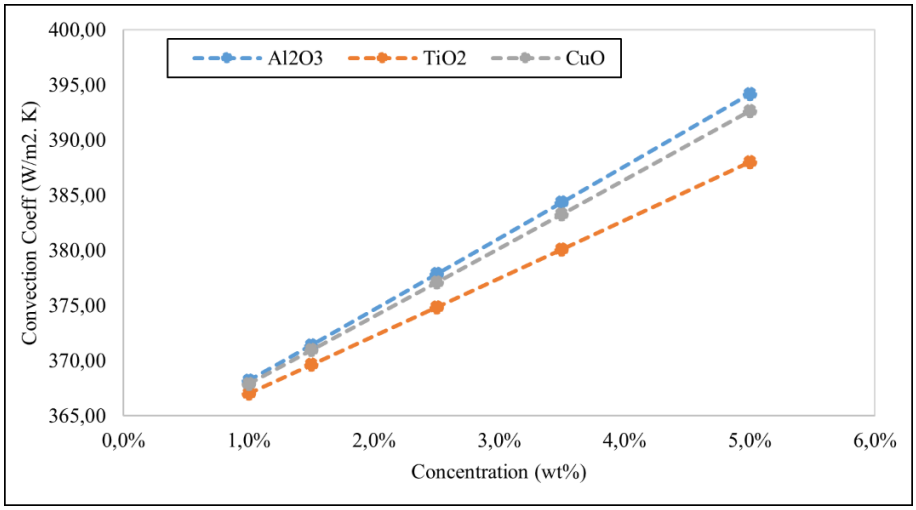


Figure 4: Convection coefficient results on simulations of nanofluid variations and concentrations.

Based on figure 4, it can be seen that the convection coefficient increases with increasing concentration of nanoparticles in all types of nanofluids used (Al_2O_3, TiO_2, and CuO). This shows that the addition of nanofluid in the working fluid increases the heat transfer between the surface of the heat exchanger and the fluid.

Increasing the convection coefficient can have a positive impact on the horizontal ground source heat pump. By increasing the heat transfer between the surface of the heat exchanger and the fluid, system efficiency can be increased. The heat pump will be able to absorb or radiate more heat into or from the ground, depending on the function of the system.

The use of Al_2O_3, TiO_2, and CuO nanofluids can provide a significant increase in convection coefficient compared to the use of base fluid. However, it should be noted that these simulations only provide data at a few concentration levels of the nanofluid and do not yet cover the entire range of concentrations that might be used in practice.

In addition, the use of nanoparticles in the heat pump system can also have other impacts, such as the occurrence of fouling on the inner surface of the pipe. Therefore, this study also analyzes this impact with reference to the Reynolds number parameter. From the calculation results obtained, it can be observed that the Reynolds number tends to increase with increasing concentration of nanoparticles in the base fluid. Increasing the concentration of nanofluid results in increasing the viscosity of the fluid, which in turn increases the value of the Reynolds number. This influence will most likely have an impact on the formation of fouling on the pipe surface.

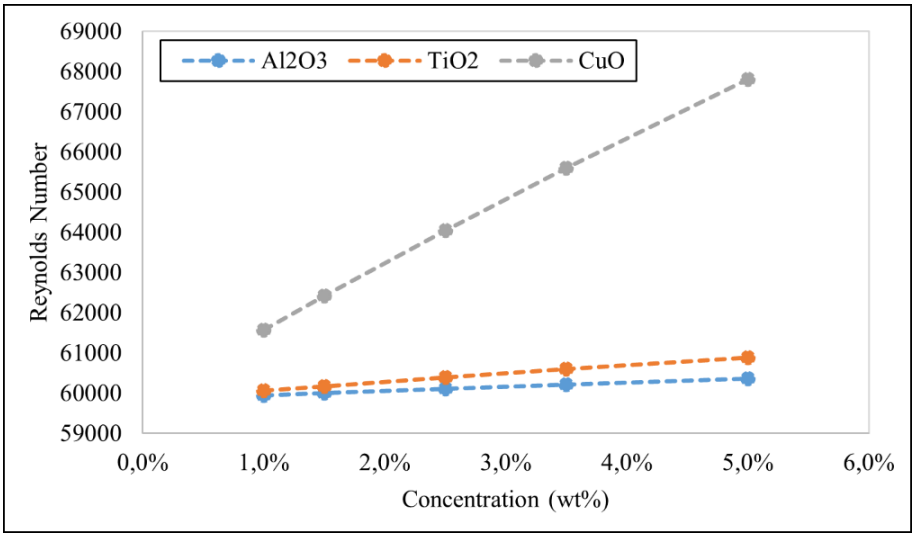


Figure 5: Reynolds number results in simulations of nanofluid variations and concentrations.

It is important to know that the occurrence of fouling phenomena on the pipe surface does not only depend on the Reynolds number. There are other factors such as the type of working fluid, temperature, operating time, and the nature of the pipe surface which also play a role in the formation of fouling. However, the Reynolds number is an important parameter in describing fluid flow patterns and can provide an initial indication of the potential for fouling.

The minimum standard for the Reynolds number required to prevent fouling from occurring in pipes may vary depending on various factors. However, generally, a sufficiently high Reynolds number is required to prevent or reduce fouling formation. A low Reynolds number can result in laminar flow around the pipe surface, creating stagnation zones or areas of low flow velocity. Under these conditions, nanofluid particles have a greater probability of settling and sticking to the surface of the pipe, causing fouling.

The generally accepted standard minimum Reynolds number is 28000 (García and Trueba 2018). In some cases, a higher Reynolds number is required to prevent significant fouling. So that the value of Re nanofluid in this study which ranges above 60000 is effective enough to prevent fouling on the inner surface of the pipe.

3.3 Heat transfer performance after nanofluid addition

Heat transfer is an important parameter indicating how effective the nanofluid is in increasing the performance of HGSHP. The following is the result of heat transfer for different materials and nanofluid concentrations.

Figure 6 shows the resulting heat transfer values in kilowatts (kW) for each material variation and concentration. The Q value indicates the amount of heat absorbed or transferred by the GSHP. The simulation results show that Al2O3 nanofluid with a concentration of 1% has a Q value of 35,553 kW. This shows an increase in performance compared to pure water which only has a Q value of 26,543 kW. Likewise, TiO_2 and CuO nanofluids at the same concentration have a higher Q value than water. Furthermore, with an increase in nanofluid concentration to 1.5%, the Q value of all nanofluid materials decreased slightly. However, this decrease is still small and insignificant.

When the nanofluid concentration was further increased to 2.5%, 3.5%, and 5%, there was a gradual decrease in the Q value for all nanofluid materials. However, it is still seen that the Al_2O_3 and CuO nanofluids still have a higher Q value than water at the same concentration.

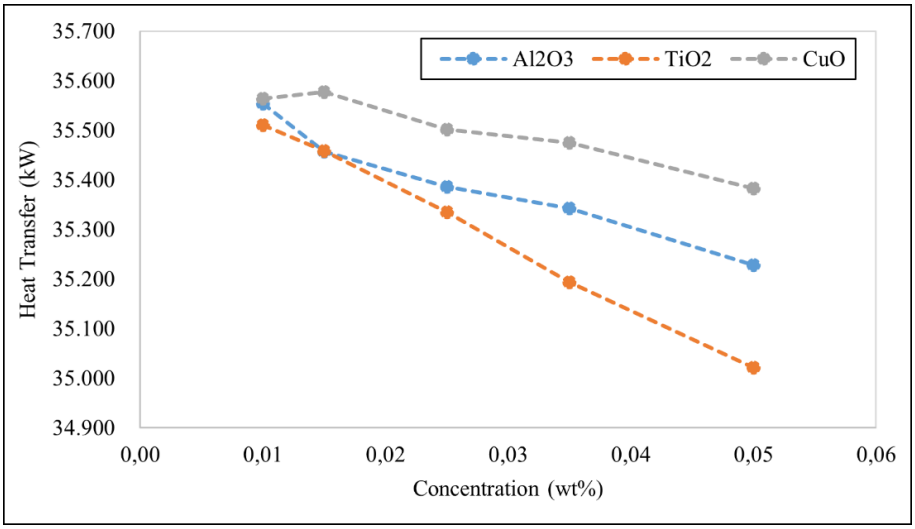


Figure 6: Heat transfer results on nanofluid variations and concentration simulations.

Based on the simulation results, it can be concluded that the use of Al_2O_3, TiO_2, and CuO nanofluids at low concentrations (1% - 1.5%) can improve the performance of the GSHP system in transferring heat. However, at higher concentrations (2,5% - 5%), the Q value tends to decrease. Therefore, choosing a nanofluid concentration of around 1% - 2% has a significant effect on the increase in HGSHP heat transfer of around 34% when compared to using water. With the highest heat transfer that is at a concentration variation of 1,5% CuO with a heat transfer of 35,578 kW.

4. CONCLUSION

Based on the results of the study, several conclusions were obtained regarding heat transfer in horizontal ground source heat pumps with variations in the working fluid nanofluids Al_2O_3, TiO_2, CuO, and concentrations.

Increasing the concentration of Al_2O_3, TiO_2, and CuO nanofluids generally increases the heat transfer (Q) of the HGSHP system. The higher the nanofluid concentration, the higher the Q value is achieved.

At concentrations from 0.01 to 0.05, CuO shows a higher Q compared to Al_2O_3 and TiO_2. In this context, CuO can be considered as the most effective nanofluid in increasing heat transfer in horizontal ground source heat pumps.

Pure water (water) has a lower Q value compared to all the nanofluids tested. This shows that the use of nanofluids in heat pump systems can significantly increase heat transfer compared to water.

Overall, this study shows that the use of Al_2O_3, TiO_2, and CuO nanofluids in a horizontal ground source heat pump can increase heat transfer compared to water. In this case, CuO shows better performance compared to other nanofluids in terms of heat transfer. However, further research is needed to understand the effects of changes in nanofluid concentration in more depth and to compare the performance of nanofluids with associated costs and environmental impacts.

REFERENCES

Abu-Nada, Eiyad. 2010. “Effects of Variable Viscosity and Thermal Conductivity of CuO-Water Nanofluid on Heat Transfer Enhancement in Natural Convection: Mathematical Model and Simulation.” *Journal of Heat Transfer* 132 (5): 1–9. https://doi.org/10.1115/1.4000440.

Awais, Muhammad, and Arafat Ahmed Bhuiyan. 2019. “Recent Advancements in Impedance of Fouling Resistance and Particulate Depositions in Heat Exchangers.” *International Journal of Heat and Mass Transfer*.

Bianco, Vincenzo, Fabio Chiacchio, Oronzio Manca, and Sergio Nardini. 2009. "Numerical Investigation of Nanofluids Forced Convection in Circular Tubes." *Applied Thermal Engineering* 29: 3632–42.

Breki, Alexander, and Michael Nosonovsky. 2018. "Einstein's Viscosity Equation for Nanolubricated Friction." *Langmuir* 34 (43): 12968–73. https://doi.org/10.1021/acs.langmuir.8b02861.

Chamkha, Ali J, S Abbasbandy, A M Rashad, and K Vajravelu. 2013. "Radiation Effects on Mixed Convection about a Cone Embedded in a Porous Medium Filled with a Nanofluid." *Meccanica* 48 (2): 275–85. https://doi.org/10.1007/s11012-012-9599-1.

Delavari, Vahid, and Seyed Hassan Hashemabadi. 2014. "CFD Simulation of Heat Transfer Enhancement of Al2O3/Water and Al2O3/Ethylene Glycol Nanofluids in a Car Radiator." *Applied Thermal Engineering* 73: 380–90.

Eiamsa-ard, Smith, and Kunlanan Kiatkittipong. 2014. "Heat Transfer Enhancement by Multiple Twisted Tape Inserts and TiO2/Water Nanofluid." *Applied Thermal Engineering* 70: 896–924.

Farajollahi, B., S. Gh Etemad, and M. Hojjat. 2010. "Heat Transfer of Nanofluids in a Shell and Tube Heat Exchanger." *International Journal of Heat and Mass Transfer* 53 (1–3): 12–17. https://doi.org/10.1016/j.ijheatmasstransfer.2009.10.019.

Florides, Georgios, and Soteris Kalogirou. 2007. "Ground Heat Exchangers—A Review of Systems, Models and Applications." *Renewable Energy* 32 (15): 2461–78. https://econpapers.repec.org/RePEc:eee:renene:v:32:y:2007:i:15:p:2461-2478.

García, Sergio, and Alfredo Trueba. 2018. "Influence of the Reynolds Number on the Thermal Effectiveness of Tubular Heat Exchanger Subjected to Electromagnetic Field-Based Antifouling Treatment in an Open Once-through Seawater Cooling System." *Applied Thermal Engineering* 140 (November 2017): 531–41. https://doi.org/10.1016/j.applthermaleng.2018.05.069.

Hajatzadeh Pordanjani, A., S. Aghakhani, Masoud Afrand, Boshra Mahmoudi, Omid Mahian, and Somchai Wongwises. 2019. "An Updated Review on Application of Nanofluids in Heat Exchangers for Saving Energy." *Energy Conversion and Management* 198 (April): 111886. https://doi.org/10.1016/j.enconman.2019.111886.

Ho, C J, and W C Chen. 2013. "An Experimental Study on Thermal Performance of Al2O3/Water Nanofluid in a Minichannel Heat Sink." *Applied Thermal Engineering* 50: 516–522. https://doi.org/10.1016/j.applthermaleng.2012.07.037.

Huminic, Gabriela, and Angel Huminic. 2012a. "Application of Nanofluids in Heat Exchangers: A Review." *Renewable and Sustainable Energy Reviews* 16 (8): 5625–38. https://doi.org/10.1016/j.rser.2012.05.023.

———. 2012b. "Application of Nanofluids in Heat Exchangers: A Review." *Renewable and Sustainable Energy Reviews*. https://doi.org/10.1016/j.rser.2012.05.023.

Indikar, Farooq, Faheem Akthar, Abdulrajak Buradi, Mohammed Rafi, Isquander Yunus, Mohammed Dafedar, Abdul Razak Kaladgi, and Balal Hassan. 2017. "Nanofluid as a Coolant for next Generation High Heat Dissipation Electronic Devices." *International Journal of Renewable Energy Technology* 8: 410. https://doi.org/10.1504/IJRET.2017.10009916.

Jalaluddin, and Akio Miyara. 2015. "Thermal Performance and Pressure Drop of Spiral-Tube Ground Heat Exchangers for Ground-Source Heat Pump." *Applied Thermal Engineering* 90: 630–37. https://doi.org/10.1016/j.applthermaleng.2015.07.035.

Lazzarin, Renato. 2001. "Ground as a Possible Heat Pump Source." In .

Linnhoff, Bodo, David R Mason, and Ian Wardle. 1979. "Understanding Heat Exchanger Networks." *Computers & Chemical Engineering* 3: 295–302.

Malhi, Yadvinder, Janet Franklin, Nathalie Seddon, Martin Solan, Monica G. Turner, Christopher B. Field, and Nancy Knowlton. 2020. "Climate Change and Ecosystems: Threats, Opportunities and

Solutions." *Philosophical Transactions of the Royal Society B: Biological Sciences* 375 (1794). https://doi.org/10.1098/rstb.2019.0104.

Menni, Younes, Ali J. Chamkha, and Houari Ameur. 2020. "Advances of Nanofluids in Heat Exchangers—A Review." *Heat Transfer* 49 (8): 4321–49. https://doi.org/10.1002/htj.21829.

Metz, Philip D. 1983. "A Simple Computer Program to Model Three-Dimensional Underground Heat Flow With Realistic Boundary Conditions." *Journal of Solar Energy Engineering-Transactions of The Asme* 105: 42–49.

Montoya, José M., and Dave Raffaelli. 2010. "Climate Change, Biotic Interactions and Ecosystem Services." *Philosophical Transactions of the Royal Society B: Biological Sciences* 365 (1549): 2013–18. https://doi.org/10.1098/rstb.2010.0114.

Murshed, S M Sohel, Kai Choong Leong, and Chun Yang. 2008. "Thermophysical and Electrokinetic Properties of Nanofluids – A Critical Review." *Applied Thermal Engineering* 28: 2109–25.

Namburu, Praveen K, Debendra Kumar Das, Krishna Tanguturi, and Ravikanth S Vajjha. 2009. "Numerical Study of Turbulent Flow and Heat Transfer Characteristics of Nanofluids Considering Variable Properties." *International Journal of Thermal Sciences* 48: 290–302.

Pak, Bock Choon, and Young I Cho. 1998. "HYDRODYNAMIC AND HEAT TRANSFER STUDY OF DISPERSED FLUIDS WITH SUBMICRON METALLIC OXIDE PARTICLES." *Experimental Heat Transfer* 11 (2): 151–70. https://doi.org/10.1080/08916159808946559.

Ranga Babu, J A, K Kiran Kumar, and S Srinivasa Rao. 2017. "State-of-Art Review on Hybrid Nanofluids." *Renewable and Sustainable Energy Reviews* 77 (C): 551–65. https://econpapers.repec.org/RePEc:eee:rensus:v:77:y:2017:i:c:p:551-565.

Ratchawang, Sorranat, Srilert Chotpantarat, Sasimook Chokchai, Isao Takashima, Youhei Uchida, and Punya Charusiri. 2022. "A Review of Ground Source Heat Pump Application for Space Cooling in Southeast Asia." *Energies* 15 (14). https://doi.org/10.3390/en15144992.

Timofeeva, Elena V, Jules L Routbort, and Dileep Singh. 2009. "Particle Shape Effects on Thermophysical Properties of Alumina Nanofluids." *Journal of Applied Physics* 106: 14304.

Tiwari, Akanksha, and Subhas Chandra Rana. 2023. "Materials Today : Proceedings Numerical Simulation on Triple Helix Ground Source Heat Exchanger for Improving Its Thermal Performance Using Nanoparticles." Materials Today: *Proceedings*, no. xxxx. https://doi.org/10.1016/j.matpr.2023.05.411.

Widiatmojo, Arif, Sasimook Chokchai, Isao Takashima, Yohei Uchida, Kasumi Yasukawa, Srilert Chotpantarat, and Punya Charusiri. 2019. "Ground-Source Heat Pumps with Horizontal Heat Exchangers for Space Cooling in the Hot Tropical Climate of Thailand." *Energies* 12 (7). https://doi.org/10.3390/en12071274.

Xuan, Yimin, and Wilfried Roetzel. 2000. "Conceptions for Heat Transfer Correlation of Nanofluids." *International Journal of Heat and Mass Transfer* 43: 3701–7.

Understanding Safeguard Requirements in Geothermal Exploration Projects: Insights from Lenders

Eviyanti[1], Afandi[1], Desak Nyoman Inten Apriani[1], and Dorman Purba[1,2]

[1]PT Sarana Multi Infrastruktur (Persero), Sahid Sudirman Center 49th floor, Jakarta, Indonesia
[2]PT ENERKA Bhumi Pratama, Cibis Park 11th floor, Jakarta, Indonesia

eviyanti.pmugeothermal@ptsmi.co.id, afandi.pmugeothermal@ptsmi.co.id, desak@ptsmi.co.id, dorman.purba@enerklaz.com

Keywords: environmental, social, safeguard, compliance, geothermal, exploration, resource, stakeholder, lender, GREM

ABSTRACT

Geothermal exploration projects carry inherent environmental and social risks that must be managed effectively. Safeguard requirements are crucial in mitigating these risks and ensuring sustainable project development. This paper aims to provide insights into safeguard requirements in geothermal exploration projects from lenders' perspectives**.**

The introduction highlights the importance of safeguard requirements and sets the research objectives. It provides an overview of safeguard requirements in geothermal exploration projects, including international standards and guidelines that lenders adhere to. The paper emphasizes the significance of safeguard requirements in lending decisions.

Next, the paper explores key safeguard aspects in geothermal exploration projects, such as environmental and social impact assessments, stakeholder engagement, land acquisition, indigenous people rights, and health and safety measures. It elucidates the relevance of each aspect in safeguarding project integrity and minimizing potential adverse impacts**.**

From the lender's perspective, the paper examines the rationale for prioritizing safeguard requirements, their role in ensuring compliance, and the challenges and benefits of incorporating safeguard requirements into financing decisions. Case studies illustrate real-world examples, providing practical insights into how lenders approach safeguard requirements in geothermal exploration projects.

The paper advocates for collaborative approaches to safeguard implementation, emphasizing the importance of stakeholder collaboration, multi-stakeholder partnerships, and knowledge sharing. It underscores the significance of capacity-building initiatives for project developers and lenders to enhance understanding and implementation of safeguard requirements.

Evaluating the effectiveness of safeguard requirements is crucial for continual improvement. The paper discusses monitoring and evaluation mechanisms and highlights the importance of assessing the impact of safeguard requirements on project outcomes. It also identifies gaps and areas for improvement in safeguard implementation**.**

In conclusion, this paper offers valuable insights into safeguard requirements in geothermal exploration projects from lenders' perspectives. By understanding the key aspects and challenges associated with safeguard implementation, project stakeholders, including lenders, project developers, and policymakers, can effectively navigate and enhance the sustainability of geothermal exploration projects.

1. INTRODUCTION

1.1 Geothermal Energy in Supporting Renewable Energy Development in Indonesia

Geothermal is a renewable source of energy that can be used directly for heating or indirectly for power production. The renewable energy pathway is not an option but a necessity for strengthening our energy security and sustainable development. Fortunately, Indonesia is not only rich in fossil fuels but also

possesses an abundance of renewable energy sources. Indonesia has the world's largest geothermal potential for at least 24 gigawatts (GW), but only 2.293 GW (9.55%) is currently being utilized (MEMR, 2022).

Indonesia continues to rely heavily on fossil-fired power generation. In 2018, the total installed capacity was 57 GW (MEMR, 2019), of which 88 percent were from fossil fuels and 12 percent renewable sources, to meet a peak demand of 40 GW (PLN-RUPTL). Important policy goals have been formulated by the National Energy Council to re-establish Indonesia's energy independence through (i) re-directing energy resources from export to the domestic market and (ii) rebalancing the energy mix towards indigenous energy supplies. The policy implies increasing the exploitation and consumption of coal and renewable energy sources, optimizing the production and consumption of gas, and transforming the energy mix by minimizing oil consumption and raising the share of renewable energy in the country's energy mix (Infrastructure Sector Assessment Program, World Bank, June 2018).

The Government of Indonesia has set a renewable energy target of 23 percent by 2025 (MEMR's Roadmap for Accelerated Development of New and Renewable Energy 2015-2025). This Multiphase Programmatic Approach (MPA) is designed to support the government in reaching this renewable energy target with a primary focus on geothermal energy. Indonesia currently has 1.95 GW of installed geothermal capacity despite an estimated 29 GW in potential resources. The addition of 4.6 GW of geothermal capacity planned in PLN's Electricity Supply Business Plan (RUPTL) 2019-2028 would require investments of approximately US$25 billion. The MPA will implement an efficient risk-sharing mechanism to achieve the scale needed to contribute to reaching the GoI's renewable energy target. To do so, it will pilot the use of an innovative financing instrument for geothermal exploration drilling and therefore leverage investments of up to US$4 billion enabling 1,000 megawatts (MW) of geothermal development by 2029. By doing so, it will avoid emitting around 187 million metric tons of carbon dioxide (MtCO2) and match the long lead time-horizon of geothermal development.

The utilization of geothermal energy is crucial in Indonesia's transition towards renewable energy. Recently, the Government of Indonesia has been accelerating renewable energy development to support carbon reduction which it governed through the Presidential Decree No. 112 of 2022 on Accelerating Renewable Development for Power Supply. Geothermal in Indonesia is a source of energy that is environmentally friendly with enormous potential reserves, however, the utilization is still not optimal. To reduce fossil-fired power generation, the planned and integrated utilization of geothermal resources shall be encouraged and enhanced.

1.2 Safeguard Requirements in Geothermal Exploration Projects

Geothermal exploration projects carry inherent environmental and social risks that must be managed effectively. Safeguard requirements are crucial in mitigating these risks and ensuring sustainable project development. To ensure the success of a project, it is crucial to identify both the positive and negative impacts of its activities at the earlier stage of the project cycle. Therefore, a strategic approach and management plan can be developed to avoid, minimize, and mitigate or compensate for adverse risks and impacts of a project as well as enhance its positive impacts in compliance with the National laws, safeguard policies and standards.

Geothermal exploration is the riskiest phase of geothermal energy development and is challenging for developers. Thus, to scale up investment in geothermal energy by reducing the risks of early-stage exploration, the World Bank approved a loan in September 2019, accompanied by grants from the Green Climate Fund (GCF) and the Clean Technology Fund (CTF), two institutions supporting climate-friendly development, through Geothermal Resource Risk Mitigation (GREM) facility.

The World Bank designed environmental and social safeguard policies for supporting borrowers in the development and implementation of projects that are environmentally and socially sustainable. PT SMI as a Financial Intermediary in collaboration with the World Bank has prepared the GREM Environmental and Social Management Framework (GREM ESMF). The document details the environmental and social safeguard policies, principles, procedures, institutional arrangements, and

workflows in avoidance, minimization, or mitigation of any adverse environmental or social impacts of infrastructure projects supported by the Geothermal Resource Risk Mitigation Project (GREM).

The key objectives and purposes of the GREM ESMF include:

1. To guide the management of the environmental and social issues arising from the implementation of the Geothermal Resource Risk Mitigation project. The GREM ESMF lays out the environmental and social planning requirements for the investment proposal development by the developers; and
2. To ensure that all stakeholders involved in the project comply with the requirements, procedures and regulations related to environmental management in accordance to prevailing Government of Indonesia (GoI) regulations and supplemental provisions in compliance with relevant World Bank Safeguard Policies.

In addition to GREM ESMF, there are the Resettlement Policy Framework (RPF) and Indigenous People Planning Framework (IPPF). The RPF is prepared in line with the relevant laws of GoI relating to involuntary land acquisition and resettlement and World Bank OP 4.12 on Involuntary Resettlement. Whereas the IPPF is prepared in line with relevant laws of GoI relating to the management of impacts and benefits of projects to Indigenous Peoples and World Bank OP 4.10 on Indigenous Peoples.

For the implementation of the geothermal exploration project, the developer should also refer to the IFC World Bank Group Environmental, Health and Safety Guidelines for Geothermal Power Generation and other relevant International Guidelines including Good International Industry Practices (GIIP) and Best Practice for geothermal exploration.

1.3 Paper Objectives and Method

The objective of this research is to offer insight related to safeguard requirements from lenders for the geothermal exploration project financed by the International Financing Institution and to provide general guidelines for investors of the geothermal developers to be eligible for funding and for supporting sustainable development. This research is based on a literature study that involved a review of reports on geothermal exploration projects, relevant provisions, publications, research articles, and guidelines on the Environmental, Health and Safety.

The research in this paper is exploring the following question:

1. What are the challenges and risks in geothermal exploration projects?
2. What is the significance of safeguard requirements in lending decisions?
3. What are the safeguards requirements for the geothermal exploration projects under GREM facility?

2. CHALLENGES AND RISKS IN GEOTHERMAL EXPLORATION PROJECT

2.1 Challenges in the Geothermal Exploration Project in Indonesia

There are various challenges for geothermal development projects in Indonesia relate to the technical, environmental, social, human resources and commercial aspects as shown in Figure 1.

The main challenges of geothermal exploration in Indonesia are summarized as follows (IGA, 2014; Poernomo, 2015; Darma, 2016; Purba, 2018; Umam et al., 2018; Purba et al., 2019; Adityatama, 2020; Purba et al., 2020; Siahaan et al., 2023):

1. Difficulty in locating the "hottest area": Geothermal resources are not always visible at the surface and can be challenging to locate without conducting detailed geological, geochemical, and geophysical (3G) surveys and drilling test wells. The unclear indications or thermal manifestations from surface studies can make it challenging to identify the most promising areas for exploration and increase the risk of drilling dry wells.

2. High exploration costs: Conducting 3G surveys, developing a reliable conceptual model, and drilling test wells can be expensive, and there is always the risk that a project will not yield a viable resource. The high upfront capital and resource uncertainties can make it difficult for developers to secure funding for exploration activities.
3. Complex geology: Geothermal resources in Indonesia are mainly located in a volcanic area with complex geological environments, making it difficult to understand the subsurface conditions and identify the most promising areas for exploration.
4. Lack of direct and reliable data: In some cases, there may be a need for more data on the geology and geochemistry of an area, making it challenging to identify potential resources and plan the exploration activities.
5. Environmental impacts: Exploration activities can have various environmental impacts, such as air and surface water pollution, soil degradation, noise, release of hazardous gases, landslides, deforestation, and the potential for groundwater contamination. Mitigating these impacts can be costly and time-consuming.
6. Social and community impacts: Exploration activities can also have social and community impacts, such as displacement of local communities and land-use conflicts. Developers need to address these impacts and engage with local communities to ensure their support and minimize the risk of project delays or cancellations.
7. Uncertain regulations: Geothermal exploration is subject to various national, regional, and local regulations. The uncertainty can make it difficult for developers to navigate the regulatory environment and can increase the risk of project delays or cancellations.

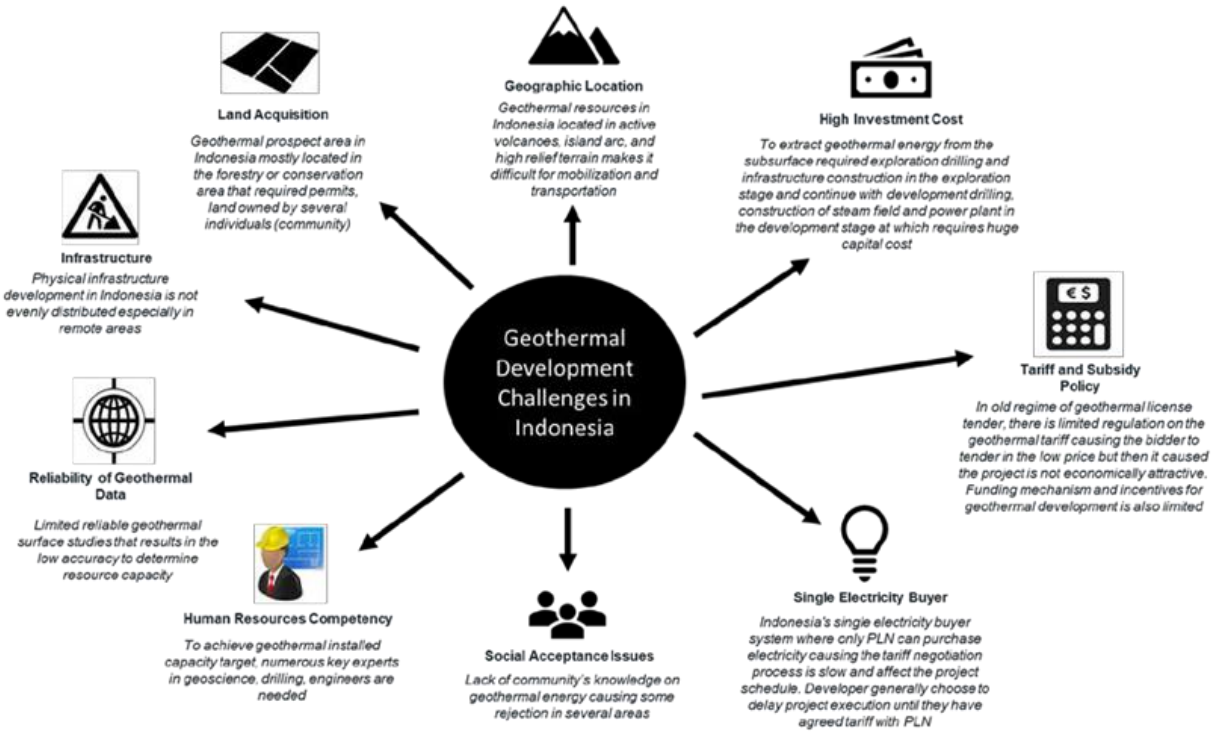


Figure 1: Geothermal Development Challenges in Indonesia (Siahaan et.al., 2023).

2.2 Environmental and Social Risks in Geothermal Exploration Projects

The majority of geothermal potential is located in or close to forest areas has raised societal concerns about environmental and social impacts, especially in forests that play an important role in supplying fresh water, harbor endangered wildlife, or have high cultural or religious values. The degree to which these social and environmental risks and impacts vary between geothermal power projects is not well understood. (PROFOR and the World Bank, 2019). Geothermal energy is a clean and sustainable source of power, however, major concerns or issues of environmental and particularly social are challenging. The developers are required to identify environmental, social, health and safety potential impacts or risks properly and comprehensively.

Geothermal exploration projects, while offering significant potential for renewable energy generation, are not without environmental and social risks. These risks can arise at various stages of the project, from exploration and development to operation and closure. Here's an elaboration on the environmental and social risks associated with geothermal exploration projects (Table 1).

Table 1: The environmental and social risks associated with geothermal exploration projects.

Environmental Risks	Social Risks
1 **Impacts due to Land Disturbance:** The construction of access roads, drilling pads, and infrastructure can result in habitat disruption and land degradation. This may impact local ecosystems, biodiversity, and soil stability. 2 **Water Resource Depletion:** Geothermal projects require large amounts of water for drilling, reservoir stimulation, and cooling. Over-extraction of water can lead to reduced groundwater levels, affecting local water sources, ecosystems, and agriculture. 3 **Water Pollution:** Chemicals used in drilling and well stimulation, as well as naturally occurring elements brought to the surface through geothermal fluids, can contaminate surface and groundwater. This pollution can harm aquatic life and pose risks to local communities relying on water sources. 4 **Induced Seismicity:** Injection and extraction of fluids into and from the geothermal reservoir can induce seismic activity. While most induced earthquakes are minor, there's a risk of larger events that could damage infrastructure and raise safety concerns. 5 **Air and Noise Pollution:** Drilling, machinery operation, and the release of gases like hydrogen sulfide can lead to air and noise pollution, affecting air quality and local communities' well-being.	1 **Land Acquisition and Resettlement:** Geothermal projects often require land acquisition, which can result in the displacement of local communities, affecting their livelihoods and traditional way of life. Inadequate compensation and resettlement processes can lead to social tensions. 2 **Cultural Heritage Impact:** Geothermal projects might encroach upon culturally significant sites or areas of historical importance to local communities. Disruption to cultural heritage can lead to social discontent. 3 **Community Health and Safety:** Potential exposure to geothermal gases and the industrial activities associated with exploration and power plant operation can pose health and safety risks to nearby communities. 4 **Employment Impact:** While geothermal projects can create job opportunities, there's a risk that local communities might not benefit as expected due to a lack of required skills or preference for outside expertise. 5 **Lack of Consultation and Participation:** Failing to involve local communities in decision-making and not seeking their input can lead to misunderstandings, opposition, and conflicts.

3. OVERVIEW OF GEOTHERMAL RESOURCE RISK MITIGATION (GREM)

The GREM Project was initiated by the Government of Indonesia (GoI) through PT SMI in collaboration with the World Bank with the objective of accelerating the development of geothermal power generation projects in Indonesia. The ultimate objective is to further stimulate the development of a clean energy source in Indonesia by de-risking it through up-front avoidance of high-risk areas and effectively mitigating social and environmental impacts through good operational management. (The World Bank Group, 2019). Under the Indonesia Geothermal Resource Risk Mitigation (GREM) project, the financing will help public and private sector developers mitigate risks in the exploration of geothermal resources, including covering a part of the cost in case of unsuccessful exploration. The GREM project will also finance technical assistance and capacity building of key stakeholders in the geothermal sector.

Under the GREM Project, a new Geothermal Resource Risk Mitigation Facility will be established. The new facility shall enable early-stage financing of geothermal projects for public and private developers to enable the increase of geothermal power generation capacities in the country. The Facility is envisaged to include three windows:

1. Government drilling or Geothermal Energy Upstream Development Project (GEUDP);
2. Public developer window; and
3. Private developer window.

Geothermal Energy Upstream Development Project (GEUDP) is a government-sponsored exploration drilling collaboration program between the Government of Indonesia and the World Bank. The program aims to develop geothermal areas that have yet to be tendered, especially in eastern Indonesia, where the area's electrification ratio is low compared to the other parts of Indonesia (Apriani et al., 2018). The source of funds for the GEUDP program comes from the PISP Fund of USD 49 million, with matching grants from the Clean Technology Fund (CTF) of USD 49 million and the Global Environment Facility of USD 6.25 million. The program also received grants from the New Zealand Ministry of Foreign Affairs and Trade (NZ MFAT) in the form of technical assistance that equals the amount of NZD 2.13 million.

MEMR, as the beneficiary of this program, will propose a geothermal prospect area to MoF to seek exploration support under the GEUDP program. Then, as the technical implementing agency, PT Geo Dipa Energi ("GDE") will conduct a preliminary assessment to see whether the proposed area is feasible to continue exploration drilling. Suppose the result shows that the proposed prospect area is viable, MoF will issue an assignment letter to GDE as the technical implementing agency and PT SMI as the financial manager to conduct the exploration drilling activities, which is supported under the GEUDP scheme.

The data acquired in the exploration drilling will be assessed by an independent party and discussed in the Joint Committee meeting to decide if the geothermal resource in the prospect area is proven and sufficient to be tendered by MEMR. Assuming that the resource is now de-risked, then MEMR will proceed with the tender process of WKP. In this stage, the participation of both public and private sector geothermal developers in the tender process is expected to increase as the geothermal resource risk has significantly reduced.

In regard to the GREM facility, it is designated to support the exploration drilling undertaken by geothermal developers who already hold the license or concession of geothermal working areas. The GREM facility is intended for SOE developers/subsidiaries of SOEs ("GREM Public Window") and private developers ("GREM Private Window"). One of the prerequisites for the geothermal developers to access this facility is that they already have the preliminary data of the prospect area/WKP. The data and information could be obtained from Preliminary Surveys, such as 3G surveys and other related studies. This information should assist the geothermal developers in concluding the feasibility of the geothermal area to proceed to the development stage so that further exploration drilling is deemed required. The unique feature of GREM is the availability of a de-risking facility or a risk-sharing scheme at which, in the event of an exploration failure, the developer does not fully bear the risks and costs of exploration.

The total commitment of GREM funding is USD 651.25 million. The pledge comes from a combination of multilateral funds, namely the International Bank for Reconstruction and Development (IBRD), Green Climate Fund (GCF), Clean Technology Fund (CTF), Global Infrastructure Facility (GIF), and Infrastructure Financing for Geothermal or *Pembiayaan Infrastruktur Sektor Panas Bumi* (“PISP funds”).

To access the GREM Public Window or Private Window facility, the developers shall have a valid geothermal exploration license or *Izin Panas Bumi* (IPB), a minimum proven track record of 3 (three) years, and a minimum equity portion of 25% of the total project cost. They must also possess geothermal data from a preliminary survey that still needs to be proven by exploration drilling to conclude the resource feasibility. Additionally, all or most of the land for exploration purposes in the working area must be legally controlled or licensed and is not currently the object of a case/dispute in any court. Finally, the implementation of the exploration project must comply with the World Bank safeguard policies and Procurement Standards.

4. THE WORLD BANK SAFEGUARDS REQUIREMENTS FOR GREM FACILITY

4.1 Overview of The World Bank Safeguard Policies

The World Bank Group is committed globally in sustainable development. The World Bank Group Strategy is securing the long-term future of the planet, its people, and its resources, ensuring social inclusion, and limiting the economic burdens on future generations. Equally, social development and inclusion are critical for all of the World Bank's development interventions and for achieving sustainable development (The World Bank Strategy, 2013). To support this strategy, the World Bank-financed project enhances opportunities for all people including vulnerable groups (women, children, disabilities, youth, and minorities) in the development process and promoting the sustainable management of natural and living resources. The World Bank developed social, environmental safeguard, and information disclosure policies to prevent and mitigate undue harm to people and their environment in a project. The borrowers or geothermal developers are required to address certain environmental and social risks in order to receive World Bank support for investment projects.

The Safeguard Policies are the mechanism for addressing environmental and social issues in a project design, implementation and operation, and they provide a framework for consultation with communities and for public disclosure.

The World Bank policies play several roles in achieving sustainable development of the development projects. These include evaluation and management of impacts and risks; provision of mechanisms for integration of environmental and social issues into decision-making; provision of a set of specialized tools to support development processes and participatory approaches; transparency and provide a platform for the participation of stakeholders in project design hence building ownership between local populations. In addition to providing guidance on measures to improve and sustain operations in specific areas, most safeguard policies provide that (a) potentially adverse environmental impacts affecting the physical environment, ecosystem functions, human health, physical cultural resources, as well as specific social impacts, should be identified and assessed early in the project cycle; (b) unavoidable adverse impacts should be minimized or mitigated to the extent feasible; and (c) timely information should be provided to stakeholders so that they have the opportunity to comment on both the nature and significance of impacts and the proposed mitigation measures. (Kazimbazi. E, 2009).

In August 2016, the World Bank adopted a new set of environment and social policies called the Environmental and Social Framework (ESF) to help protect people and the environment in the investment projects it finances. As of October 1, 2018, the ESF applies to all new World Bank investment project financing. However, The GREM facility financed by the World Bank still applies the World Bank Operational Policies (OPs) /Bank Procedures (BPs) since the GREM was set up before the effectiveness of the ESF.

Therefore, to effectively implement OPs/BPs, the ESF's ESSs should also be referenced to enhance understanding and improve approaches. The Environmental and Social Standards ("ESS") in the ESF have a more comprehensive approach to environmental and social risk. The ESF addresses a wider range of environmental and social risks than under the safeguard policies, Thus, for the implementation of the OPs/BPs, the ESF could also be referred to strengthen understanding and improve approaches.

Table 2: The World Bank ESS, Safeguard Policies (OPs/BPs) and the New Key Elements of the Standards (Modified from The World Bank Environmental and Social Framework, Implementation Update, September 2020).

The ESF	OPs/BPs	New Key Elements
ESS1: Assessment and Management of Environmental and Social Risks and Impacts	OP/BP4.01(Environmental Assessment)	Integrates Environmental and Social Assessment; includes requirements related to non-discrimination and social inclusion; proportionality and adaptive management; use of the ESCP
ESS2: Labor and Working Conditions	OP/BP4.01 (Environmental Assessment) and EHS Guidelines	Prohibits child labor and forced labor, heightened focus on OHS, grievance mechanisms
ESS3: Resource Efficiency and Pollution Prevention and Management	OP4.09 (Pest Management) and EHS Guidelines	Promotes efficient management of energy, water, and other resources and materials; hazardous materials management; pesticides; GHG assessment mandate
ESS4: Community Health and Safety	OP/BP4.37 (Safety of Dams) and EHS Guidelines	Assess risks and impacts on communities; Design of safe and resilient infrastructure, equipment operation, products, services, road safety, hazardous materials; emergency preparedness
ESS5: Land acquisition, Restrictions on Land Use and Involuntary Resettlement	OP/BP4.12 (Involuntary Resettlement)	Greater clarity on treatment of state land, land titling, access to common resources, voluntary transactions, forced evictions
ESS6: Biodiversity Conservation and Sustainable Management of Living Natural Resources	OP/BP4.04 (Natural Habitats) and OP/BP4.36 (Forests)	More detail and descriptive definition of habitat; expanded requirement to assess and mitigate impacts on biodiversity including in primary supply chains; biodiversity offsets; management of living resources in additional sectors (e.g. agriculture)
ESS7: Indigenous Peoples/Sub- Saharan African Historically Underserved Traditional Local Communities	OP/BP4.10 (Indigenous Peoples)	Clearer definitions of IP, requires FPIC in specified circumstances
ESS8: Cultural Heritage	OP/BP4.11 (Physical Cultural Resources)	Enhanced consultation with affected communities, intangible heritage
ESS9: Financial Intermediaries	OP/BP 4.01 (Environmental Assessment)	Establish E&S procedures commensurate with FI nature, risk level and impact
ESS10: Stakeholder Engagement and Information Disclosure	Consolidates WB Engagement Provisions	Meaningful consultation, access to information and grievance redress through the life of project

4.2 The World Bank Environmental Safeguard Policies Triggered by the Geothermal Exploration Project

4.2.1 OP/BP 4.01 Environmental Assessment (EA)

OP/BP 4.01 is the Umbrella Safeguards Policy which specifies the environmental assessment process used to ensure compliance with the other safeguard policies. The objectives of the policy are to help ensure the environmental and social soundness and sustainability of investment projects; and to support integration of environmental and social aspects of projects into the decision-making process.

In general, EA is as a process, that evaluates a project's potential environmental risks and impacts in its area of influence; examines project alternatives; identifies ways of improving project selection, siting, planning, design, and implementation; and includes the process of mitigating and managing adverse environmental impacts throughout project implementation.

The policy emphasizes that a screening process for each proposed project as early as possible is required to determine the appropriate extent and type of environmental assessment for an appropriate study proportional to potential impacts and risks. There are four categories of environmental assessment. A Geothermal exploration project will fall into either Category B or Category A Classification. Category B projects would be where the impacts would be local, reversible and readily managed with proven or standardized mitigation measures. Category A projects are those with significant, sensitive, complex, irreversible and unprecedented potential adverse environmental and social impacts that may affect an area broader than the sites of facilities subject to physical work. The assessment of potential impact should also consider the social community or social living of the residents around the geothermal field location.

During EA process, the borrower shall consult project-affected group and local nongovernmental organizations (NGOs) as early as possible and take their view into account. The EA document shall be disclosed before appraisal formally begins.

4.2.2 OP/BP 4.04 Natural Habitats

The objective of the policy is to promote environmentally sustainable development by supporting the protection, conservation, maintenance, and rehabilitation of natural habitats and their functions.

Those natural habitats which are (a) Legally protected (IUCN Categories I-V); (b) Officially proposed for protection; (c) Recognized as protected by traditional local communities; (d) Areas needed to maintain viability of the above; (e) Area recognized to be of high conservation value.

This policy outlines the World Bank policy on biodiversity conservation taking into account ecosystem services and natural resource management and those used by project affected people (PAP). Projects must assess potential impacts on biodiversity. The policy strictly limits circumstances under which damage to natural habitats can occur, and prohibits projects that likely result in significant conversion or degradation of critical natural habitats. Where a prospective geothermal site is located in an area that is designated as *hutan lindung* (HL) or ‘protected forest area, to remain in forest cover for watershed protection’ or conservation area, or similar, this policy will apply. Impacts will be assessed in the Environmental and Social Impact Assessment (ESIA) process.

The World Bank does not finance projects involving significant conversion of natural habitats unless there is no feasible alternative for the project and its location; comprehensive analysis demonstrates that the overall benefits substantially outweigh the environmental cost and project includes mitigation measures acceptable to the Bank.

4.2.3 OP/BP4.36 Forest

The objective of this policy is to assist borrowers to harness the potential of forests to reduce poverty in a sustainable manner, integrate forests effectively into sustainable economic, development, and protect the vital local and global environmental services and values of forests. The Bank does not finance projects that, in its opinion, would involve significant conversion or degradation of critical forest areas or related critical natural habitats.

This policy recognizes the need to reduce deforestation and promote sustainable forest conservation and management. The geothermal prospect areas could be within a forest area as defined by its protection status based on the GoI regulations as well as the definition of forests under the Policy. The impacts on forest health and functions, and the impacts on affected persons that rely on forest resources, will be assessed as part of the ESIA and Resettlement Action Plan processes and mitigation measures will be incorporated into the Environmental and Social Management Plan (ESMP) and Land Acquisition and Resettlement Action Plan (LARAP.)

4.2.4 OP/BP 4.11 Physical Cultural Resources

This policy sets out World Bank requirements to avoid or mitigate adverse impacts resulting from project development on cultural resources. It is likely that PCR will be found near geothermal exploration projects. In some cases in Indonesia, local communities consider the manifestations of geothermal energy as sacred. The GREM ESMF includes the requirements for preparing PCR Management Plans (PCRMP), which will be developed as part of the ESIA and ESMP processes, as well as the requirement for a chance find procedure to be attached to every ESMP.

4.2.5 OP/BP 4.10 Indigenous People

This policy requires the Government to engage in a process of free, prior and informed consultations with indigenous peoples, as described by the policy in situations where indigenous peoples are present in, or have collective attachment to, the project area and for the preparation of an Indigenous Peoples Plan (IPP) and/or Indigenous Peoples Planning Framework (IPPF). The objectives of the policy are that broad community support from Indigenous Peoples in the project area should be obtained and that the policy aims to minimize impacts and provide culturally appropriate benefits and mitigation measures.

4.2.6 OP/BP 4.12 Involuntary Resettlement

This policy addresses direct economic and social impacts from the project activities that will cause (a) involuntary taking of land resulting in (i) relocation or loss of shelter, (ii) loss of assets or access to assets or (iii) loss of income sources or livelihoods and (b) involuntary restriction of access to legally designated parks and protected areas resulting in adverse impacts on the livelihoods of the displaced persons. The policy requires siting of project infrastructure to be so chosen so as to avoid these impacts altogether or to minimize them to the extent possible. Where these cannot be avoided, the policy requires the preparation of either or both of these instruments (i) resettlement policy Framework, (ii) Resettlement Action Plan, and for meaningful consultations with potentially affected people. The policy prohibits Community donations of lands for location-specific infrastructure.

4.2.7 OP/BP 4.37 Safety of Dams

When the Bank finances a project that includes the construction of a new dam, this Policy requires that the dam be designed and its construction supervised by experienced and competent professionals. It also requires that the Borrower adopt and implement certain dam safety measures for the design, bid tendering, construction, operation, and maintenance of the dam and associated works. The Policy is triggered because the drilling process requires storage and settling ponds for brine and other drilling fluids. The requirements of the Policy will be included in the sub-borrower legal agreement, design contracts, and drilling contracts, and the activities and outputs will be monitored under the ESMF and the monitoring of sub-project safeguard instruments.

4.3 The Environmental and Social Standards of PT SMI

The geothermal exploration project shall also comply with the Environmental and Social Standards of PT SMI ("PT SMI ESS") which are commensurate with the World Bank Policies. PT SMI ESS is comprised of ten elements which are:

1. ESS-1: Assessment and management of environmental and social risks and impacts
    - Prevent, or if prevention is impossible, to minimize, mitigate, or compensate for the negative impacts on the environment and local communities.

- Ensure that permits, mandated by the government to identify and assess positive or adverse environmental and social impacts, are obtained by project proponents prior to the project execution.

2. ESS-2: Labor and working conditions
   - Create, improve, and maintain relationships between the management and the workers.
   - Encourage fair treatment without discrimination, equal opportunities for workers, and efforts to comply with the law. Preventing children labor and forced labor. Encourage safe and healthy working conditions as well as protect and promote worker health.
3. ESS-3: Pollution prevention and abatement
   - Prevent or minimize negative impacts on human health and environment by avoiding or minimizing pollution from project activities. Encourage the reduction of emissions that contribute to climate change.
4. ESS-4: Safety, health and security
   - Prevent or minimize the risks and impacts on health, safety and security of workers and the surrounding community both in routine and non-routine activities.
   - Ensure protection of personnel and property is done properly so as to prevent or minimize risks to the community's safety and security.
5. ESS-5: Land acquisition and resettlement
   - Avoid the negative impact or at least minimize the risk of involuntary resettlement.
   - Mitigate the social and economic impacts of land acquisition on the affected people by providing compensation for loss of assets at replacement cost; and ensuring that resettlement activities are undertaken properly, through information disclosure, consultation and informed participation of those affected.
   - Improve or at least restore the livelihoods and standards of living of the relocated people.
6. ESS-6: Biodiversity conservation and natural resources management
   - Protect and conserve biodiversity and encourage sustainable development and natural resource utilization by applying integrated conservation techniques.
7. ESS-7: Indigenous peoples and local community
   - Protect Indigenous Peoples and local communities from development that is not in accordance with their educational, social and cultural levels, and thus impacts them adversely.
   - Encourage Indigenous Peoples and local communities to partner with the developers and share social and economic benefits of projects.
8. ESS-8: Cultural heritage
   - Protect the cultural heritage from the negative impacts of project activities and support its preservation.
   - Encourage the project developers to take responsibility towards protecting the cultural heritage around the project area.
9. ESS-9: Energy conservation and environment-friendly energy
   - Support energy conservation as a saving effort in the resources used in order to safeguard natural resources and encourage the planned and directed resource use in a sustainable manner.
   - Encourage sustainable development and energy use through an integrated application of conservation having the development priorities.
   - Promote the development of environment-friendly green energy facilities which are as an effort to increase new and renewable energy
10. ESS-10: Consultation and grievance mechanism
    - Encourage information transparency and encourage the participation of community and other stakeholders as fair and profitable consulting efforts.
    - Encourage community participation in sustainable development in the affected area as an effort to facilitate the culture of consensus and democracy in the project and affected communities through a grievance mechanism

4.4 The Gaps between Government Regulations and the World Bank Safeguard Policies

For the GREM facility, the project must also comply with the applicable National Laws and Regulations. There are some gaps identified between the applicable GoI regulations and the World Bank Safeguard Policies which the comparison of key features is presented in Table 3. To comply with both systems, where there is conflict between the National Laws/Regulations and the World Bank Policies, the highest standard prevails. It means the project shall apply the most restrictive in terms of avoiding or minimizing social and environmental impacts.

Table 3: Comparison between GOI Laws/Regulation and the World Bank Policy.

No.	Topic	Indonesian Regulation	The World Bank Policy
1.	Applicable Safeguard Instrument	Geothermal exploration requires only an Environmental Management Plan and Monitoring Plan (UPL-UKL), regardless of potential impacts, according to GOI Regulation No. 5 of 2021 Appendix I in the Energy and Mineral Resources Sector.	OP4.01 requires an assessment of safeguard instruments depending on the classification of activity based on risk
2.	Associated Facilities	The GOI laws and regulations consider project activities discretely - consider each phase as a separate environmental permit process, and thus require separate application and obtainment of approvals accordingly (GOI Regulation No. 22 of 2021 Appendix III)	OP4.01 Environmental Assessment requires an assessment of associated facilities where they are considered part of the Project (either geographically, or over time),
3.	Utilization of Forest Area	Remove barriers to carrying out geothermal exploration and exploitation activities in forests and protected areas - take into account the low-impact use of ecosystem services and that geothermal is accepted and increasingly considered as a nationally strategic activity (Geothermal Law No. 21 of 2014, Article 5, Section 2)	The World Bank policies (OP 4.36 and 4.04) have maintained their requirements and standards regardless of the activities and require full impact assessment / significant mitigation before sub-project appraisal, or not funding certain exploration activities – that may result in degradation or removal of critical habitats
4.	Involuntary Resettlement	Land acquisition plan based on a feasibility study, the project suitability to the spatial plan.	Different planning instruments must be prepared to achieve the objectives of the policy and must cover all aspects of the proposed resettlement (LARAP)
5.	Eligibility of Indigenous People	Indigenous Peoples are covered by the land acquisition and resettlement legislation once they have been legally recognized	IPs are covered when screening identifies the presence of IPs as per characteristics in OP4.10 policy (which does not require any legal recognition).

4.5 Safeguard Instruments and Permits Requirements for the GREM Facility

For compliance with the World Bank policies and eligibility for the GREM facility financing, the developer shall ensure that the project is implemented in accordance with the provisions of the GREM ESMF, mitigation plans in each safeguard instrument, and its supplemental instruments in a manner satisfactory.

As a prerequisite of being financed under GREM facility, at earlier stage the developer is mandatory at minimum to submit an Environmental Management Effort - Environmental Monitoring Effort (*Upaya Pengelolaan Lingkungan - Upaya Pemantauan Lingkungan* or UKL-UPL) including the Environmental Permit/Approval, an approved final draft of Environmental and Social Impact Assessment (ESIA) and Environmental and Social Management Plan (ESMP) as part of their proposal document.

The key safeguard instruments and permits that are required for the GREM facility are summarized in Table 4.

Table 4: The Key Safeguard Instruments and Permits Requirements for the GREM Facility.

Stage	Safeguard Instrument/Permit	Remarks
GREM Facility Application (Proposal)	Approved UKL – UPL	Has been approved by the authority. To comply with the applicable GoI laws and regulations;
	ESIA and ESMP (Approved Final Draft)	To comply with the World Bank policies and GREM ESMF. ESMP is specifically prepared for managing the impacts and risks of the project.
	Environmental Permit/Approval	Has been issued by the Ministry of Environment and Forestry
	Forest Area Use Permit, if applicable	If the permit is not yet issued, the developer is required to provide details on the current status of the permitting process
Financing Approval Process	Final ESIA and ESMP	To be approved by PT SMI and the World Bank. Finalization and disclosure of the UKL-UPL, ESIA, and ESMP documents are minimum requirements for financing approval by the Financing Committee.
Before Construction and Drilling Activities Commence	Sub-plans and procedures of the project ESMP	Sub-plans and procedures that need to be prepared are subject to the results of Environmental and Social Due Diligence (Corrective Action Plan).
	Final Stakeholder Engagement Plan (SEP) and Grievance Redress Mechanism (GRM)	These documents shall be prepared in project preparation from the outset of the ESIA study. Involve stakeholders at the early stage of the project cycle to ensure their participation and input.
	Land Acquisition and Resettlement Action Plan (LARAP) and Livelihood Restoration Plan (LRP)	If any land /assets and/or any loss of income (livelihood) are affected by the project. No work begins until land acquisition and resettlement has been completed.
	Indigenous People Plan (IPP)	If triggered in the ESIA and ESMP
	Physical Cultural Heritage Management Plan (PCHRMP) and Chance Find Procedure (CFP)	Despite the physical cultural heritage is not triggered, the Chance Find Procedure is still required.
	Gender Action Plan (GAP) and Gender Based Violence (GBV) Risk Management	This is an instrument as required by the World Bank policy for proposing gender equality in the design and implementation of projects, and to

Stage	Safeguard Instrument/Permit	Remarks
		protect women in the project area from gender-based violence
	Forest area Use Permit (PPKH)	Issued by the MoEF or the authority in accordance with the applicable related regulation
	Surface Water Extraction Permit (SIPPA)	Issued by the Ministry of Public Works and Housing or the authority in accordance with the applicable related regulation
	Contractor – ESMP (C-ESMP) and Standard Operation Procedures	The C-ESMP shall be prepared by an awarded Contractor and approved/cleared by PT SMI and the World Bank before work begins

5. SIGNIFICANCE OF SAFEGUARD COMPLIANCE

In the geothermal development project, the exploration phase is considered the most critical phase in which the challenges are not only technical but also environmental and social aspects. Geothermal exploration activities are generally located in sensitive areas that cause various potential environmental and social impacts in which sensitive receptors are more at risk.

Prior to commencing a geothermal exploration initiative, it is crucial to ascertain pivotal criteria such as the project's proximity to sensitive receptors and potential societal concerns. For example, if the project is located near or within a forest area designated as a conservation or protection forest, it may adversely impact biodiversity. Moreover, insufficient awareness among the local people regarding geothermal energy poses a significant challenge to the project's acceptance, potentially resulting in resistance from the community. As part of the ESIA study, a thorough analysis will be conducted to identify any possible environmental and social impacts and risks that may arise. Comprehensive measures will be prepared to mitigate these potential impacts and ensure that the project is executed in a responsible and sustainable manner. Therefore, management of environmental and social impacts and risks is critical for projects' successful development. Inappropriate handling of these issues can result in negative consequences such as the termination of a project, delays, and/or costly mitigation measures.

5.1 Implementation and Monitoring of Safeguards for GREM Project

The project's sustainable development is achieved through the effective implementation of safeguard policies and standards. Monitoring the implementation of environmental and social safeguards is crucial in identifying problems at an early stage, allowing for timely and efficient solutions. Evaluation is used to assess the effectiveness of management planning measures in achieving their objectives, such as in compliance with World Bank policies and adhering to provisions in the GREM ESMF. Therefore, the developer shall prepare a detailed implementation process in their Project Operation Manual.

Early identification and resolution of problems is possible through monitoring, including identifying changes in plans and failures to follow them. Planning in advance is crucial for effective monitoring and evaluation during project design and implementation. Environmental and social management plans determine the monitoring requirements based on the project's impacts and risks. Additionally, baseline data is necessary to monitor and evaluate implementation progress. Last but not least, the management plans should clearly specify the responsible agencies or personnel for monitoring, particularly those that require coordination across multiple institutions. The implementation of safeguards requires collaboration from all relevant stakeholders and institutions (Central Government and Local Government).

For the Environmental and Social Safeguards Process, the implementation and monitoring step is a critical step to ensure the safeguard requirements compliance. The developer will prepare the safeguards instruments and be responsible for the implementation of mitigation. PT SMI will review, provide comments and clearance the instruments, and be responsible for supervision and enforcement.

In brief, the implementation and monitoring shall pay attention to the following:

1. Integrate safeguards aspects into geothermal exploration plans;
2. Prepare all additional instruments and detailed ESMP sub-plans as required by the ESMF, IPPF, RPF, and the Corrective Action Plans (CAPs) from the Environmental and Social Due Diligence process;
3. The ESMP will include measures that have been identified as Good International Industry Practices;
4. Include the ESMP in the Contractor's bid documents and the Contractor's contract. Contractor's selection process will include the capacity to implement ESMP, and UKL/UPL;
5. The Contractor will be required to prepare a Contractor's ESMP before work begins. The Contractor's ESMP will document, in detail, how the Contractor will fulfill its roles and responsibilities as documented in the Project ESMP;
6. No work will begin on site (including ancillary works such as access roads) until land acquisition and resettlement has been completed and PT SMI Safeguards Team and the World Bank have cleared the Contractor's ESMP;
7. Monitor and supervise the Contractor's ESMP implementation and be responsible for implementing other aspects of the project ESMP not under the Contractor's control;
8. Continually review, adapt and update the ESMP and sub-plans as necessary throughout the project in response to new risks, new activities and as a result of near misses or incidents and return to PT SMI for clearance;
9. Responsible for leasing, purchasing land through 'willing buyer/willing seller' or implementing LARAP for involuntary land acquisition/resettlement, including providing entitlements and other support to the affected and displaced persons;
10. Training that will be carried out by the developer and/or a third-party consultant, where necessary, in accordance with the capacity building plans in the ESMP;
11. Supervision, monitoring and reporting will be carried out by the Developer of the Contractor and the detailed requirements of the ESMP.

The Environmental and social safeguard appraisal in the GREM funding process is presented in in Figure 2 below.

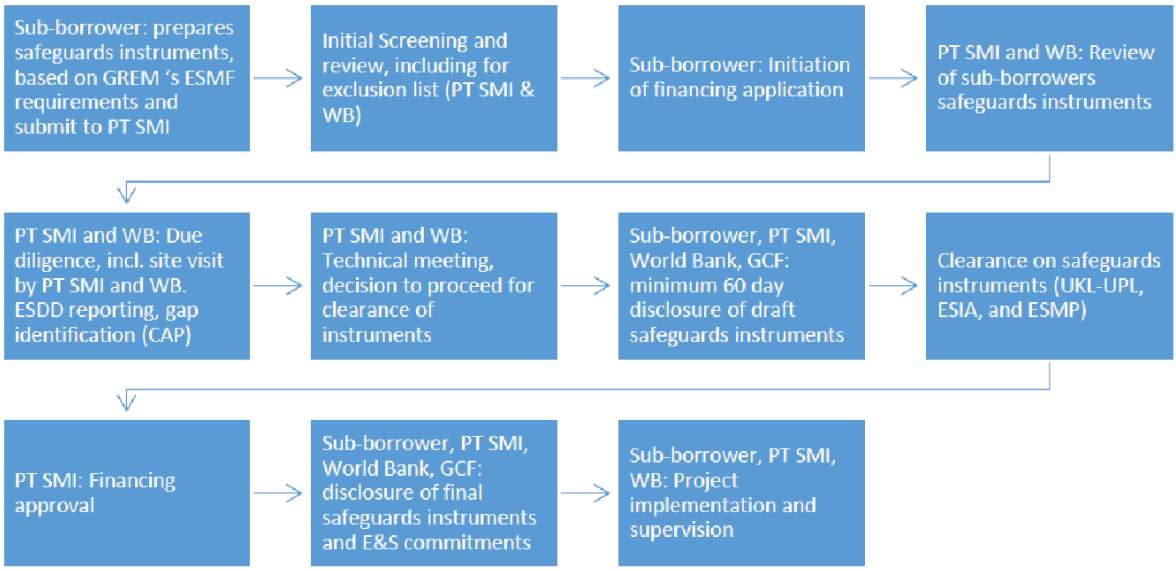


Figure 11: Environmental and Social Safeguard Appraisal in GREM Facility Funding Process.

5.2 The Challenges and Benefits in Safeguard Implementation

It is essential that the borrowers or developers prioritize safeguard requirements at the early stage of the project cycle. From the lender's perspective, by complying with safeguard requirements and adhering to the applicable National regulations, the World Bank safeguard policies, and provisions in the ESMF, the geothermal developers can increase their eligibility for funding and demonstrate commitment to sustainable practices.

In the preparation of a geothermal exploration project, PT SMI identified some areas where the developer experienced challenges with the safeguards requirements. The key findings are summarized below:

1. Safeguard Instruments Preparation (ESIA, ESMP, and others):
    - The scope of the ESIA (International Standards) is wider than the National Environmental Impact Assessment (UKL-UPL or AMDAL). The preparation of safeguard instruments shall fulfill the provisions of the GREM ESMF to adhere to the World Bank policies, RPF, and IPPF. Developers faced more efforts in preparing the safeguard instruments to meet the World Bank policies and International Standards.;
    - The project area of influence was not established in the ESIA document appropriately. It should cover project footprints, ancillary facilities, and associated facilities.
    - Improper screening and scoping process to define the categorize the document and define the scope of the ESIA study. It is required to ensure the involvement of subject matter experts in the process.
    - Baseline data did not accurately represent the current baseline conditions of sensitive receptors. Moreover, the baseline data should be collected to provide a comprehensive of the current situation for both dry and wet seasons.
    - Limited information on the project activities: A detailed description of project planning and activities is crucial for the ESIA study. A detailed project description and representative baseline data are required to assess the potential impacts and risks thoroughly and comprehensively. However, during the preparation of ESIA, the initial project design that explains in detail the exploration plan was not yet available. The design alternatives should be considered in the ESIA study for further impact assessment and mitigation measures identification.

2. Project Organization and team capacity: Limited dedicated EHS personnel to manage a project and limited knowledge and experience in geothermal development projects that will be crucial during the safeguards implementation and monitoring of the project. The project organization should be set up at an early stage to prepare safeguard instruments and implement the safeguard requirements.

3. Stakeholders engagement and consultation: Lack of proper engagement and consultation as well as a lack of information on the potential impacts and risks of the proposed geothermal exploration activities.

4. Land-related issues: The challenges included the permitting process to secure the project area within a protected forest area, unclear land ownership, communal land, and social forestry issues. The effort required for land acquisition, some community lands or especially *tanah adat* or communal land might be difficult if not impossible to acquire. In the exploration phase where local people are not familiar yet with the geothermal project, there is a high possibility that they will hesitate to sell or lease their land to the geothermal developer, particularly if the land is being used to cultivate productive plants, like rice, coffee, cocoa, etc. (Purba et al., 2019).

Properly preparing a project by incorporating safeguard instruments and engaging stakeholders effectively will benefit the project. By meeting safeguard requirements, the project is more likely to be

accepted by local communities, implemented smoothly for geothermal exploration, and contribute to sustainable development.

5.3 Evaluation of Safeguard Implementation

For the effectiveness of safeguard implementation, it is imperative to consider but not limited to the followings:

1. A comprehensive ESIA and ESMP will help the developers to identify, avoid, minimize, and mitigate for adverse impacts and risks as well as enhancing the positive impacts of project to achieve project sustainable development. The capacity building on the World Bank safeguard requirements to the developers and their ESIA consultant is beneficial to enable them in assessing the impacts and the mitigation plans thoroughly and comprehensively to avoid, minimize, and mitigate or compensate for adverse impacts to comply with the World Bank policies and Good International Industry Practice (GIIP) standards. This also will make the ESIA a reliable basis for decision-making;
2. ESMP shall be reviewed regularly during its implementation for any improvement on the mitigation measures of impacts due to new or non-anticipated impacts. The developers shall ensure effective implementation of the ESMP, which the potential environmental and social impacts being managed and mitigated effectively for sustainable development;
3. Consultations should be held with key stakeholders to determine potential concerns and issues associated with the project as early as possible in the project cycle and through the life of the project. The proposed project activities and its potential impacts shall be socialized to stakeholders including local communities transparently;
4. Capacity building to communities and other stakeholders on the geothermal development project is important to enhance their knowledge on geothermal energy as a renewable energy in comparison with other renewable energy sources. The public's lack of understanding of the importance of geothermal projects frequently leads to rejection, resulting in delays in geothermal development initiatives. This circumstance is most common when geothermal projects are still in the discovery stage and local governments, development corporations, and local communities still recognize each other and have not yet created trust between each side—social dynamic conditions and public acceptance issues that can be stopper of geothermal project. (Fadhillah et al., 2022 and 2023);
5. Multi-stakeholder collaboration and partnerships play an important role in the success of a project. The early involvement of the community and other stakeholders will build their participation towards the project. With continuous, transparent and effective communication about the project and its potential impacts and an approach that takes into account local culture, any concerns from the community can be discussed and solutions sought as early as possible. With this approach, it is expected that there will be no rejection of the project.

6. DISCUSSION

The paper focuses on the safeguard requirements, frameworks, and processes associated with the Geothermal Resource Risk Mitigation (GREM) facility application for geothermal exploration projects. It highlights the critical steps and instruments necessary to ensure the mitigation of environmental and social impacts, comply with regulations, and adhere to World Bank safeguard policies. The discussion covers various aspects, including the GREM Safeguard Framework, safeguard instruments, appraisal processes, and implementation and monitoring procedures.

The GREM Safeguard Framework, outlined by PT SMI, lays the foundation for managing environmental and social issues arising from GREM-supported projects. It provides guidance for compliance with prevailing government regulations and World Bank safeguard policies, facilitating consistent and responsible project implementation. Additionally, the Resettlement Policy Framework (RPF) and Indigenous People Planning Framework (IPPF) ensure proper management of impacts on communities and cultural heritage.

Safeguard instruments play a pivotal role in the GREM facility application process. These instruments, including Environmental Management Effort - Environmental Monitoring Effort (UKL-UPL), Environmental and Social Impact Assessment (ESIA), and Environmental and Social Management Plan (ESMP), form the core of the proposal. They must be prepared according to National Laws/Regulations, World Bank policies, and PT SMI's Environmental and Social Standards (ESS). These documents, along with supplementary plans for aspects like land acquisition, indigenous peoples, and cultural heritage, collectively ensure the comprehensive consideration of environmental and social factors.

The appraisal process involves reviewing these safeguard instruments to ensure they align with the GREM Safeguard Frameworks. PT SMI's Project Management Unit (PMU) plays a crucial role in this review, ensuring that projects are compliant and adequately address potential impacts.

The subsequent sections delve into the implementation and monitoring of safeguards. They emphasize the integration of safeguards into project plans, preparation of detailed implementation processes, monitoring contractor compliance, conducting regular reviews, and adapting strategies in response to new risks or incidents. PT SMI's supervision is key to ensuring adherence to safeguard instruments and standards throughout the project lifecycle.

In the pursuit of sustainable geothermal energy development, the GREM facility application process stands as a comprehensive approach to addressing environmental and social concerns associated with geothermal exploration projects. By adhering to stringent safeguard instruments, developers ensure that their activities are in line with both national regulations and international best practices, as embodied by the World Bank's policies.

The GREM Safeguard Framework, coupled with well-prepared safeguard instruments, not only guarantees compliance but also serves as a blueprint for responsible project management. The inclusion of Resettlement Policy Framework and Indigenous People Planning Framework underlines the commitment to safeguarding communities and cultural heritage.

Through a thorough appraisal process, these safeguard instruments are fine-tuned to align with the specific project context. This meticulous approach is carried forward into the implementation and monitoring phases, where ongoing review and adaptation ensure that projects remain environmentally sound and socially responsible.

In essence, the GREM facility application process underscores the importance of striking a balance between energy development and environmental and social preservation. This approach not only contributes to the sustainable growth of geothermal energy but also sets a precedent for responsible resource development worldwide.

REFERENCES

Himberg. H: Comparative Review of Multilateral Development Bank Safeguard Systems. Consultant, Operations Policy and Country Services (May 2015).

Kasimbazi, E.: Compliance with Safeguard Policies of The World Bank and African Development Bank, *Proceedings*, 29th Annual Conference of the International Association for Impact Assessment Accra International Conference Center, Accra, Ghana (2009).

Prasetya.M.,Nurdin, Muhammad.,Kushendratno, Agus.W. : Forest Area Boundary Situation Survey: A National Land Strategic Program to Support Land Tenure Security in Indonesia, FIG e-Working Week, Smart Surveyor Land and Water Management-Challenges in a New Reality Virtually, Netherlands, 21-25 June 2921.

PROFOR and the World Bank Group.: Rapid Environmental and Social Assessment of Geothermal Development in Conservation Forest Areas In Indonesia (August 2019)

PT PLN (Persero).: Rencana Usaha Penyediaan Tenaga Listrik (RUPTL) (September 2021).

PT SMI.: Indonesia Geothermal Resource Risk Mitigation Project Developer Manual. (2022).

PT SMI. Indonesia Geothermal Resource Risk Mitigation Project GREM (P166071) Environmental and Social Management Framework. (2019).

Purba, D, Adityatama, D, Umam, M., Muhammad, F.: Key Considerations in Developing Strategy for Geothermal Exploration Drilling Project in Indonesia, Proceedings, 44th Workshop on Geothermal Reservoir Engineering, Stanford University, Stanford, California, February 11-13, 2019

Siahaan, M., Septiani,G., Purba,D: Geothermal Exploration Project De-risking: Discussion on Various Schemes, *Proceedings*, 48th Workshop on Geothermal Reservoir Engineering, Stanford University, Stanford, California, February 6-8, 2023

The World Bank.: The World Bank Environmental and Social Framework, World Bank Environmental and Social Policy for Investment Project Financing (2017).

The World Bank Group.: The World Bank Group Strategy. Washington, DC: World Bank Group (October 2013).

The World Bank.: Environmental and Social Policies. https://www.worldbank.org/en/projects-operations/environmental-and-social-policies (Accessed on 31 August 2023)

The World Bank.: Preparing Feasibility Studies for the Financing of Geothermal Projects. ESMAP. An Overview of Best Practices. Washington, DC.(2021)

The World Bank.: Geothermal Handbook: Planning and Financing Power Generation. ESMAP. Technical Report 002/12.Washington DC(2012).

The World Bank.: Scaling Up Renewable Geothermal Energy in Indonesia. ESMAP. Washington DC (2014)

The World Bank.: Safeguards and Sustainability Policies in a Changing World. IEG Study Series. An Independent Evaluation of World Bank Group Experience.Washington, DC (2010)

The World Business Council for Sustainable Development.: Guidelines for Environmental and Social Impact Assessment. Cement Sustainability Initiatives. (August 2016)

Unlocking the Potential: A Preliminary Study on Geothermal Direct Use Business Models and Potential Applications in Indonesia

M. Rizqi Al Asy'ari[1], Daniel W. Adityatama[1], Dorman Purba[2], Adika Bagaskara[1], and Nadya Erichatama[2]

[1]GEOENERGIS, Cibis Nine 11th Floor, Jakarta Selatan 12560, Indonesia
[2]PT ENERKA Bhumi Pratama, Cibis Park 11th floor, Jakarta, Indonesia

rizqialasyari21@gmail.com, rizqialasyari@geoenergis.com

Keywords: geothermal, direct use, direct utilization, Indonesia

ABSTRACT

Direct use of geothermal energy refers to the immediate use of heat energy rather than converting it into electricity or other forms of energy. Geothermal energy has gained significant attention as a sustainable and renewable energy source, with the potential to meet various energy demands. However, the utilization of geothermal resources for direct applications beyond electricity generation has been relatively underexplored. Despite Indonesia's high potential of geothermal energy, its geothermal direct utilization is very small compared to other countries. There is no report or update regarding the new geothermal direct use facility in Indonesia since 2015. This contrasts with the geothermal power generation in Indonesia, which is currently number two in the world in terms of installed capacity, behind the USA. But, unfortunately it is safe to assume that geothermal direct use in Indonesia seems to be ignored compared to geothermal utilization for power generation.

The objective of this study is to identify and analyze potential business models that can leverage geothermal energy for direct use applications in Indonesia and also conduct preliminary direct use potential application mapping in various geothermal working area in Indonesia. The research methodology involves a thorough review of existing literature, case studies, and interviews with industry experts to gather insights and perspectives on geothermal direct use. Additionally, this study examines the regulatory and policy framework related to geothermal direct use in Indonesia, identifying potential barriers and opportunities for business development. The analysis highlights the need for supportive policies, incentives, and collaboration among stakeholders to promote the growth of geothermal direct use projects.

Furthermore, the study assesses the economic viability of geothermal direct use business models, considering factors such as market demand, and sustainability considerations. In conclusion, this research hopefully can provide valuable insights and contribute to the understanding of the economic, environmental, and social dimensions of geothermal direct use, emphasizing the importance of tailored approaches and policy support for successful implementation. The outcomes of this study can serve as a preliminary foundation for decision-makers, investors, and industry players to explore and capitalize on the untapped potential of geothermal energy for direct use applications in Indonesia.

1. INTRODUCTION

1.1 Geothermal Energy Status in Indonesia at a Glance

Geothermal energy, harnessed from the Earth's internal heat, stands out as a promising and sustainable power source that aligns seamlessly with the global transition towards cleaner and renewable energy alternatives. Given its immense geothermal potential, Indonesia has emerged as a focal point for geothermal exploration and development, showcasing the nation's unwavering commitment to curbing carbon emissions and ensuring energy security. The geothermal energy development project possesses inherent traits of being environmentally friendly, with low carbon emissions, although requiring substantial initial investments and featuring an extended period for returns. Hence, it is imperative for both investors and geothermal developers to effectively oversee and manage their projects (Al Asy'ari, Adityatama, & Purba, 2023; Al Asy'ari, et al., 2022). As the world grapples with the urgent imperative

of addressing climate change, unlocking the full potential of geothermal energy becomes nothing short of crucial.

Indonesia, situated within the Pacific Ring of Fire, is graced with abundant geothermal potential due to its tectonic activity and volcanic landscapes. Indonesia, renowned for its abundant geothermal reserves approximately 23.357 GW (EBTKE, 2022). Based on Thinkgeoenergy (2023), Indonesia is currently become 2nd largest geothermal producer countries with total installed capacity is approximately 2,236 MW. This geothermal wealth positions Indonesia as one of the world's leading geothermal energy producers and provides a unique opportunity to explore diverse applications beyond conventional power generation. The current updated information of geothermal powerplant installed capacity is shown in Figure 1.

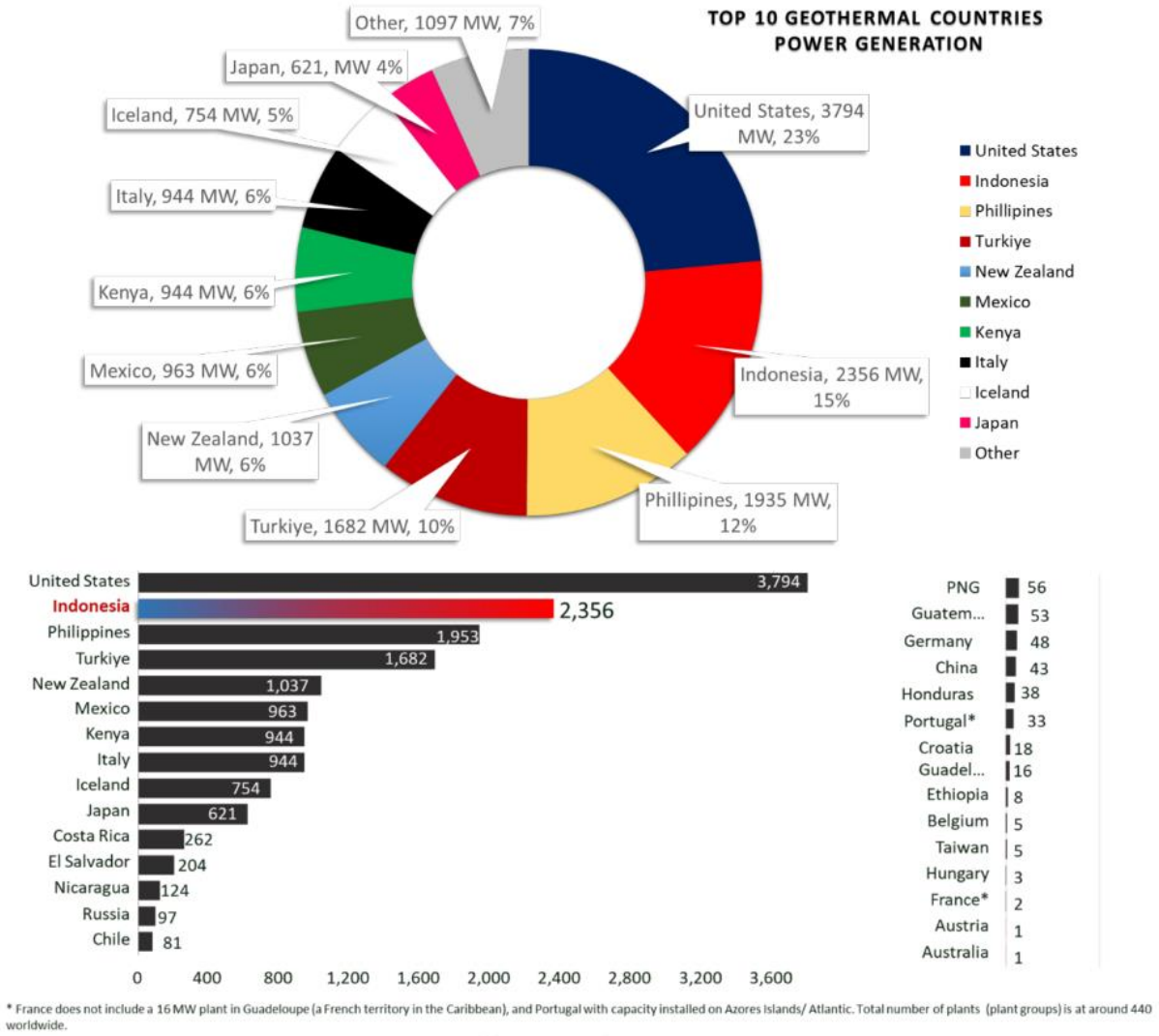


Figure 1: Worldwide update geothermal power plant installed capacity as per January 2023. Modified design from (Richter, 2023; Thinkgeoenergy, 2023).

This country has potential and opportunities to exploit geothermal energy not only for electricity generation but also for direct-use applications. Geothermal direct use involves harnessing the naturally occurring heat from geothermal reservoirs for various purposes beyond power generation. These applications encompass district heating, greenhouse cultivation, industrial processes, and even aquaculture. As the demand for sustainable energy solutions continues to surge, the exploration of these diverse direct-use applications becomes nothing less than imperative.

While geothermal power generation has received considerable attention, the possibilities presented by geothermal direct use remain relatively untapped. This study seeks to illuminate this underexplored potential, with a focus on the myriad benefits, challenges, and business models associated with harnessing geothermal energy directly.

However, realizing the full potential of geothermal direct use requires concerted efforts from various stakeholders. Policymakers must provide a supportive regulatory framework that facilitates project development and ensures fair allocation of risks and rewards. Investors need to recognize the long-term benefits and opportunities presented by geothermal direct use projects. Communities and end-users play a crucial role in embracing these solutions and reaping the benefits they offer.

1.2 Research Background

Despite Indonesia's vast geothermal energy potential, its utilization for geothermal direct applications remains significantly smaller compared to other countries. There have been minor updates regarding new geothermal direct utilization facilities in Indonesia since 2015. This stands in stark contrast to geothermal power generation in Indonesia, which currently holds the second position globally in terms of installed capacity, trailing only behind the USA. Regrettably, it is evident that geothermal direct utilization in Indonesia has been relatively overlooked when compared to the emphasis placed on geothermal utilization for power generation. The latest update of Indonesia’s position is illustrated in Figure 2.

Despite the potential of geothermal direct use in Indonesia, there exists a research gap regarding its applications and business models in the Indonesian context. One of major solution for boosting geothermal direct use application in Indonesia is develop the direct use business in commercial scale.

1.3 Research Objectives and Methods

This preliminary study aims to delve into the realm of geothermal direct-use business models and their potential applications across various geothermal sites in Indonesia. It covers the identification and conduct analyze of potential business models that can harness geothermal energy for direct applications in Indonesia. Additionally, the study aims to conduct a preliminary mapping of potential direct use applications across various geothermal working areas in the country. Simply, the objective of this study can be broken down into the following points as follows:

- Investigating the current landscape of geothermal direct use applications globally and in Indonesia.
- Exploring the various business models that can drive the implementation of geothermal direct use projects.
- Identifying potential geothermal working areas in Indonesia that are conducive to direct use applications.

By comprehensively analyzing these elements, this paper aim to contribute to the broader discourse on sustainable energy utilization and help stakeholders make informed decisions about integrating geothermal direct use into Indonesia's energy portfolio. As the nation embarks on a path towards achieving its renewable energy targets, harnessing the untapped potential of geothermal direct use promises not only to drive economic growth but also to establish a more environmentally responsible energy sector.

The subsequent sections of this paper will delve deeper into the concepts of geothermal direct use applications, exploring different business models that can facilitate their implementation, and identifying potential geothermal working areas in Indonesia. The research methodology entails a comprehensive review of existing literature, case studies, and interviews with industry experts. These approaches are employed to gather insightful perspectives and valuable insights into the realm of geothermal direct use.

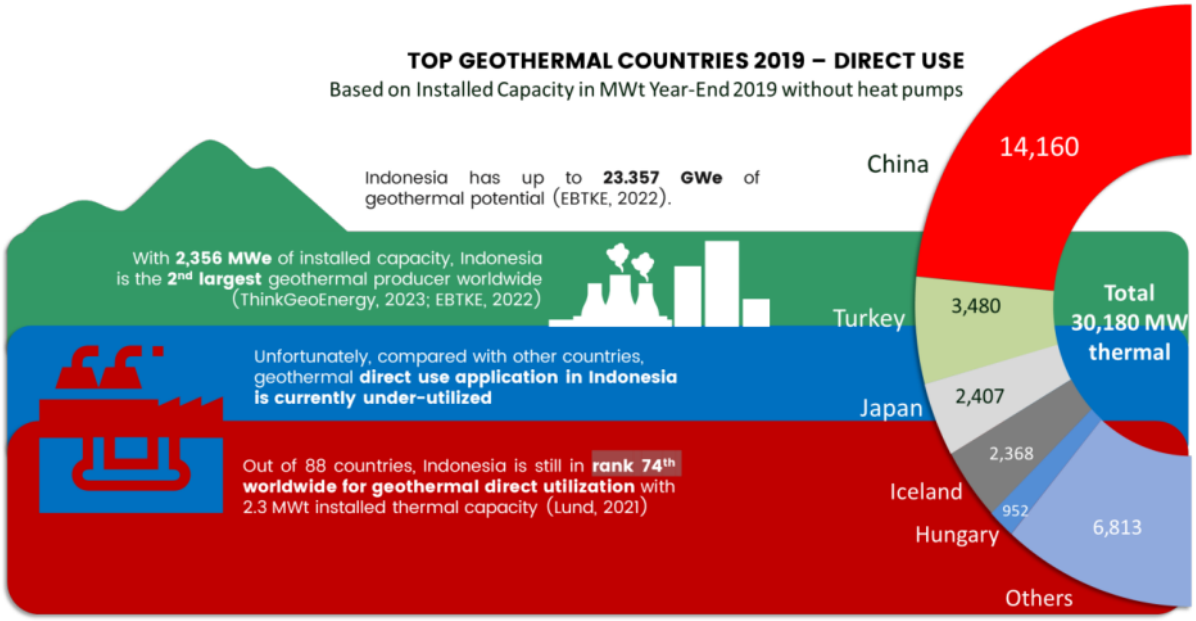


Figure 2: Latest Worldwide and Indonesia geothermal direct use status (Bagaskara et al., 2023; Richter, 2023; Lund & Toth, 2021).

The journey towards a greener energy landscape may be challenging, but the rewards are abundant. By embracing applicable business models, tapping into potential geothermal working areas, and addressing challenges head-on, Indonesia can unlock the full potential of geothermal direct use. As we look ahead, this paper is expected to become one of a steppingstone towards realizing a more resilient, prosperous, and sustainable future, where geothermal energy stands as a beacon of progress and possibility.

2. GEOTHERMAL DIRECT USE AT A GLANCE AND ITS STATUS

Geothermal energy's direct use goes beyond electricity generation, encompassing applications that have the potential to transform industries. District heating leverages geothermal heat for space heating and cooling, and Indonesia's urban centers could greatly benefit from this sustainable solution. Greenhouse cultivation exploits geothermal heat to foster agricultural productivity in controlled environments. Moreover, industries can integrate geothermal energy into various processes, from drying to desalination. The aquaculture sector, too, holds promise for utilizing geothermal heat to enhance fish farming practices.

Geothermal direct use, an emerging facet of geothermal utilization, involves harnessing the heat directly from geothermal reservoirs for non-electric applications. As the world seeks to decarbonize its energy systems and combat climate change, understanding and harnessing geothermal direct use becomes imperative. This section delves into the background and reviews existing literature surrounding geothermal direct use applications and their potential in Worldwide and Indonesia.

Figure 3: Typical geothermal direct use heat energy sources.

Geothermal direct use applications encompass a diverse range of sectors that can benefit from harnessing the Earth's heat directly. The typical geothermal direct use applications and their potential implications for Indonesia is described below:

- District Heating: District heating involves distributing geothermal heat through a network of pipes to provide space heating and cooling for residential, commercial, and industrial buildings. In Indonesia, where urban centers experience both energy demand and environmental concerns, geothermal district heating could emerge as an efficient and eco-friendly solution. By displacing fossil fuel-based heating systems, geothermal district heating could significantly reduce greenhouse gas emissions and enhance energy efficiency.
- Greenhouse Cultivation: Geothermal energy can be channeled to provide a controlled environment for greenhouse cultivation. By maintaining optimal temperatures for plant growth, geothermal heat can extend growing seasons, increase crop yields, and improve the quality of produce. Indonesia's rich agricultural landscape makes greenhouse cultivation a compelling application, particularly for enhancing food security and promoting sustainable farming practices.
- Industrial Processes: Industries rely heavily on heat for various processes, including drying, pasteurization, and sterilization. Geothermal energy can be integrated into industrial operations, reducing reliance on fossil fuels and lowering operating costs. Industries such as food processing, paper production, and textile manufacturing could potentially benefit from geothermal heat, resulting in both economic and environmental gains.
- Aquaculture and Fish Farming: Geothermal direct use can be harnessed to optimize conditions for aquaculture and fish farming. Maintaining specific water temperatures can enhance fish growth rates, reduce mortality rates, and improve overall fish health. Indonesia's thriving aquaculture industry, particularly in regions with geothermal resources, presents an opportunity to revolutionize fish farming practices by utilizing geothermal heat.

Each of these geothermal direct use applications holds significant promise for Indonesia's sustainable development. By diversifying the utilization of geothermal energy, the country can address multiple challenges, including energy security, greenhouse gas reduction, job creation, and economic growth. However, it's important to acknowledge that while the potential benefits are compelling, successful implementation requires addressing technical, regulatory, and financial considerations.

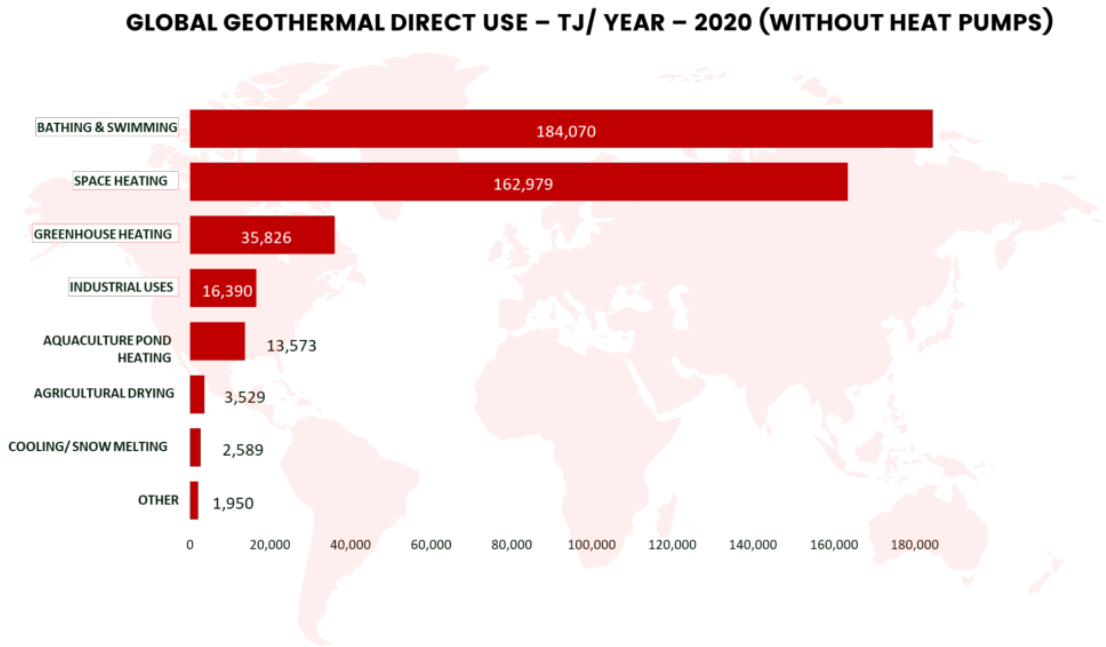


Figure 4: Current global geothermal direct use application status. Modified from (Richter, 2023; Lund & Toth, 2021).

2.1 Latest Applications Status Worldwide

The adoption of geothermal energy for direct use applications has been gaining momentum worldwide as nations seek to transition to cleaner and more sustainable energy sources. Several countries have made significant strides in implementing geothermal direct use projects, showcasing the versatility and potential of this approach. As shown in Figure 4, the current global geothermal direct use is dominated by bathing & swimming also the space heating (Richter, 2023; Lund & Toth, 2021).

Then, based on Thinkgeoenergy forecast, it is expected that there will be significant growth from 2020 to 2030 with total 470,000 TJ or equivalent with 212% (Richter, 2023). The forecast is shown in Figure 5.

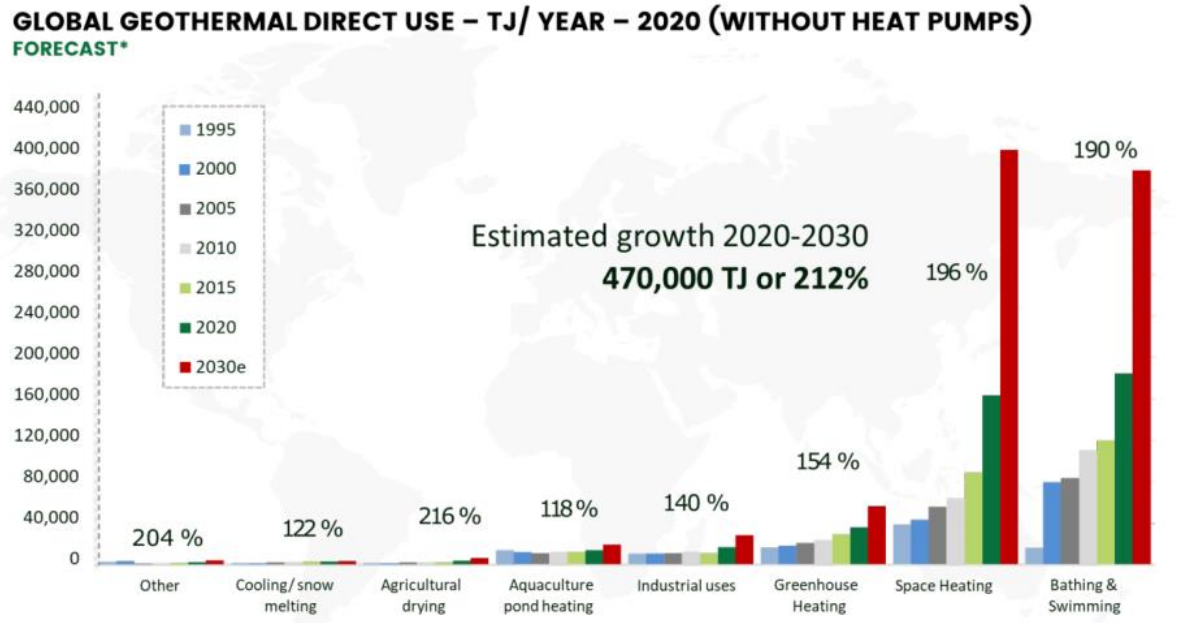


Figure 5: Global geothermal direct use forecast. Base data source from (Lund & Toth, 2021) and forecast Data from (Richter, 2023).

The overview of the current worldwide status of geothermal direct use applications and highlights some noteworthy examples is explained below:

- District Heating Systems: District heating systems powered by geothermal energy have gained popularity in countries such as Iceland and Sweden. The Reykjavik district heating system in Iceland, for instance, utilizes geothermal resources to provide heating for over 90% of its buildings, moreover in Iceland also apply the integrated/cascaded uses for other direct use application. Similarly, the city of Stockholm in Sweden has successfully integrated geothermal energy into its district heating network, reducing carbon emissions and dependence on fossil fuels.
- Greenhouse Cultivation: Geothermal energy has revolutionized greenhouse cultivation in various regions. The Netherlands has embraced geothermal-powered greenhouses, allowing farmers to control temperatures and create optimal growing conditions year-round. This innovative approach has increased crop yields and reduces the need for conventional heating methods.
- Industrial Applications: Countries like the United States and Turkey have harnessed geothermal energy for industrial processes. The Oregon Institute of Technology in the U.S. operates a successful geothermal industrial park, where businesses benefit from the availability of geothermal heat for manufacturing and production. In Turkey, the Tuzla industrial zone utilizes geothermal energy for heating, cooling, and drying processes.
- Aquaculture and Fish Farming: Geothermal direct use has also found applications in the aquaculture sector. In Hungary, the town of Hévíz uses geothermal water to cultivate fish in

temperature-controlled environments. This practice has resulted in higher fish yields and improved fish health.

The adoption of various business models has facilitated the implementation of geothermal direct use projects. Energy Service Companies (ESCOs) have been instrumental in enabling businesses and communities to benefit from geothermal heat without upfront capital investment. Public-Private Partnerships (PPPs) have driven collaboration between governments and private entities, accelerating project development.

International collaborations and research initiatives also have contributed to the growth of geothermal direct use. Organizations like the International Geothermal Association (IGA) and the Geo-Heat Center at the Oregon Institute of Technology have played pivotal roles in advancing knowledge sharing, capacity building, and best practices.

The current worldwide status of geothermal direct use applications showcases the feasibility and benefits of harnessing the Earth's heat for diverse purposes beyond electricity generation. As countries continue to embrace sustainable energy solutions, the global momentum behind geothermal direct use serves as an inspiration for Indonesia and other nations seeking to unlock the potential of this abundant and renewable resource.

2.2 Indonesia Current Status

In Indonesia, the business model for geothermal direct use (GDU) has predominantly been based on Corporate Social Responsibility (CSR), the example of the business is shown in Figure 6. This means that companies engage in GDU projects as a part of their commitment to social responsibility rather than as a core business venture. CSR projects are generally small-scale and designed to address specific community needs or to enhance a company's public image. They may not aim for long-term sustainability or extensive development. As these projects are often secondary to a corporation's primary business objectives, they may lack comprehensive planning and substantial investment needed for large-scale GDU development.

Moreover, the geothermal direct use with CSR type might has financial constraints, the CSR budgets are typically constrained and are not intended for substantial investment in infrastructure and technology. Since CSR projects are not driven by profit, they may not attract additional investment or financial support from other stakeholders. As a results from this hypothesis, the current geothermal developer is reluctant to significantly develop the geothermal direct use.

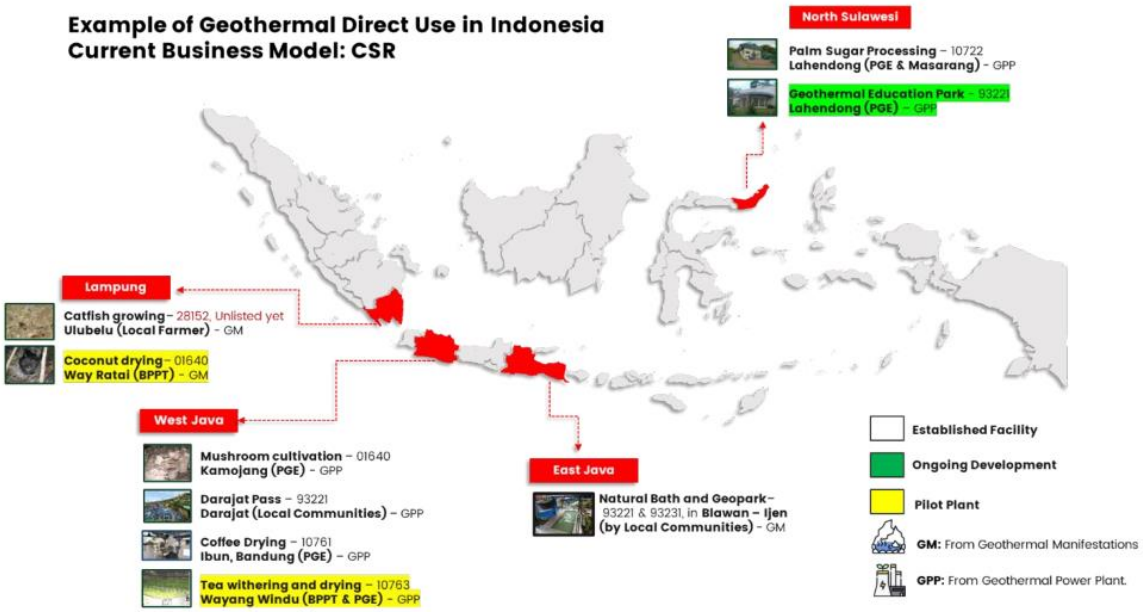


Figure 6: Example of geothermal direct use application in Indonesia.

Indonesia has already several regulations that regulate the geothermal direct use business in Indonesia. Bagaskara et al. (2023) already summarize each applicable regulation that currently applied in Indonesia. The latest one that might be concerned is regulation of Minister of Energy and Mineral Resources Regulation No. 5 of 2021 regarding Standards for Business Activities and Product in the Implementation of Risk Based Business.

Simply, this regulation is This law governs the standards related to geothermal business licensing for direct utilization, encompassing the requirements for KBLI (Klasifikasi Baku Lapangan Usaha Indonesia) licensing through the relevant ministries or institutions, the general business prerequisites in the form of SLO (Surat Layak Operasi), and the procedures for obtaining such an SLO. The illustration and list of KBLI is shown in Figure 7 below. However, not all the direct use business application types are listed on the regulation.

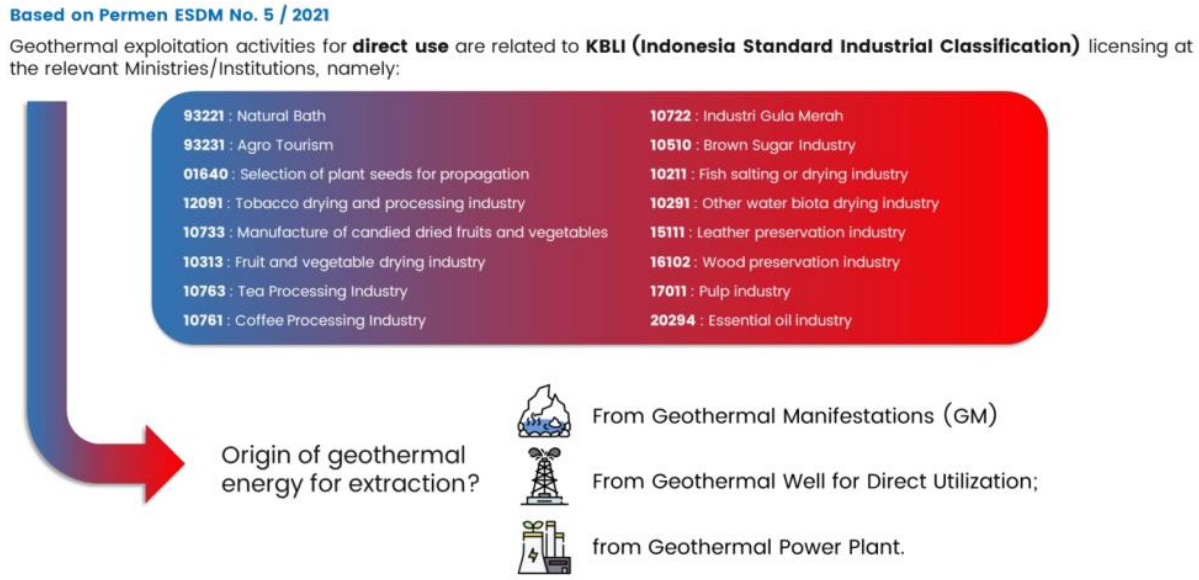


Figure 7: *Klasifikasi Baku Lapangan Usaha Indonesia* (KBLI) for geothermal direct use business.

Based on the worldwide review on the geothermal direct use application, the potential application that might be applicable for Indonesia context especially in commercial use is summarized below:

- **Greenhouses and Agricultural Applications**: Agriculture plays a significant role in Indonesia's economy, and the integration of geothermal energy can revolutionize this sector. Geothermal heating in greenhouses can enable year-round cultivation, improving crop yield and quality. The constant supply of heat from geothermal sources can create optimal growing conditions, particularly for temperature-sensitive crops. Additionally, geothermal energy can be employed for crop drying, reducing post-harvest losses and energy costs.
- **Industrial Processes**: Indonesia's growing industrial sector could benefit from the adoption of GDU. Several industrial processes require significant heat, such as in the food and beverage industry for pasteurization and drying, or in the textile industry for dyeing and processing. By utilizing geothermal heat, industries can reduce operational costs and minimize greenhouse gas emissions. The proximity of some industrial zones to geothermal resources makes this application particularly appealing.
- **Aquaculture**: Indonesia, as one of the world's largest fish producers, holds great potential for applying geothermal energy in aquaculture. Heating aquaculture ponds with geothermal energy can maintain optimal water temperatures, accelerating fish growth and enhancing production. This practice can be particularly valuable for species that require specific temperature ranges, offering a sustainable and efficient solution.
- **Spas and Recreational Facilities**: The natural hot springs found in various regions of Indonesia provide an opportunity for therapeutic and recreational facilities. Developing geothermal spas could boost tourism and offer health benefits. Moreover, geothermal energy

could be used to heat swimming pools and other recreational facilities, adding value to the hospitality industry.

Indonesia's geothermal potential offers diverse opportunities for direct use applications, ranging from agriculture to industrial processes to recreation. While some of these applications are still in the exploratory phase, they represent viable avenues for sustainable development. Leveraging geothermal energy aligns with Indonesia's commitment to renewable energy and provides a pathway to enhance various sectors of the economy. Partnerships between government, industry, and research institutions will be key to realizing the full potential of geothermal direct use in the country.

3. GEOTHERMAL DIRECT USE BUSINESS MODELS

3.1 Geothermal direct use business model at a glance

Geothermal direct use represents a wide array of applications, from heating and cooling buildings to industrial processes, agriculture, and recreational uses. The diversity of applications requires various business models to suit different markets, regulatory environments, technological advancements, and community needs. In general, the authors broken down the business model into two types that described below:

Table 1: Typical geothermal direct use business models.

Models Category	GDU Business Model	Brief Explanation
Traditional Business Models	Corporate Social Responsibility (CSR) based Model:	As previously discussed, CSR-based models involve companies investing in GDU as a part of their social responsibility initiatives. While admirable, this model may limit the scalability and sustainability of geothermal projects, as it primarily focuses on community benefits rather than profit.
	Government-Led Models:	Governments can invest in geothermal projects, either through public funding or public-private partnerships (PPPs). This approach often aims to achieve energy security and environmental goals.
	Private Investment Models:	Private companies can invest in GDU projects to create profit-driven ventures. This model typically seeks high returns on investment and might require significant capital, technology, and risk management. This model of direct ownership entails an entity, such as a municipality or private company, owning and operating the geothermal direct use facility. In this model, the entity assumes full responsibility for project development, financing, and operation. Direct ownership offers maximum control and long-term benefits, including potential revenue generation and energy cost savings. However, it also entails higher upfront investment and risks.
Innovative Business Model	Community Ownership Models:	In this model, local communities invest in and own geothermal projects, often through cooperatives or community funds. It fosters local engagement, sustainable development, and ensures that benefits are shared within the community.
	Hybrid Models / Public-Private Partnerships (PPPs):	Simply, this model is combining features from different traditional models, hybrid models can foster collaboration between public, private, and community stakeholders. It can help in distributing risks and leveraging diverse funding sources. PPPs involve collaboration between the public sector (government) and private entities to develop and operate geothermal direct use projects. PPPs distribute risks and responsibilities between partners, allowing governments to leverage private sector expertise and financing. While PPPs can streamline project implementation and reduce public funding burdens, they require robust regulatory frameworks and clear allocation of risks and rewards.
	Energy Service Company (ESCO) Models:	Simply, ESCOs design, build, finance, own, and operate GDU projects, selling the thermal energy to end-users. It provides a one-stop solution and can be attractive for end-users who don't want to invest in owning and operating geothermal systems. ESCOs offer an alternative model where a specialized entity provides geothermal direct use services to end-users. Under this arrangement, the ESCO designs, finances, installs, and operates the geothermal facility, and the end-users pay for the delivered energy or services. ESCOs mitigate financial and technical risks for end-users, enabling them to adopt geothermal direct use without upfront capital investment. This model can accelerate adoption but requires effective contractual agreements and performance monitoring
	Green Financing and Impact Investing Models:	These models attract investment from parties interested in environmental benefits and social impact. They can leverage global interest in sustainable development and climate change mitigation.

It is important to note that the challenges and considerations of the geothermal direct use business model can be affected by various aspect. Different business models may require distinct regulatory support, incentives, and frameworks to thrive. The choice of business models might depend on the technological maturity, innovation, and the specific application of GDU. Engagement with local communities, alignment with social goals, and consideration of cultural aspects can be crucial in the success of a business model. Funding availability, risk management, and return on investment also become considerations will heavily influence the choice and success of a business model.

Developing suitable business models for GDU is a complex but essential aspect of unlocking its potential. Both traditional and innovative models have roles to play, and their selection should consider the unique attributes of the geothermal resources, market demands, community needs, and regulatory landscape. Collaboration, innovation, and alignment with broader energy and environmental goals will be key to fostering successful geothermal development through various business models.

In summary, selecting the right business model is a critical step in driving the adoption of geothermal direct use applications. Each model offers distinct advantages and challenges, and its appropriateness depends on the specific application, project scale, and local context. As Indonesia navigates its transition to sustainable energy solutions, embracing innovative business models will be instrumental in unlocking the full potential of geothermal direct use for the nation's benefit.

3.2 Geothermal Direct Use General Business Canvas

This paper assesses several general scenarios in developing geothermal direct use business canvas. The scenario is listed as follows:

- Direct use facilities managed by geothermal power company for CSR / community development.
- Direct use facilities managed by geothermal power company (geothermal developers) for commercial use.
    - Scheme 1: Geothermal developers only sell the steam, and the direct use facility is managed by third party / other business.
    - Scheme 2: Geothermal developers manage end-to-end of direct use from extraction to application/sales.

3.2.1 Geothermal direct use facilities managed by geothermal power company for CSR / community development.

This type of geothermal direct use business generally refers to the utilization of geothermal energy, with a focus on providing sustainable energy solutions. It serves as a means for companies to give back to society through CSR programs, aimed at improving the quality of life in local communities.

Geothermal direct use facilities managed by geothermal power companies as part of Corporate Social Responsibility (CSR) or community development programs represent a strategic alignment of energy production with broader social and community goals (Fadhillah et al., 2023). This approach not only taps into geothermal resources for power generation but also leverages the same to foster community well-being, empowerment, and sustainability.

Geothermal power companies may adopt direct use projects as part of their commitment to social responsibility. By investing in community-oriented projects, these companies signal a commitment to the broader well-being of the areas where they operate. Close collaboration with local communities ensures that projects are designed to meet genuine needs and priorities, fostering a sense of ownership and alignment with community values.

Geothermal direct use in the context of CSR can also promote awareness of geothermal energy and increase public literacy about this clean energy source. Furthermore, such implementation aligns with the United Nations Sustainable Development Goals (SDGs), particularly Goal 7, which targets ensuring access to affordable, reliable, sustainable, and modern energy for all. By utilizing geothermal energy,

companies, including third parties, can manifest their commitment to sustainability and a reduced carbon footprint. This can enhance their reputation and foster positive relationships with stakeholders.

The illustration scheme of this direct use business model is shown in Figure 8 and the typical business model canvas is shown in Figure 9.

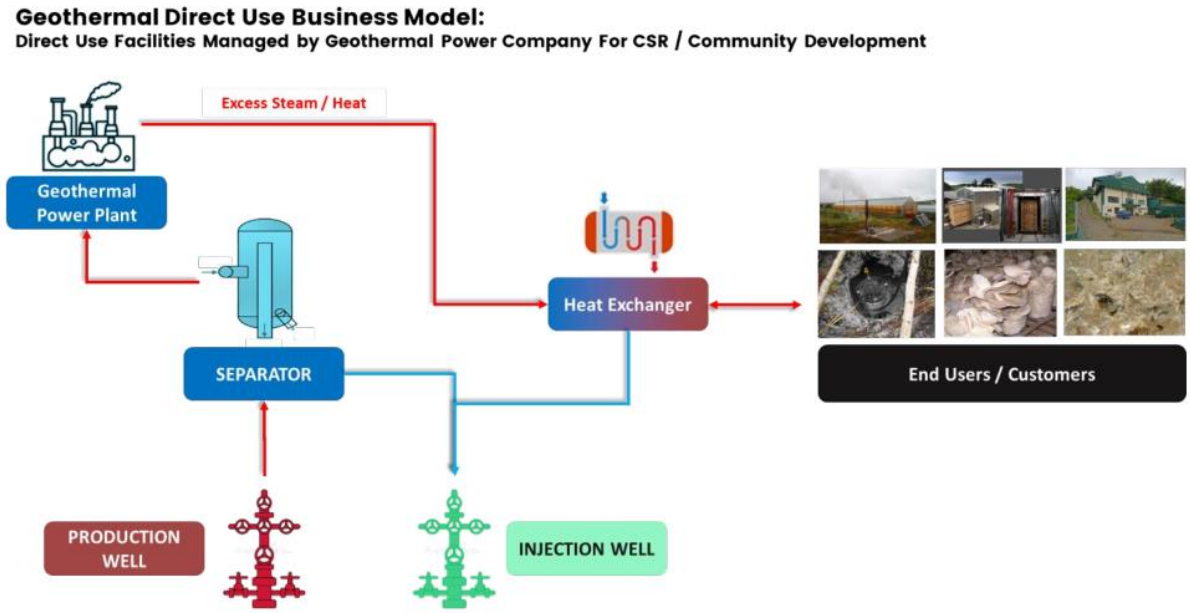


Figure 8: Illustration of direct use facilities managed by geothermal power company for CSR/community development.

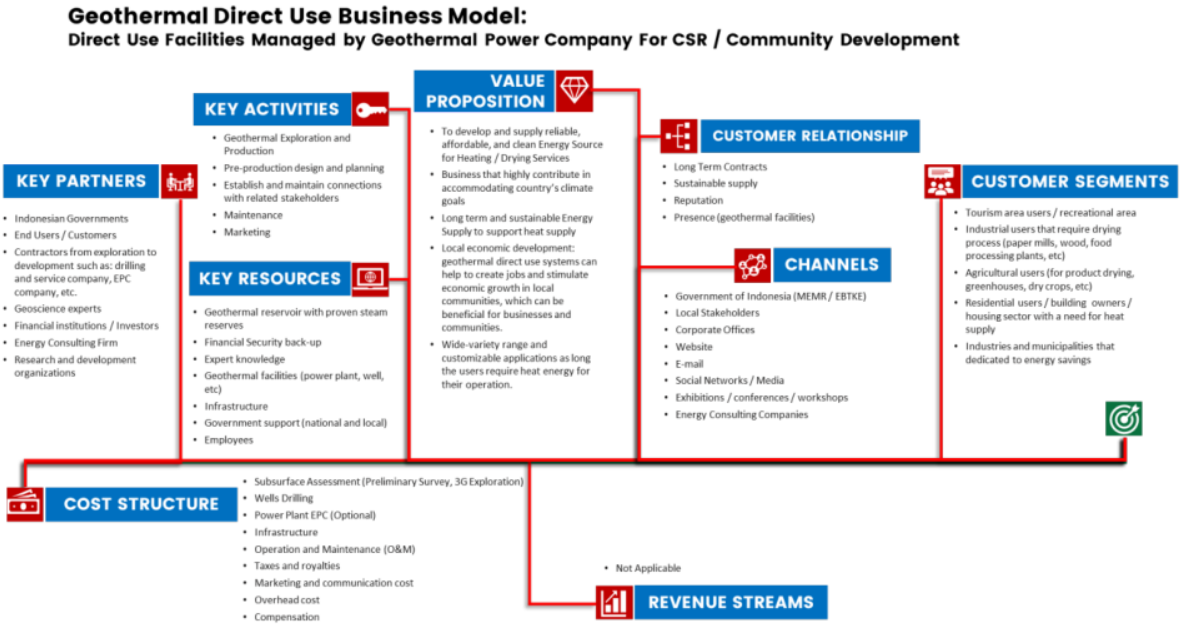


Figure 9: Typical business model of direct use facilities managed by geothermal power company for CSR/community development.

Geothermal direct use facilities managed by geothermal power companies for CSR and community development encapsulate a holistic approach to energy production and societal advancement. By weaving together commercial, environmental, and social threads, these projects have the potential to create multifaceted benefits that resonate with both local communities and broader sustainable development goals. Successful implementation requires a well-crafted strategy, meaningful collaboration, innovative thinking, and a deep commitment to shared values and objectives.

3.2.2. Geothermal direct use facilities managed by geothermal power company (geothermal developers) for commercial use.

Contrary to the previous section that focused on developing geothermal direct use for CSR, this approach to geothermal energy centers on commercialization. The main objective here is to gain additional revenue by selling heat energy, either through partnerships with third parties or by managing the process directly from end to end, all the way to the customer. Utilizing the excess heat or steam from a geothermal developer's power generation can help improve the competitiveness of operations and reduce their environmental footprint.

Commercial direct use applications may vary, depending on the surrounding businesses and industries near the geothermal working area. Generally, this type of business may include, but is not limited to:

- Providing process heat for manufacturing and industrial operations such as food and beverage production, textile manufacturing, and other industries that require high-temperature heat.
- Heating and cooling commercial buildings like offices, hotels, and malls.
- Supplying hot water for commercial swimming pools, hot springs, spa resorts, aquaculture, and other types of tourist attractions that require heat energy.
- Supporting other businesses that require heat energy as part of their services or processes.

An example of direct use facilities managed by geothermal power companies for commercial use is the utilization of geothermal fluid for heating and cooling data centers. Given that data centers require significant energy for cooling and heating, geothermal energy can offer a sustainable and reliable source. The excess heat generated from the data center can also be repurposed for other commercial uses, like space heating, hot water, and industrial process heat.

Another innovative example of commercial direct use applications is desalination. According to Jauhari et al. (2019), this method can be employed to produce fresh water from saline water by using geothermal energy to heat the water. This heating makes it possible to separate salt and other minerals through evaporation or other processes, particularly beneficial in arid regions where fresh water is scarce. Overall, there is a diverse range of potential uses for direct use facilities operated by geothermal power companies. These facilities can offer businesses and other commercial operations environmentally friendly and economically viable energy solutions.

Scheme 1: Geothermal developers only sell the steam, and the direct use facility is managed by third party / other business.

This geothermal direct use scheme typically pertains to entities, other than geothermal power companies, directly utilizing geothermal energy sourced from the subsurface. The scope of heat energy application varies widely, from district heating to industrial and commercial processes The business models that related to geothermal direct use that managed by other entity of geothermal developers (third parties' company) can take various forms of models that depends on specific application and goals both the geothermal developers and third parties. The general illustration scheme of this direct use business model is shown in Figure 10 and the typical business model canvas is shown in Figure 11.

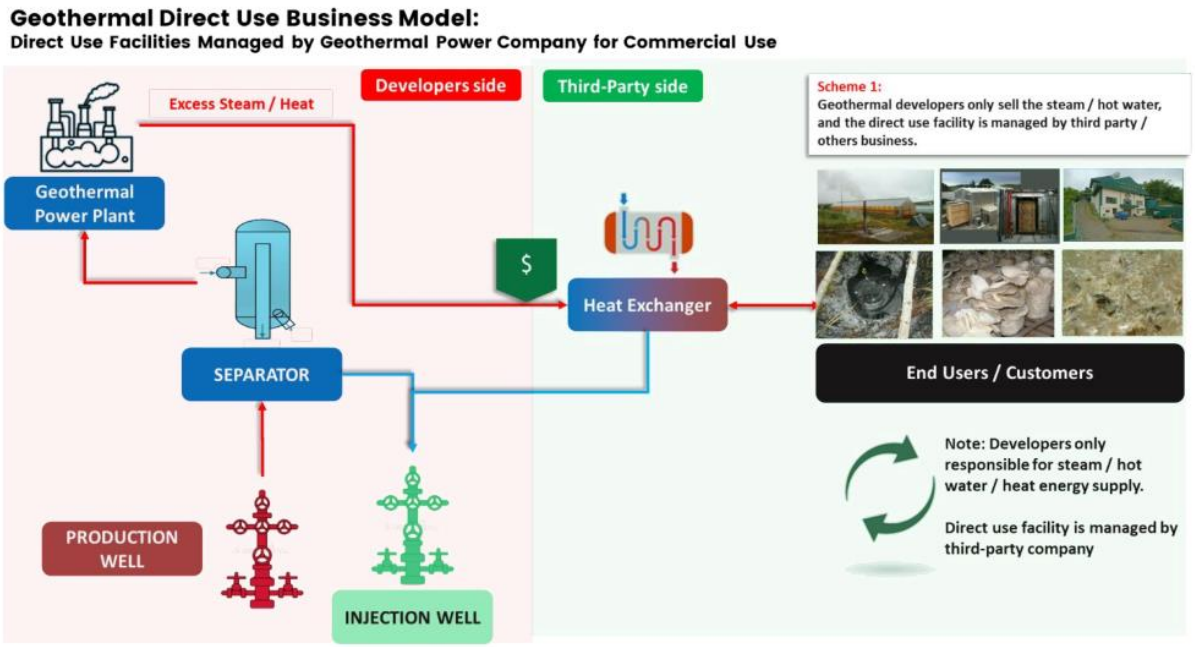


Figure 10: Illustration of direct use facilities managed by geothermal power company for commercial use when the Geothermal developers only sell the steam, and the direct use facility is managed by third party / other business.

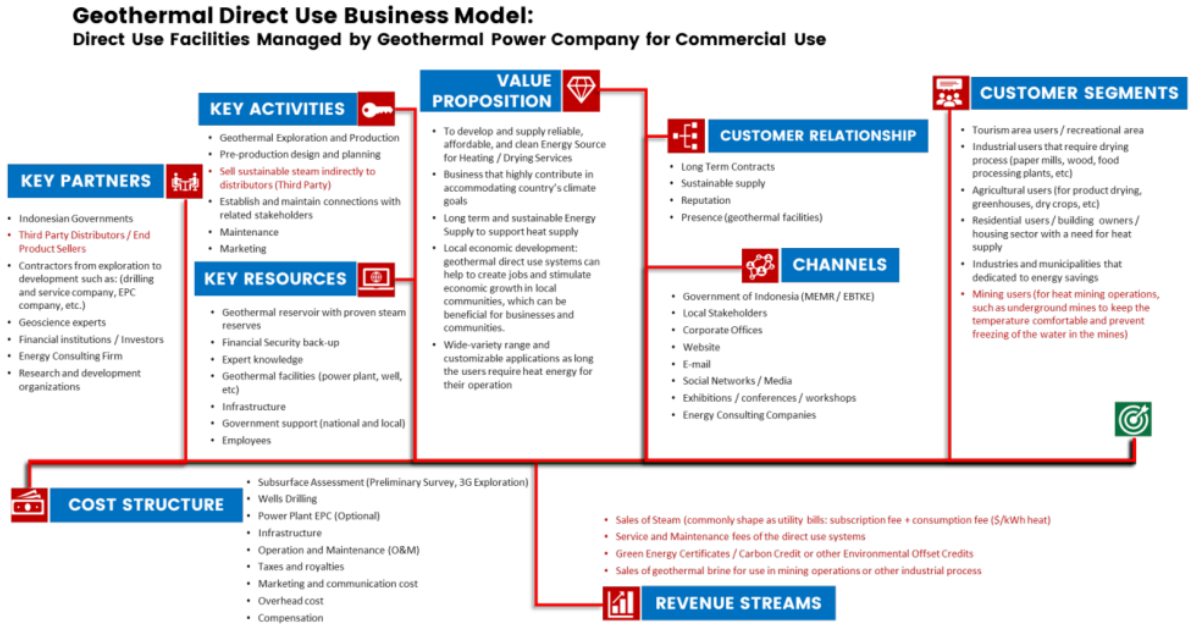


Figure 11: Typical business model of direct use facilities managed by geothermal power company for commercial use when the Geothermal developers only sell the steam, and the direct use facility is managed by third party / other business.

Scheme 2: Geothermal developers manage end-to-end of direct use from extraction to application/sales.

This scheme of geothermal direct use generally refers to the comprehensive business of geothermal energy managed by developers involved in every aspect of the process. This includes everything from exploration and development to production and delivering end-use to customers. Essentially, these companies might be engaged in both power generation and direct use projects, handling the entire procedure from inception to completion.

In general, this scheme implements a fully integrated business model. This means that geothermal developers are accountable for all aspects of the direct use project, ranging from exploration and drilling to operating the facility or selling the produced energy to customers. The model enables the company to exert full control over the supply chain and the quality of the geothermal fluid, leading to better management of costs and revenue streams. It is often utilized for large-scale projects, where the developer has both the resources and expertise to manage the entire venture. However, this model also requires a substantial investment and risk-taking by the developer, as they must independently secure customers and finance the project.

One key advantage of this business model is the geothermal power company's ability to control the quality and reliability of the energy supplied. By overseeing the entire process, from production to delivery, the company can ensure that the energy is used efficiently and effectively. Furthermore, it can leverage its expertise in geothermal energy to offer technical support and consultation to its customers.

Another significant benefit of this model is its contribution to reducing greenhouse gas emissions and supporting sustainable development. Utilizing geothermal energy enables customers to decrease their dependence on fossil fuels and diminish their carbon footprint, aiding in climate change mitigation and the transition to a low-carbon economy.

End-to-end management of Direct Use facilities by a geothermal power company also opens opportunities for revenue diversification and growth. By making these facilities available to customers, the company can cultivate additional income streams, helping to counterbalance the costs of geothermal power generation. Moreover, by supplying a reliable and sustainable energy source, the company can attract new clients and broaden its customer base.

In the specific context of Indonesia, geothermal direct use managed, owned, and fully operated by geothermal developers presents a strategic choice. Developers can opt to run this business as part of their power companies or create a subsidiary as a special mission vehicle (SMV) to manage co-product businesses besides geothermal power generation, including the direct use business."

The illustration scheme of this direct use business model is shown in Figure 12 and the typical business model canvas is shown in Figure 13.

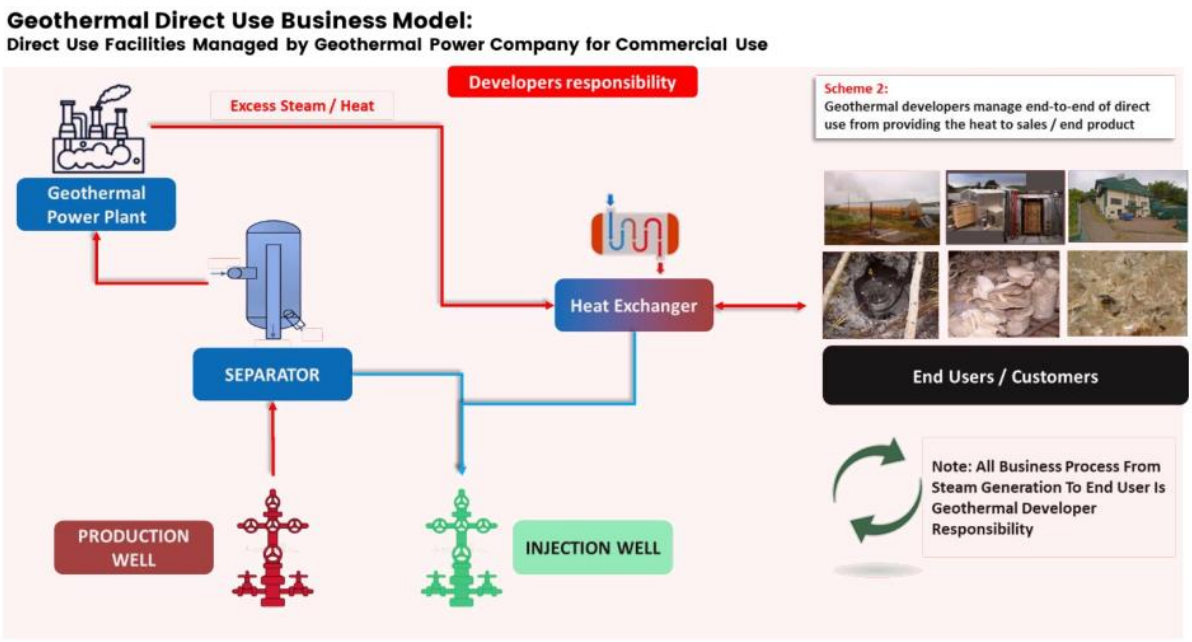


Figure 12: Illustration of direct use facilities managed by geothermal power company for commercial use when the geothermal developers manage end-to-end of direct use from extraction to application/sales.

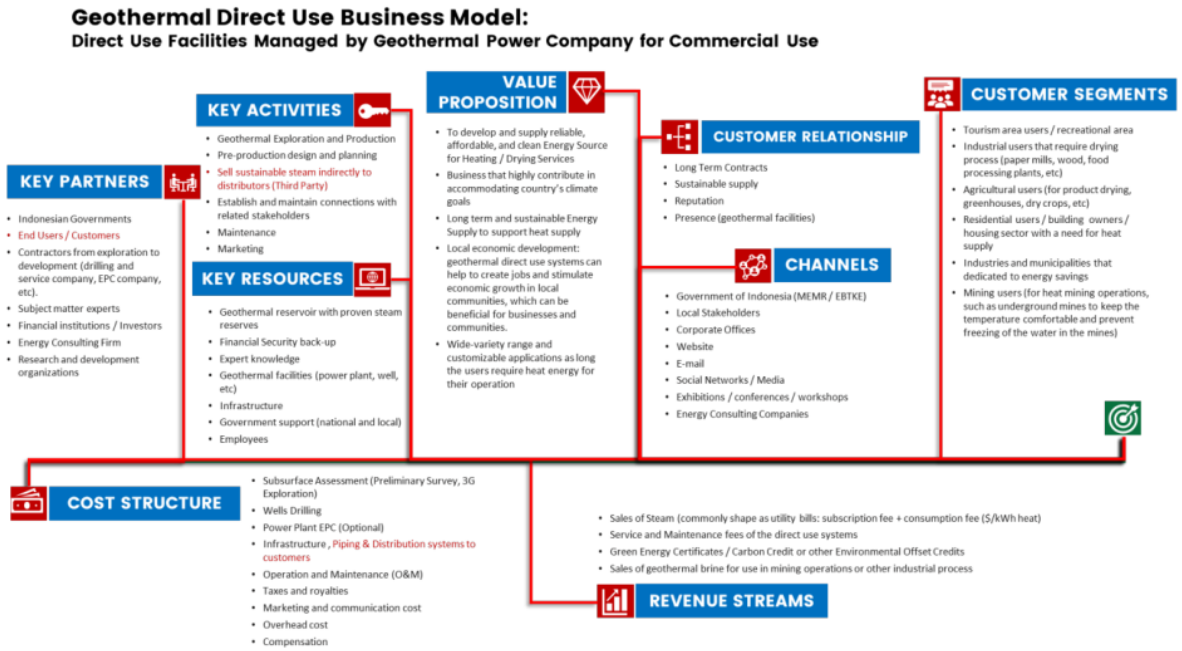


Figure 13: Typical business model of direct use facilities managed by geothermal power company for commercial use when the geothermal developers manage end-to-end of direct use from extraction to application/sales.

3.3. Potential Opportunities and Challenges from Geothermal Developers Side

Commercial geothermal direct use offers a promising path to leveraging natural resources for diverse applications. Careful planning, understanding of pros and cons, and learning from successful implementations can pave the way for broader adoption, contributing to energy efficiency, sustainability, and economic growth. From the geothermal developers point of view, as shown in Table 2, there are several points that is require to be understand and prepared.

Direct Use	Required Study	Pros	Cons	Proven example
Geotourism park and hot spring water Geothermal developers can develop integrated geotourism in conjunction with the location of the geothermal power plants (PLTP), and establish direct use facilities that can enhance the local economy around the PLTP	• A study on the tourism potential or visitors' potential for the area to be developed as a geotourism park. • A study of marketing strategies for introducing the geotourism park to the general public. • A feasibility study on the economic impact of direct use projects for geotourism on the core business of geothermal developers, through enhancing national and international reputation. • A detailed analysis of the project's impact on local health, safety, environment, and socio-economic aspects, along with the risks that may be faced during the development of facilities (risk assessment).	• Potentially become an icon for geothermal developers as the leading geothermal developer in Indonesia, and serve as one of the educational centers for renewable energy (especially geothermal) for the community. • Has the potential to enhance the economy since the pricing scheme can be negotiated directly with the beneficiaries in the industrial sector (not dependent on the ceiling tariff scheme). • Optimizes resources to produce derivative products with better selling prices compared to the ceiling tariff for electricity sales (Possibility to become a new revenue stream for geothermal developers). • Potentially be used as an educational tool for the community and to promote the advantages of geothermal energy such as clean energy, renewable and sustainable energy, etc. • Has the potential to increase the income of the local community collaborating in the development of the facilities of the geotourism park.	• Establishing a geotourism park with hot spring water amenities can involve significant investment in infrastructure development, maintenance, and ongoing operational costs. • Income from Geotourism does not necessarily have an significant direct impact on the revenue of geothermal developers. It is more likely to first affect the reputation, and then create a domino effect on stakeholders' confidence in the geothermal developer's business approach, which also prioritizes the enhancement of the local economy. • Finding a suitable location for geotourism park near surface thermal manifestations and/or geothermal power plant with sufficient space and access to build the facility complex might be problematic in terms of permitting, land acquisition, and access road	• Blue Lagoon, Iceland. This integrated geotourism facility is located next to Svartsengi geothermal power plant. • Whakarewarewa thermal village, New Zealand. This tourism cultural village facility Part of Rotorua geothermal field. • Waikita thermal spring, New Zealand.
In Integrated Geothermal Direct Use Facilities or Cascading Geothermal Direct Use Facilities, The geothermal energy is extracted from geothermal wells or excess steam can be	• A study on the potential offtakers/demand for heat energy in the targeted sectors (business potential, economic activities of local stakeholders that can cooperate by utilizing geothermal energy directly). • An economic analysis of the integrated direct use project on the core business of geothermal	• There's potential for economic improvement since the pricing scheme can be directly negotiated with beneficiaries in the industrial sector (not dependent on the ceiling tariff scheme). • Resource optimization can yield derivative products with better selling prices compared to the ceiling tariff for electricity sales (This has the potential to become a new revenue stream for geothermal developers).	• Establishing a geotourism park with hot spring water amenities can involve significant investment in infrastructure development, maintenance, and ongoing operational costs. • The permitting and concession process to local government might take longer time due to various different facilities to beinstalled, thus may require different permitting process from more than one	• Geothermal Industrial Park Cascaded Use for supplying heat energy for various company in Hellisheiði – Iceland (ESMAP, 2022) • Wairakei and Rotorua, Geothermal Power

Direct Use	Required Study	Pros	Cons	Proven example
distributed through a network of pipelines to different users or facilities. The highest temperature and pressure geothermal fluid is first used for high-temperature applications, and then the lower temperature and pressure fluid is cascaded for lower-temperature applications. This allows for multiple uses of the geothermal heat before the fluid is eventually reinjected into the reservoir Geothermal Developers can develop integrated geothermal direct use near the location of geothermal power plants (PLTP), and establish direct use facilities that can enhance the economy in the vicinity of the PLTP.	developers, through enhancing national and international reputation. • A study on the social aspects of development planning as a basis for social engineering to ensure the project can run smoothly. • A detailed analysis of the project's impact on local health, safety, environment, and socio-economic aspects, along with the risks that may be faced during the development of facilities (risk assessment).	• Cascaded use of heat energy from the geothermal power plant can create multiple income streams and aid in harnessing the underutilized natural resource. • It can be used as an educational tool for the community and to promote the benefits of geothermal energy, such as clean energy, renewable and sustainable energy, and more.	offices or instances in province or district level. • Finding a suitable location near surface thermal manifestations or geothermal power plant with sufficient space and access to build the facility complex might be problematic in terms of permitting, land acquisition, and access road (Especially if the industry that will be cooperated or become partnerships does not have a factory/industrial building close to the location of the geothermal power plant)	Station in New Zealand uses cascading geothermal systems to provide both electricity generation and direct use applications, including industrial processes and agricultural activities.

4. CONCLUSION

Geothermal direct use in Indonesia holds great potential for sustainable energy solutions. This paper explores its diverse applications and business models, shedding light on how the country can tap into geothermal resources for a cleaner future. Geothermal direct use can lower emissions, ensure energy security, and drive economic growth. Collaboration among stakeholders, including policymakers, investors, and communities, is essential for success.

In Indonesia, a country with vast geothermal resources, the opportunities for leveraging GDU are particularly pronounced. However, realizing this potential requires a concerted effort across multiple dimensions:

- Technological Innovation: Continuous investment in R&D, technology adaptation, and integration will drive efficiency and effectiveness in GDU applications.
- Regulatory Support: Crafting supportive policies and simplifying compliance processes are crucial for facilitating GDU development.
- Economic Viability: Developing a robust financial framework that includes diverse funding options and public-private partnerships can ensure the economic success of GDU projects.
- Social and Environmental Responsibility: Emphasizing community engagement, environmental stewardship, and alignment with sustainability goals underscores the broader positive impact of GDU.

Adaptable Business Models: Moving beyond CSR-based models and creating adaptable and scalable business models will foster sustainable growth in the GDU sector. By embracing applicable models, utilizing geothermal sites, and addressing challenges, Indonesia can unlock this potential for a greener, more prosperous future.

5. PATH FORWARD AND RECOMMENDATIONS

While this paper sheds light on the potential of geothermal direct use applications in Indonesia, there are avenues for further research and recommendations that can propel the nation towards a more sustainable and energy-efficient future. Building upon the insights presented, there are several paths forward about future research and offers recommendations to guide stakeholders in advancing the adoption of geothermal direct use as follows:

- **Comprehensive Feasibility Studies**: Future research should encompass in-depth feasibility studies for specific geothermal direct use projects. These studies should consider technical, economic, social, and environmental aspects to provide a holistic understanding of project viability.
- **Technological Innovation**: Research into innovative technologies can enhance the efficiency and cost-effectiveness of geothermal direct use applications. Advancements in heat exchange systems, temperature control, and distribution networks can drive implementation.
- **Stakeholder Engagement**: Engaging communities, end-users, and local authorities is pivotal. Future research could delve into effective engagement strategies that promote local ownership, knowledge sharing, and collaboration for successful project implementation.
- **Policy Framework Enhancement**: Developing clear and supportive regulatory frameworks is essential. Research could focus on assessing existing policies and recommending improvements that facilitate geothermal direct use projects.
- **Financial Mechanisms**: Exploring financing mechanisms, including incentives, subsidies, and financing options, can encourage private sector involvement and reduce financial barriers for geothermal direct use projects.
- **Capacity Building**: Strengthening technical expertise through capacity building initiatives and knowledge exchange programs can empower local communities and professionals to actively contribute to geothermal direct use projects.

- **Collaborative Research**: Collaborative research endeavors between academia, industry, and government can drive innovation and provide actionable insights for effective geothermal direct use implementation.

There are several recommendations that might be applicable for relevant stakeholders with details as follows:

- **Establish a Geothermal Direct Use Task Force**: The government could create a dedicated task force to streamline regulations, promote knowledge sharing, and drive the adoption of geothermal direct use applications.
- **Encourage Public-Private Partnerships (PPPs) and Commercial Project**: Facilitating PPPs can leverage private sector expertise, funding, and innovation to accelerate geothermal direct use projects.
- **Develop Incentive Mechanisms**: Introducing financial incentives and support mechanisms can incentivize investment in geothermal direct use, thereby catalyzing project implementation.
- **Streamline Licensing and Compliance Processes**: Simplify and expedite licensing procedures to reduce barriers to entry. Provide clear guidelines and support for navigating compliance requirements.
- **Prioritize Capacity Building**: Prioritizing training and education programs that build technical capacity and raise awareness about geothermal direct use can nurture a skilled workforce.
- **Develop and Promote Hybrid Business Models**: Encourage the creation of adaptable business models that combine traditional and innovative approaches. Tailor business models to align with local needs, resources, and cultural considerations.
- **Move Beyond CSR-Based Models for Scalability**: Explore alternative models that enable scalable and sustainable GDU development. Balance profitability with social and environmental goals.

As Indonesia embarks on a path towards sustainable energy development, embracing geothermal direct use applications can be a transformative step. By embarking on research endeavors and embracing recommendations, stakeholders can collectively harness the untapped potential of geothermal energy and contribute to a greener, more resilient energy landscape for generations to come.

REFERENCES

Al Asy'ari, M., Adityatama, D., & Purba, D.: Geothermal Field Management: Various Cases from Top Geothermal Producer Countries. *PROCEEDINGS, 48th Workshop on Geothermal Reservoir Engineering Stanford University*. Stanford, California: Stanford University, (2023).

Al Asy'ari, M., Tobing, J., Purba, D., Fadhillah, F., Kandou, S., & Adityatama, D.: Carbon Emissions Reduction in Geothermal Drilling Project: A Preliminary Study. *ITB International Geothermal Workshop 2021*. Bandung, Indonesia: IOP Conference Series: Earth and Environmental Science, Volume 1014, (2022).

Bagaskara, A et al.: Exploring New Ideas to Promote and Improve Geothermal Direct Use in Indonesia, *Proceedings, 48th Workshop on Geothermal Reservoir Engineering Stanford University*. Stanford, California: International Geothermal Association (IGA), (2023).

EBTKE.: Pengembangan Panas Bumi di Indonesia, (2022).

ESMAP.: Direct Utilization of Geothermal Resources. Washington DC: World Bank, (2022).

Lund, J and A Toth.: Direct Utilization of Geothermal Energy 2020 Worldwide Review, *World Geothermal Congress 2020+1*. Reykjavik, Iceland, (2021).

Richter, Alexander.: Low enthalpy geothermal an attempt to positioning. (2023).

Thinkgeoenergy.: *ThinkGeoEnergy's Top 10 Geothermal Countries 2022 – Power Generation Capacity (MW)*. 10 January 2023. <https://www.thinkgeoenergy.com/thinkgeoenergys-top-10-geothermal-countries-2022-power-generation-capacity-mw/>, (2023).

Social Safeguard Measures in Geothermal Exploration: Fulfilling Requirements for the Geothermal Resource Risk Mitigation Program

Afandi[1], Chandra Hasudungan[1], Desak Inten[1], Eviyanti[1], and Dorman Purba[1,2]

[1]PT Sarana Multi Infrastruktur (Persero), Sahid Sudirman Center 49th floor, Jakarta, Indonesia
[2]PT ENERKA Bhumi Pratama, Cibis Park 11th floor, Jakarta, Indonesia

afandi.pmugeothermal@ptsmi.co.id

Keywords: social safeguard, geothermal exploration, GREM, societal challenges, World Bank, social safeguard policies, social safeguard instruments, drilling, Indonesia

ABSTRACT

Geothermal exploration in Indonesia plays a critical role in achieving the national target for renewable energy development. However, the early exploration phase often faces challenges related to social safeguards, primarily attributed to a communication gap between geothermal developer companies and local communities. To secure funding from lenders, potential borrowers must fulfil specific requirements to demonstrate their commitment to social safeguard measures. Failure to understand and address these requirements can lead to project delays and pose significant risks to the project's success.

In this context, the Geothermal Resource Risk Mitigation Program (GREM), a geothermal exploration funding program by The World Bank and The Ministry of Finance, aims to support geothermal exploration projects in Indonesia. This program highlights the urgency to accelerate geothermal exploration activities and emphasizes the significance of effective communication and stakeholder engagement in managing social impacts. The GREM program also sets forth specific requirements that potential borrowers must fulfil to showcase their adherence to social safeguard standards.

This paper examines the social safeguard issues that arise during geothermal exploration in Indonesia and explores the necessary measures to fulfil GREM's requirements. Drawing on case studies and best practices, it presents a comprehensive approach to address social safeguard concerns, encompassing social impact assessments, stakeholder engagement plans, resettlement and livelihood restoration measures, indigenous peoples' rights protection, health and safety protocols, local employment opportunities, and sustainable community development initiatives.

By understanding and fulfilling GREM's social safeguard requirements, geothermal developers can enhance their eligibility for funding and demonstrate their commitment to responsible and sustainable practices. The paper underscores the critical role of proactive planning, effective communication, and robust monitoring and reporting mechanisms to ensure successful geothermal exploration projects aligned with national targets while safeguarding the interests of local communities and the environment.

1. INTRODUCTION

1.1 Background

Geothermal exploration projects in Indonesia play an important role in achieving national targets for renewable energy development. However, it is often the case that geothermal exploration projects in Indonesia face the crucial challenge of protests and even rejection from some local community that against the presence of geothermal projects. Some local community in geothermal manifestation areas have already know that natural heat can be used for a number of practical applications and that geothermal projects can also provide important benefits to the region and communities in the project area. However, there are some people who are concerned about the impact that large projects (especially for power generation) can have on the environment and economy of the area. Therefore, different positions are formed in public opinion in areas where geothermal projects are to be initiated, with some people being supportive, others conditionally encouraging, and others opposing the implementation of projects in their area.

According to Cataldi (2001) different positions on the acceptance of geothermal exploration projects depend on several local factors, including socio-economic conditions, cultural background, and individual or group interests. Most frequently, though, when news spread on the possibility to have a geothermal project initiated in a given area, many of its residents eulogize natural heat with terms like clean, cheap, friendly, benign, green, sustainable, and the like, thus creating a favorable climate for the implementation of the project. However, individual and collective attitude towards geothermal development usually changes with time as the project reaches the drilling stage and works begin for installation of equipment and plants. Indeed, undesirable effects may result from these activities on i) ecosystem (air, land, flora, fauna, and superficial and underground water); ii) human health (from water pollution, noise, and gas emission); and iii) economy (detrimental impact on some production activities and tourism, and damages to crops and private properties). Moreover, iv) reaction often grows against landscape modifications and alteration of natural features of cultural or religious interest, caused by civil and industrial works, and by changes in the use of public areas resulting from project activities. In short, people's opinion on the impact that geothermal development may have in a given area is a matter of economic and social aspects (Cataldi: 2001).

There have actually been quite a number of studies from experts that discuss the importance of social acceptance and building public trust in geothermal exploration projects, such as the study conducted by Fadhillah et al. (2022 and 2023), Cataldi (2001), and Kubota, (2013). From the previous studies the experts have consider that in achieving social acceptance requires trust between the developers and the local communities, which can be achieved through the implementation of certain strategies. According to Ferdino R. Fadhillah et all (2022 and 2023) social acceptance issues as non-technical issues for geothermal project that need to be solved to prevent the social risk will lead to project delay/stop that lead to cost overrun, and loss of reputation. Fadhilah recommends several actions could be considered to obtain acceptance, such as comprehensive community development program, excellent project planning and implementation to shape the good reputation of geothermal industry corporates, and clear communication to all stakeholders to keep the commitment and maintain communication to local stakeholders and in mitigating community rejection issues.

Whilst according to Raffaele Cataldi (2001) social acceptance is an important requisite for the smooth implementation of geothermal projects. The three main conditions to win project acceptance by communities residing in the work area are: i) minimization of environmental impact; ii) avoidance of adverse effects on people's health; and iii) creation of direct benefits for local populations. Cataldi take into account to meet these conditions, the project owner should be prepared to bear specific burdens in the form of external costs, whose amounts (depending on the site, type, and size of the project) range, on the average, between 1-2% and 2-4 % of the total construction cost, for direct use projects and multi-purpose projects, respectively.

Last but not least is the opinions of Hiromi Kubota (2013) where from his research shows that the societal acceptance of geothermal power by local stakeholders is the fundamental barrier as it affects almost all other barriers, such as financial, technical, and political risks. Therefore, the project managers and local government officials should always strongly be concerned about the adverse impacts of geothermal projects and improving the risk management of geothermal projects.

If we consider the opinions from the experts above, the development of geothermal exploration projects in many parts of the world shows the potential to cause significant social impacts and social risks. If these social impacts and social risks are not addressed promptly from the very beginning in an appropriate and measurable manner, they can lead to project delays/terminations that lead to cost overruns and loss of company reputation. As a way to prevent and mitigate these risks, the social safeguard management measures must be a top priority.

1.2 Objective

This study in particular is expected to raise awareness of the importance of implementing appropriate measures in preventing social risks and at the same time to achieve public trust in geothermal exploration project through the implementation of social safeguards. Specifically, this study will discuss the social safeguards instruments supported by the GREM (Geothermal Resource Risk Mitigation)

Project to guide investors in their efforts to avoid, minimize, or mitigate adverse social impacts and risks arising from geothermal exploration projects.

By understanding and fulfilling the social safeguards requirements under the GREM, geothermal developers are expected not only to improve their eligibility for funding from the GREM scheme, but also importantly to ensure the success of geothermal exploration projects in accordance with national targets, and international social safeguards performance standards, while maintaining the sustainability of local communities and the environment.

1.3 Research Questions and Research Methodology

This study aims to provide awareness related to the importance of implementing appropriate measures in preventing and managing social risks in geothermal project exploration through the implementation of social safeguard management measures by providing the analysis related to the question below:

1. What is the potential social impact and risk of geothermal exploration projects in Indonesia?
2. What are the factors that cause social impacts and risks in geothermal exploration projects in Indonesia?
3. How can the social safeguards instruments support the project to prevent and mitigate the social impacts and risks of geothermal exploration projects?

In conducting this study, the author conducted a literature study by collecting and analyzing available data related to published cases of social impacts and social risks, especially based on previous research studies conducted by geothermal experts towards geothermal exploration projects in Indonesia. In addition, the author also used data and information obtained directly from field observations of the implementation of several geothermal exploration projects in Indonesia, especially those in the GREM project implementation.

2. SOCIETAL CHALLENGES IN GEOTHERMAL EXPLORATION PROJECTS IN INDONESIA

2.1 Negative Stigma Towards Geothermal Exploration Projects

There are several factors that contribute to the emergence of a negative stigma towards geothermal exploration projects in Indonesia, including the first factor is the spatial characteristics of geothermal exploration project locations. Most geothermal potential in Indonesia is in or close to forest areas. This has raised societal concerns about environmental and social impacts, especially in forests that play an important role in supplying fresh water, harbor endangered wildlife, or have high cultural or religious values. Environmental and social impacts and risks associated with geothermal power development are complex and significant and the degree to which these risks and impacts vary between geothermal power projects is not well understood (Ampaire, 2020). In addition, the location of geothermal project exploration near to community's plantations, residential areas, or tourism areas, as well as in the territory of indigenous communities or cultural heritage sites. The existence of these factors will certainly lead to high sensitivity to environmental, community health and safety, community's livelihood, and socio-cultural aspects of local communities.

The second factor is that in making project designs, developers sometimes do not involve the social and environmental safeguard team, which makes project designs pay less attention to the existence of sensitive conditions of the physical and social environment aspects in the project plan area. The existence of spatial characteristics that have the potential to cause high social sensitivity in geothermal exploration projects as described above is also exacerbated by the third factor, namely the absence of earnest social and environmental safeguard management by developers. Although efforts to manage social and environmental safeguards in geothermal exploration projects is one of the main requirements that must be carried out by developers, for example through the obligations of UKL-UPL, AMDAL, or ESIA, but mostly it is still done as an ornament to simply fulfilling obligations from the government or lenders. Another crucial social safeguard aspect that is often neglected by geothermal exploration projects is the reluctance to involve affected communities and other project's interest parties as early as possible in the preparation of the project plan.

The fourth factor is, as explained earlier, the limited understanding of the community and perhaps other stakeholders at the regional/local level about geothermal energy projects. Some people think that geothermal projects are like "mining" projects that can be detrimental because they can degrade natural ecosystems and are harmful to human life. As a result of this perception, some environmental activists have raised the issue that the exploration of geothermal projects could lead to an escalation of disasters that cannot be predicted and mitigated effectively in the field.

2.2 Geothermal Exploration Projects Impact and Societal Challenges

The existence of several factors that contribute to the negative stigma as mentioned above has eventually in some cases made the presence of a geothermal exploration project difficult to gain support and acceptance from the local community. According to Fadhillah et al. (2022 and 2023) the project impact and community concern in geothermal exploration project can be triggered at the following stages of project implementation below:

1. **Preliminary and 3G survey**
   According to ESMAP (2012), this phase usually includes field activity such as field mapping, geological-geochemistry samples collection, geophysics equipment stationing, and geohazard identification. The preliminary infrastructure survey is conducted by observing access road conditions. The field team could conduct the informal interview with the community to gather general views and responses to the geothermal project during this phase.
   The local community has been involved in the project's early phase as guides and field assistants. Furthermore, the locals also could facilitate accommodation, transportation, and supplies for the team during survey activities. The activities affect the community since the field team would trespass the local land to obtain field data. The manifestation fluid sampling could disturb local daily activities since it may associate with water resources, local tourism destination, and scarce or sacred places.
2. **Infrastructure preparation and drilling**
   The infrastructure preparation also performs the land acquisition process where the project owner is willing to buy the local land that would be used as drilling infrastructure. The land acquisition led to changes of local occupation since most locals worked as farmers and planters on their land before the project owner acquired it to be prepared for drilling infrastructure (Purba et al., 2021). The community concern could arise related to the loss of their occupation as their primary economic income and assumed the project has low benefit to the community since no sustainable occupation option. Drilling infrastructure involves mass land clearing activities and deforestation to prepare the access road, well pad, and basecamp area. This condition would trigger the concern of the community related to fear of wild animals' entrance to villages and endangering the ecosystem (Ibrohim, Prasetyo, & Rekinagara, 2019). The large-scale civil work that includes heavy equipment mobilization and massive soil material needs to be executed to develop and improve the infrastructure. Those activities impact the community since it induces soil contamination on water flow lines, dirty roads, and dust.
   While on the drilling activities, public concern is related to using extensive local water sources for drilling operations. The community feared that activity would induce contamination and loss of water sources for the local community. Furthermore, the community is concerned about drilling risks such as H2S gas and blowout events (Adityatama, Purba, & Kristianto, 2018). This phase involves large workers consisting of local and non-local workers. It raises local concerns about the different cultures and social values between local and non-local workers in daily interaction.

Based on data available from Fadhillah et al. (2022 and 2023) there are identified 14 geothermal working area that have experienced with societal challenges, which are: Gn. Lawu, Baturaden, Gn. Talang, Gn. Rajabasa, Kaldera Danau Banten, Wae Sano, Tabanan, Dieng, Gn. Ciremai, Sorik Marapi, Sokoria, Bittuang, and Tampomas. With reference to the analysis of typical geothermal challenges in Indonesia from Fadhillah et al. (2022 and 2023), it is acknowledged that in term of societal challenges there are two barriers or limitations that slow down the process of geothermal development in Indonesia. The limitations related to social issues including; local communities' rejection and high cost of land

indemnification. One of the renowned cases is in Mount Lawu, there are any community's rejection because of lack of understanding of geothermal energy that supported by misinformation related to negative impact of geothermal project. As the results, the project was stopped until nowadays and government pull out this area from geothermal development roadmap. Other case of community rejection also occurred in the Waesano geothermal exploration project due to the assumption from some local people that the location of the drilling point is in the living space of community, ranging from settlements, farmlands, water sources, traditional houses, churches, and schools so that it is feared that it will threaten the safety of Waesano community.

Table 1: Typical Geothermal Challenges in Indonesia (extracted and Adapted from Fadhillah et al., 2022 and 2023).

Categories	Challenges	Remarks
Upstream challenges	Land acquisition issues	In general, the local community uses the flat area in Indonesia's volcanic area for agriculture or housing. Providing the acquisition cost for a family's livelihood in rural Indonesia is often tricky, especially if the land is their only asset. One mitigation strategy is allowing enough time for the landowner to move from one source of livelihood to another. Negotiation is frequently tough if the property buyer (geothermal developer or local government) demands a strict timeline for the landowner to leave the land they have worked on for years (Purba, 2021b).
Additional challenges	Lack of public understanding on geothermal energy	The public's lack of understanding of the importance of geothermal projects frequently leads to rejection, resulting in delays in geothermal development initiatives. This circumstance is most common when geothermal projects are still in the discovery stage and local governments, development corporations, and local communities still recognize each other and have not yet created trust between each side—social dynamic condition and public acceptance issues that can be stopper of geothermal project.

3. SOCIAL SAFEGUARD IN SUPPORTING GEOTHERMAL EXPLORATION PROJECT

3.1 Social Safeguard as Instruments to Prevent and Mitigate Undue Harm to Communities During the Development Process.

Social safeguard policies are an important tool developed by international financial institutions to prevent and mitigate undue harm to communities during the development process. When project proponents identify and design projects, safeguards for affected communities should be undertaken after an assessment of all potential risks and social impacts (positive or negative) associated with development interventions. Social safeguards should help define measures and processes to effectively manage risks and enhance positive project impacts. Social safeguard policies aim to prevent and mitigate undue harm to people and their environment in the development process, to compensate affected people and to restore livelihoods to at least the level prior to development intervention. Through the implementation of social safeguard policies, it is expected to serve not only as a tool to improve the quality of project proposals, but also as an opportunity for affected community members and other stakeholders to engage in the implementation of the development process and increase their sense of ownership of the project whatever of the source of financing.

Most International Financing Institutions (IFIs) require the application of safeguards to approve projects, and while protocols and formats vary, the issues considered are common. In addition, an increasing number of countries are enacting the application of safeguards through a range of investment planning, policies and regulations aimed at achieving more sustainable development. Safeguard policies frequently rely on internationally agreed standards and guidance in an effort to not create duplication of efforts or conflicting requirements for project sponsors.

The World Bank itself has provisions contained in Environmental and Social Policies that aim to ensure that the community and the environment can be protected from potential adverse impacts that may be caused by the implementation of a development project. In principle, the Environmental and Social

Policies of the World Bank seek to identify, avoid, and minimize all forms of potential harm that may arise because of the implementation of a development project on humans and the environment. Through this policy, the World Bank requires borrowing governments to address certain environmental and social risks to obtain support from the World Bank for investment projects. To this end, environmental and social management systems will be incorporated into project design and implementation in order to improve the effectiveness, benefits, and sustainability of development outcomes.

In August 2016, the World Bank has adopted a new set of environmental and social policies called the Environmental and Social Framework (ESF). Starting October 1, 2018, the ESF applies to all new investment project financing funded by the World Bank. The new World Bank's Safeguard framework provides broad coverage of environmental and social issues, including important developments related to transparency, non-discrimination, social engagement, public participation, and accountability. The ESF also places greater emphasis on building the capacity of borrower governments themselves to address environmental and social issues. The World Bank's environmental and social policies aim to ensure that communities and the environment are protected from the potential adverse impacts of the projects it finances. The policy helps identify, avoid, and minimize harm to communities and the environment. The policy also requires borrowing governments to address certain environmental and social risks in order to receive World Bank support for investment projects.

In brief, the objectives of the World Bank Safeguard Policies are as follows:

- Safeguard policies are a way to integrate environmental and social issues into decision making.
- Support participatory approaches and transparency.
- Effective implementation of Safeguard Policies is essential to achieve Sustainable Development
- Provide a set of specialized tools to support development process.
- Ensure that environmental and social issues are thoroughly evaluated in project preparation and supervision.
- Avoid, minimize, mitigate and/or compensate for adverse environmental and social impacts of Bank-supported projects.
- Provide a mechanism for consultation with project affected peoples (PAPs) and civil society (including NGOs);
- Fully disclose relevant project information to PAPs and public stakeholders; and
- Supervise safeguards compliance and outcomes during project implementation.

3.2 GREM Facility

Indonesia is one of the world's largest producers of geothermal energy, with significant untapped potential for further development. Meanwhile, Indonesia continues to rely heavily on fossil-fired power generation. In 2018, the total installed capacity was 57 gigawatts (GW) of which 88 percent from fossil fuels and 12 percent renewable sources, to meet a peak demand of 40 GW. Important policy goals have been formulated by the National Energy Council to re-establish Indonesia's energy independence through (i) re-directing energy resources from export to domestic market and (ii) rebalancing the energy mix towards indigenous energy supplies. The policy implies transforming the energy mix by minimizing oil consumption and raising the share of renewable energy in the country's energy mix and consumption of coal and optimizing the production of gas.

The Government of Indonesia (GoI) has set the renewable energy target of 23 percent by 2025. The World Bank is assisting the Government of Indonesia in establishing a Geothermal Resource Risk Mitigation (GREM) Facility ("the Facility") to support exploration drilling by state-owned and private sector developers. The main objective is to scale up investment in geothermal energy development in Indonesia. This will be achieved through providing about US$ 375 million for upstream resource development (i.e., exploration and delineation drilling) – the riskiest phase of geothermal development. The Facility will be managed by PT Sarana Multi Infrastruktur (Persero) ("PT SMI") as the financial intermediary, and it consists of two facilities: (i) Public Sector Window and (ii) Private Sector Window.

The GREM Project supports the GoI in reaching this target by scaling up investments in geothermal energy development and reducing greenhouse gas emissions in the country. As a climate co-benefit, the Project is expected to avoid over 112 MtCO2e over the 30-year lifetime. It is also expected that the proposed Project will also bring employment for skilled and unskilled workers engaged in drilling, civil works, infrastructure construction, and auxiliary services.

PT SMI through the Facility will provide geothermal developers with a debt package for exploration drilling, with the possibility of another package for delineation drilling. The financing support will confirm whether there is sufficient productive steam resource for power generation. After the resource is largely confirmed, the developer can use project finance for exploitation drilling and power plant development.

For the public sector window, there will be a de-risking component using funding from the Government of Indonesia under the Dana Pembiayaan Infrastruktur Panas Bumi ("PISP Fund") if the resources are not confirmed, or the exploration comes to an unfeasible result (please see the Ministry of Finance ("MoF") Regulation No. 80/KMK.08/2022). Meanwhile, for the private sector window, the debt package will be evenly split between a loan financed by the World Bank and a financial instrument funded by the Green Climate Fund and/or the Clean Technology Fund. The financial instrument will be based on so-called the fair-market value of the Special Purpose Vehicle at the time the Sponsor chooses to buy back the financial instrument, thus creating a risk-sharing mechanism.

The GREM facility comprises the following components:

Component 1 – Geothermal Resource Risk Mitigation (US$455 million for Phase 1)[1]. Component 1 will support the establishment of a geothermal resource risk mitigation facility (the Facility), which will provide financing to mitigate the risk of resource confirmation (including exploration and delineation drilling) of eligible public sector entities, and eligible private sector developers (each a Developer, and typically, a special purpose vehicle (SPV) established by their owner (Sponsor) for the development of a specific geothermal site).

Component 2 – Technical Assistance and Capacity Building (US$6.25 million for Phase 1)[2]. Component 2 will finance support to PT SMI in the set up and management of the Facility. This include PT SMI's incremental operating costs as well as procurement of highly specialized (geotechnical, legal, and financial) consulting services to support the rigorous evaluation of sub-financing proposals, validation of complex geoscientific data, supervision of environmental and social safeguards compliance by the sub-borrowers.

The GREM Facility is another initiative to complement the previous Geothermal Energy Upstream Development Project (GEUDP) which also supported by The World Bank and funded by Clean Technology Fund (CTF) and Global Environment Facility (GEF). Under the GREM Project, PT SMI (the project implementing agency) provides sub-borrowers with debt financing for resource confirmation drilling, through provision of loan and de-risking facility with total amount of up to US$ 30 million for each exploration subproject. The eligible expenses include site preparation, construction of drilling infrastructures (road, well pad), drilling works, well testing, site support services, and update of pre-feasibility study post-exploration drilling. The developers who are interested to apply for the facility shall submit a proposal to PT SMI which consists of company information, technical documents, and safeguards documents, with detail as described in the GREM's operations manual. A Gender Action Plan (GAP) is also required to be submitted by the developers.

[1] Consisting of US$150 million from IBRD, US$97.5 million from the GCF, US$72.5 million from the Clean Technology Fund (CTF), US$75 million from GoI's PISP , which will leverage US$60 million in private developers' equity.

[2] Consisting of US$2.5 million from GCF, US$2.5 million from CTF, and US$1.25 million from the Global Infrastructure Facility (GIF).

3.3 The World Bank Social Safeguard Policies Triggered by the Geothermal Exploration Project

3.3.1 OP/BP 4.10 Indigenous People (IPs)

The criteria for Indigenous Peoples have the following characteristics:

1. The existence of awareness and self-recognition as a social group that has the same historical background, origins, and ancestors, and is recognized by other parties around it.
2. There is a collective attachment to a certain territory, which geographically becomes a separate habitat from other groups.
3. Have cultural, social, economic, political and legal values and institutions that distinguish them from other groups.
4. Has a language, or at least a dialect of its own.

Indigenous Peoples have specific rights over land or natural resources, as defined in Operation Policy 4.10. To respect these rights, there are more stringent requirements related to engaging Indigenous People, which often means using forms of engagement that give greater decision-making authority to representatives of these communities, including Free, Prior and Informed Consultation (FPIC). The FPIC is as an effective process ensures that Indigenous Peoples are meaningfully engaged and have sufficient information about the project and sufficient time to be involved in decisions. The implementation of FPIC is based on the principle of respect and self-determination. Respect principle means Indigenous Project-Affected People are treated with full respect and recognizing the project is in their home and they must live with all impacts. Accordingly, the indigenous culture should permeate Project-IP interactions. Whilst self-determination means affected the indigenous communities will be granted their right to collaborate with other project stakeholders to determine their own indigenous development trajectory. Therefore, the Indigenous People can freely make decisions without coercion, intimidation, or manipulation from external parties.

The FPIC shall be applied if:

- The project impacts on customary lands or resources.
- The project causes relocation of Indigenous People from traditional or customary land.
- Cultural heritage was significantly affected by the project.

The objectives of the policy are that broad community support from Indigenous Peoples in the project area should be obtained and that the policy aims to minimize impacts and provide culturally appropriate benefits and mitigation measures. As described by the policy in situations where indigenous peoples are present in, or have collective attachment to, the project area and for the preparation of an Indigenous Peoples Plan (IPP) and/or Indigenous Peoples Planning Framework (IPPF).

3.3.2 OP/BP 4.11 Physical Cultural Resources (PCR)

Physical Cultural Resources (PCR) can be defined as Movable or immovable objects, sites, structures, groups of structures, and natural features and landscapes that have archaeological, paleontological, historical, architectural, religious, aesthetic, or other cultural significance. The presence of a project in an area will potentially have an impact on disturbance, degradation, desecration of cultural sites or artefacts because of land disturbances, land acquisition, impacts on geothermal features or landscapes.

OP/BP 4.11 is a requirement of the World Bank to avoid or mitigate adverse impacts resulting from project development on cultural resources. It is possible that PCR will be found near geothermal exploration projects. In some cases, in Indonesia, local communities consider geothermal energy manifestations as sacred. The ESMF includes requirements for preparing a PCR Management Plan (PCRMP), which will be developed as part of the ESIA and ESMP processes, as well as requirements for chance discovery procedures that will be attached to each ESMP.

Considering the physical cultural resources may not be known or visible; therefore, it is important that a project's potential impacts on physical cultural resources be considered at the earliest possible stage of the project planning cycle. The project to determine the existence of Physical Cultural Resources within project area within Environmental Assessment and develop risks mitigation measure.

The Physical Cultural Resources management shall be applied if:

- Project carries out excavations, demolition, changes to the surface of the earth, or similar activities that will change other physical environments.
- Located in a protected/conservation area or its buffer zone.
- Located in a cultural heritage area and/or strongly suspected of being a cultural heritage area.
- Projects that are planned as protected/conservation areas and/or cultural heritage areas.

Basically, the project should avoid this cultural heritage area. If this is not possible, then the project must carry out studies to find opportunities to manage its impacts:

- Relocating and/or modifying the project's physical footprint.
- Carry out conservation and rehabilitation in place (in situ);
- Relocation of cultural heritage objects.
- Doing documentation.
- Strengthen the capacity of the government responsible for managing cultural heritage.
- Building a monitoring system for managing cultural heritage.
- Arrange the management schedule and the costs needed to carry out the management.
- Registering the findings of the said cultural heritage.
- Develop a Cultural Heritage Management Plan.

If a project activity may affect cultural heritage, the project proponent will consult with affected communities that have cultural heritage as part of their longstanding culture. The project proponent will consult with affected communities to identify important cultural heritage, and include in the project proponent's decision-making process the views of affected communities. This consultation will also involve relevant national and local governments authorized to protect such cultural heritage.

3.3.3 OP/BP 4.12 Involuntary Resettlement (IR)

This policy addresses direct economic and social impacts from the projects activities that will cause:

(a) Involuntary taking of land resulting in (i) relocation or loss of shelter, (ii) loss of assets or access to assets or (iii) loss of income sources or livelihoods.
(b) Involuntary restriction of access to legally designated parks and protected areas resulting in adverse impacts on the livelihoods of the displaced persons. The policy requires siting of project infrastructure to be so chosen so as to avoid these impacts altogether or to minimize them to the extent possible.

The OP/BP 4.12 mechanism shall be applied if:

- Acquisition of land / property which displaces people physically and / or economically.
- The presence of the project causes involuntary restriction of access to areas that are important to the community such as agricultural land, water sources, parks, forests, and others which may lead to adverse impacts on livelihoods.

The objective of Involuntary Resettlement policy is to avoid or minimize involuntary resettlement, if this is not possible; assist displaced persons in improving or restoring their livelihoods and living standards relative to pre-displaced levels or to levels before the commencement of the project, whichever is higher. The policy will cover loss of shelter, assets and access to assets, loss of income sources or means of livelihood, whether people must move.

The basic principles:

- Avoid, and if not possible minimize, land acquisition and resettlement/relocation through adjustment of technical design of the Project Activity or change of project location.
- Where these cannot be avoided, the policy requires the preparation of either or both instruments (i) resettlement policy Framework, (ii) Resettlement Action Plan, and for meaningful

consultations with potentially affected people. The policy prohibits community donations of lands for location-specific infrastructure.
- Carry out socialization of detailed information to PAPs concerning activity plan and possible required land acquisition and/or resettlement/relocation.
- Conduct survey to identify the PAPs and their land/assets affected by Project Activity, and identification on loss of income source or economic activity of PAPs due to Project Activity.
- Conduct consultation with PAPs to determine any available schemes for land acquisition and resettlement, and estimation of land acquisition and resettlement schedule.
- Provide procedures for the handling of grievances and complaints of PAPs.
- All mutual agreements made in the formulation of Comprehensive LARAP or Abbreviated LARAP. The comprehensive LARAP shall be implemented with criteria (1): Total Residents Relocated is more than 200 people/40 families and or (2) PAPs loses total Asset/ Productive Income more than 10%. The Abbreviated LARAP shall be implemented whenever the impact resulting from the project's land acquisition is less than 200 people/40 families or PAPs loses total asset/productive income less than 10%.
- Contains procedures for monitoring of the implementation of Comprehensive LARAP or Abbreviated LARAP.

Specific Principles:

- Each PAP is entitled to receive compensation for the loss of their land and all assets attached to it, regardless of the status of land rights.
- Each PAP that experiences a loss of income and source of livelihood is entitled to receive assistance to restore their income and livelihood and be given assistance during the transition period to recover their living conditions.

Special consideration shall be applied if project conduct land acquisition on traditional or customary land. If the Sub Borrower proposes to acquire traditional or customary land and adverse impacts can be expected, the Borrower will take the following steps and obtain their FPIC:

a) Document efforts to avoid and otherwise minimize the area of land proposed for the project.
b) Document efforts to avoid and otherwise minimize impacts on natural resources subject to traditional ownership or customary use or occupation.
c) Conduct a culturally appropriate social impact assessment to assess the project's potential impacts, both positive and adverse, on Indigenous Peoples.
d) Ensure that affected Indigenous Peoples are informed of:
    i. their land rights under national law, including any national law recognizing customary use rights.
    ii. the scope and nature of the project; and
    iii. the potential impacts of the project.
e) Conduct meaningful consultations, to increase the effective participation of Indigenous Peoples.
f) Addressing intergenerational issues among Indigenous Peoples, including the special needs of women, youth and children within indigenous communities.
g) Provide grievance handling mechanisms that is culturally appropriate, gender sensitive, and directly accessible to the affected Indigenous Peoples without incurring costs and without retribution.

3.4 Social Related Safeguard Instrument

3.4.1 Stakeholder Engagement and Information Disclosure

Stakeholder engagement is an inclusive process that is conducted throughout the program and/or activity cycle (planning stage, implementation stage to program closure stage). Stakeholder engagement at the beginning of the activity development process is a key step and is considered the most effective because it determines the assessment, management, evaluation and monitoring of potential impacts arising from the implementation of activities. The frequency and intensity of stakeholder engagement

efforts will be adjusted to the scale, level of risk and impact of the project. The greater the scale, level of risk and impact of the project will demand a higher frequency and intensity of stakeholder engagement efforts from the project proponent.

The expected objectives of the stakeholder relationship building exercise are:

- Enable the project to obtain and receive inputs on project design, implementation risks, impacts, and appropriate mitigation measures from various stakeholders.
- Assists the project in developing strong, constructive, and responsive relationships with interested parties and project-affected people.
- Can support project oversight and help identify potential environmental and social issues that the project could potentially cause early on.
- Can support the long-term environmental and social sustainability of the project, increase community acceptance of the project, and contribute to the successful design and implementation of the project.

The stakeholder engagement process includes:

1. Identification and analysis of stakeholders

The project proponent identifies stakeholders consisting of (i) potentially affected communities, namely disadvantaged communities and vulnerable groups; (ii) parties related to the implementation of activities; and (iii) parties who have an interest in the ongoing activities.

2. Planning of stakeholder engagement methods

The project proponent develops a Stakeholder Engagement Plan that includes strategies and steps that will be implemented to capture all stakeholder participation, concerns, and needs for the planning and implementation of activities, especially gender, vulnerable groups and communities that are potentially disadvantaged by the implementation of activities. The stakeholder engagement plan also includes timelines, methods and approaches, and types of information needed in the stakeholder engagement process as well as disclosure of information to stakeholders during the stakeholder engagement process throughout the program and/or activity cycle. The stakeholder engagement plan and implementation must also consider the involvement of gender or vulnerable groups at 30% as affirmative action in the overall program implementation. The stakeholder engagement plan is developed by considering the interests and characteristics of stakeholders as well as the level of involvement in the implementation of activities.

3. Public information disclosure

The project proponent will disclose the activity plan to stakeholders as early as possible to provide access to information in a transparent, equitable manner and in accordance with socially and culturally acceptable norms and language, especially to gender and vulnerable groups, related to the potential risks and impacts caused by the implementation of programs and / or activities as well as plans for managing and monitoring these potential impacts.

In general, the disclosure of such information at least includes: (i) the purpose, nature and scale of activities; (ii) the period and timeframe for the implementation of activities; (iii) the types of sub-activities and the level of risk that may cause impacts on the community, and mitigation plans and monitoring of potential environmental and social impacts; (iv) the proposed stakeholder engagement plan and aspects required from stakeholders; (v) the time, agenda, approach and method of consultation, disclosure of information and provision of access to information related to public consultations / similar meetings, minutes of meeting results and reporting; and (vi) disclosure of information related to the complaint handling mechanism and the procedure for complaints to be followed up.

In ensuring access to information, the activity proponent discloses information in relevant local languages and in a manner that is accessible to all communities based on their respective cultures and considers the special needs of vulnerable groups (such as, disability groups, groups with minimum language literacy, gender, communities with language differences and limited access).

4. Consultation with stakeholders

Meaningful consultation with stakeholders is carried out as early as possible to obtain stakeholders' initial views on the activity plan. This consultation is expected to get input, criticism and suggestions from stakeholders to identify risks and potential impacts as well as environmental and social management suggestions. The consultation process is expected to take place on an ongoing basis along with the emergence of impacts on the implementation of activities.

In carrying out consultation with stakeholders, the activity proponent discloses information related to the activity plan that is relevant, transparent, objective, meaningful and easily accessible within a period that allows and in accordance with the culture, approach and language that can be understood by stakeholders.

5. Stakeholder engagement during activity implementation

The process of consultation and stakeholder engagement is carried out until the end of the program and/or activity implementation by referring to the stakeholder engagement plan. The project proponent will request input and suggestions from stakeholders on the performance of environmental and social protection implemented by the project proponent and the mitigation measures implemented as stated in the Environmental and Social Protection Commitment. If there are impacts that have not been listed in (i) environmental and social management and monitoring documents; and (ii) the activity's Environmental and Social Protection Commitment, the project proponent will consult with stakeholders regarding mitigation measures for additional impacts (direct impacts, derivative impacts, cumulative impacts or impacts arising from supporting facilities). Strategies and plans for the management and monitoring of such additional impacts will be included in the adjusted Environmental and Social Safeguards Commitment.

6. Grievance Redress Mechanism

The project proponent will establish a grievance redress mechanism to respond to complaints and reports related to the implementation of activities. This grievance redress mechanism is expected to handle any relevant reports quickly and effectively, transparently, easily accessible to all parties, at no cost/retribution and in accordance with the culture at the location of activity implementation.

The project proponent will also inform related reporting channels and procedures at the beginning of the activity implementation. Furthermore, the activity proponent will also inform affected parties regarding the grievance redress process and make available to the public a grievance log that includes responses to relevant grievances. The grievance redress process will be conducted in a culturally appropriate manner and will be objective, sensitive, and responsive to the needs and concerns of project-affected parties. The mechanism will also include anonymous reporting.

SEP Institutional Management

To be able to carry out the stakeholder engagement process effectively the project proponent is expected to be able to develop an institutional governance through the following strategies:

1. Execute the Program Implementation Plan to support stakeholder engagement activities within the company/Project.
2. Development of an organizational structure taking into account the management needs of stakeholders and social risks that have been identified along with a framework of roles and responsibilities of each related unit;
3. Periodic monitoring and evaluation include regular updating of databases and stakeholder issues, documentation of stakeholder engagement activities, as well as reviewing the effectiveness and improvement of stakeholder engagement strategies and social risk management.
4. Increasing organizational capacity through structuring stakeholder governance systems and existing HR training programs.
5. Effective and efficient funding support for implementation of stakeholder management strategies and social risk mitigation.

3.4.2 Gender Action Plan (GAP) and Gender Based Violence (GBV) Risk Mitigation

It is acknowledged that women and girls in World Bank-funded project areas have the potential to experience or be exposed to discrimination and gender-based violence. Gender inequality in society may be caused by the factors of sub-ordination, marginalization, multiple burdens, violence, and labelling (stereotyping). Therefore, through World Bank financed operations expected can contribute to the mitigation, prevention and response of discrimination and violence experienced by women and children.

Gender equity refers to situations where all people, women and men, girls and boys, are valued equally, have an equal position, and can share equally and fairly in the distribution of power, knowledge, resources and opportunities. With the realization of gender justice, it is hoped that everyone, both women and men will be free from a series of gender-based socio-cultural-economic-political systems which repress and oppress individuals or social groups.

Nationwide data by the Geothermal Directorate under MEMR indicates that, from a survey of the 12 leading developers in the sector with a total number of employees is 1408, just 14 percent of these are female. Most of these employments are of administrative nature rather than managerial or technical positions. At the project sites, from MEMR sample, the number of women employed in technical and managerial roles was found to be smaller than men, with just a total of 15 women in these positions across all 12 companies. This data would suggest that this is predominantly male dominating sector.

To tackle this gender gap, all subproject to be financed under the GREM Facility are required to propose a GAP and GBV Risk Management as part of the sub-project funding proposal. The sub-borrowers will prepare and present the GAP and GBV Risk Management as part of the agreement to fund the sub-project. A Gender Action Plan (GAP) is an instrument that serves as a roadmap for proposing gender equality in the design and implementation of projects. The content of the GAP document will include mainly about the proposed percentage of women shall be employed by the project locally at site in technical roles. In addition, the project also expected to develop Standard operating procedures (SOP) developed for gender-informed geothermal workplace health and safety.

Whilst Gender-based violence (GBV) Risk Management refers to approach and plans to prevent and respond to the occurrence of harmful threats or actions directed at an individual or group based on their gender. GBV can include physical, psychological, sexual, economic, legal, political, and social harm, as well as other forms of harm, abuse, and/or control. This type of violence is rooted in structural gender inequalities and power imbalances. It is both a symptom of gender inequality and a tool to reinforce this inequality.

During the project preparation, a gender assessment was prepared to analyze barriers and gaps associated to gender in the activities financed by the project and identify areas (frequently call gender entry points) to promote gender parity in the sector. In addition, there will be increased knowledge and sensitization of project operators on preventing and responding to incidents of violence based on gender and against children.

In implementing GAP and GBV action plan the sub borrower shall be assisted and coached by a gender expert provided by PT SMI and the World Bank. The main task of gender expert is to enhance the capacity of the developers to understand the implementation of gender informed approaches through provide intensive assistance to developers to ensure the submission of GAP and GBV Risk Mitigation Plan documents by developers to PT SMI as a condition for sub-loan approval or first disbursement of sub-loans can be fulfilled properly.

4. DISCUSSION

Social acceptance is an important requisite for the smooth implementation of geothermal projects, especially at the exploration phase. Based on the results of the study as previously mentioned, it is known that in several geothermal exploration projects in Indonesia are still facing Societal Challenges due to the presence of negative stigma towards geothermal exploration projects. There are several identified factors that contribute its condition mainly the spatial characteristics of geothermal

exploration project locations that is in or close to forest areas, community's plantations, residential areas or tourism areas, as well as in the territory of indigenous communities or cultural heritage sites. The existence of these factors will certainly lead to high sensitivity to environmental, community health and safety, community's livelihood, and socio-cultural aspects of local communities. In addition, the project often pays less attention to the existence of sensitive receptors of the physical and social aspects in the project plan area, as well as less attention to the importance of social safeguard management, and reluctance to involve affected communities and other project's interest parties as early as possible of project implementation. There also the emergence of miss perception among community and perhaps other stakeholders at the regional/local level about geothermal energy projects which is perceived similar with "mining" projects that detrimental to natural ecosystems and are harmful to human life. As a result of these factors at the end has contributed to the negative stigma as mentioned above has eventually in some cases made the presence of a geothermal exploration project difficult to gain support and acceptance from the local community.

This study aims to provide awareness related to the importance of implementing appropriate measures in preventing and managing social risks in geothermal project exploration through the implementation of social safeguard management measures. Based on previous research studies conducted by geothermal experts and field observations on the implementation of several geothermal exploration projects in Indonesia, especially on the implementation of the GREM project, the author concludes that there are four main requirements for the project to be accepted by the community living in the working area, namely: i) preventing or minimizing environmental and social impacts, ii) avoiding negative impacts on public health and safety, iii) fostering good relationships as early as possible with stakeholders, and iv) providing direct benefits to the community.

To fulfill this condition, the project owner must prepare appropriate and measurable social safeguards instruments. In other site, PT SMI with supporting from the World Bank and the Government of Indonesia has establishing a Geothermal Resource Risk Mitigation (GREM) Facility ("the Facility") to support exploration drilling by state-owned and private sector developers. The main objective is to scale up investment in geothermal energy development in Indonesia. In implementing the GREM PT SMI imposes the social safeguard policies and safeguard instruments as an important tool developed by international financial institutions to prevent and mitigate undue harm to communities during the project development process.

The social safeguard policies aim to prevent and mitigate undue harm to people and their environment in the development process, to compensate affected people and to restore livelihoods to at least the level prior to development intervention. Through the implementation of social safeguard policies and safeguard instruments, it is expected to serve not only as a tool to improve the quality of project proposals, but also intended as an opportunity for the project proponent to prepare and implement social safeguard management measures. In addition, the safeguard policy and safeguard instrument will be benefit for affected community members and other stakeholders to engage in the implementation of the development process, and increase their sense on benefit and ownership of the project. In this way, it is hoped that the realization of a sustainable geothermal exploration project with broad community and stakeholders support can be achieved.

REFERENCES

Ampaire, Charlotte. *Environmental and Social Impacts of Geothermal Development in Conservation Forest Areas in Indonesia*. Profor, World Bank Group. *https://www.profor.info/content/environmental-and-social-impacts-geothermal-development-conservation-forest-areas-indonesia*. Accessed at 4 August 2023. (2020).

Cataldi, Raffaele. *Social Acceptance of Geothermal Projects: Problems and Costs.* Romania: IGA standard. *https://www.geothermalenergy.org/pdf/IGAstandard/ISS/2001Romania/cataldi.pdf.* Accessed at 2 August 2023. (2001).

Ibrohim, A., Prasetyo, R. M., & Rekinagara, I. H. *Understanding Social Acceptance of Geothermal Energy: A Case Study from Mt. Lawu, Indonesia*. IIGW. Bandung: IOP Conference. (2019).

Kubota, Hiromi. Determining barriers to developing geothermal power generation in Japan: Societal acceptance by stakeholders involved in hot springs. Japan: Energy Policy Volume 61, October, Pages 1079-1087. (2013)

PT SMI. *Indonesia Geothermal Resource Risk Mitigation Project Developer Manual*. https://ptsmi.co.id/strategiccooperation/grem. (2022*).*

PT SMI. *Indonesia Geothermal Resource Risk Mitigation Project GREM* (P166071) Environmental and Social Management Framework. https://ptsmi.co.id/strategiccooperation/grem. (2019*).*

Purba, D., Chandra, V. R., Fadhillah, F. R., Wulan, R. D., Soedarsa, A., Adityatama, D. W., & Umam, M. F. *Drilling Infrastructure Construction Challenges in Geothermal Exploration Project in Eastern Indonesia.* World Geothermal Congress. Reykjavik: WGC. (2021).

Wibowo, Rimun. Overview of OP 4.12. ESS5 (Include DDR) and GoI Regulation on Land Acquisition. Equator Group (PT. EQI & LPM EQ). (2023).

World Bank. *Environmental & Social Framework for IPF Operations, ESS5: Land Acquisition, Restrictions on Land Use and Involuntary Resettlement.* (2018-a)

World Bank. Environmental & Social Framework for IPF Operations, *ESS7: Indigenous Peoples/ Sub-Saharan African Historically Underserved Traditional Local Communities.* (2018-b).

World Bank. *OP 4.11 Physical Cultural Resources for GREM Project.* Training Module. (2023-a)

World Bank. *Stakeholder Engagement & FPIC 101 Workshop*. Workshop Module. (2023-b)

World Bank. *Stakeholder Engagement at GREM Project*. Training Module for PIUs. (2023-c)

World Bank. *Gender Aspects for GREM.* Training Module. (2023-d).

World Bank. *Gender Based Violence & Violence Against Children Mitigation*. Workshop Module. (2023-e).

This page is intentionally left blank

Part 5:
General

Acceleration of Geothermal Investment and Revenue

Aditya Negara[1], Sepriandi Maulana[1], Richard Alexander[2], and Muhammad Andhika[3]

[1]Medco Energi
[2]KSORKA
[3]ECOLAB

aditya.negara@medcoenergi.com, sepriandi.maulana@medcoenergi.com,
richard.alexander@ksorka.com, muhammad.andika@ecolab.com

Keywords: Acceleration, regulation, incremental model

ABSTRACT

Indonesia plans to have an energy mix by increasing the proportion of renewable energy to 23 percent in 2025 and 31 percent in 2050, this will lead to 17 percent of energy savings in 2025. The plan is found in Government Regulation Number 79 of 2014 regarding the National Energy Policy. Nevertheless, Indonesia's geothermal development still faces numerous challenges, mostly because of the relatively complex and lengthy business/investment processes, while geothermal power plant technology is advancing rapidly. However, utilization of geothermal energy to produce electricity is already mature with diverse technologies. Several types of power plants, including direct-steam, flash, binary, and mixed cycle/hybrid, have been implemented. In 2023, no less than 25 countries' geothermal power plants were already installed, with a total capacity of 16.13 GWH. Indonesia contributes more than 2 GWh with 16 sites across the country, which is only overshadowed by the USA with total production of 3.7 GWh (Richter, 2023).

Due to its nature, geothermal power plant development has some unique obstacles. One of the biggest issues is mapping the resources. The more comprehensive and complete the geoscience data, the uncertainty would be less thus exploration cost could be less considering that drilling cost will take 25 to 30% of the development cost (IRENA (2017)). In this context, knowledge regarding the prospective locations and characteristics of geothermal energy resources is essential for investors and developers, particularly during the development phase. Moreover, geothermal energy potential data sources and location specific development plans should be made accessible and updated periodically. Government attempt to lower exploration risk by launching Geothermal Finance aid, Geothermal Resource Risk Mitigation (GREM), and Government Drilling. It is estimated that these programs will attract investors and developers interested in geothermal project development in Indonesia.

Another downside of geothermal business is it has to wait until the surface facilities and power generation system are fully installed to generate revenue. A new approach to this issue is by adopting the concept of incremental development model (Aditya et al, 2022). This continuous and parallel power plant development method is estimated to be able to expedite the Commercial Operation Date (COD) process up to 4 times which takes place between 4th to 8th years. The revenue generation will be accelerated and the utilization of geothermal power plants will be more efficient and more orderly in time.

With drilling optimization and incremental development method, the risk of geothermal development could be mitigated and revenue stream would cash in quicker than previous conservative methods. This will attract more business entities to involve in the geothermal industry hence help the government plan on energy mix program.

In terms of geothermal field development, from exploration, exploitation to the operation of the geothermal power plant itself, various permits and licenses are required. Often this is what makes the development process take a relatively long time, especially since the issuance of PP 22 of 2021 where for the entire energy sector the management and approval of permits has become centralized in various ministries although it is undeniable that there is simplification in terms of screening, weaknesses are also found where the existing system is in progress to be connected between ministries. Given the

development of investment in the energy sector in Indonesia which continues to grow but cannot be adapted by acceleration on the permitting side, the development of geothermal energy becomes less attractive in the eyes of investors.

This is a challenge for all stakeholders, especially the government, which needs to issue relevant regulations where priority is given to renewable energy developers in obtaining approvals and permits. In the future, it is hoped that multilevel approval and permitting can be simplified through a single system, through a special department that specifically handles renewable energy.

1. INTRODUCTION

The permitting process in the geothermal industry in Indonesia is a complex and time-consuming process that can be a major obstacle to the development of geothermal projects. In order to simplify this process and encourage the development of geothermal resources, it is important to issue relevant legislations that prioritize renewable energy development especially when obtaining approvals and permits.

One approach to simplifying the permitting process is the creation of a multilevel approval and permitting system that is specifically designed to handle renewable energy projects. This system could be streamlined and standardized to ensure that the permitting process is as efficient and cost-effective as possible. By creating a system that is tailored to the needs of renewable energy developers, the permitting process can be made more efficient and less cumbersome, reducing the burden on developers and encouraging investment in the geothermal industry.

Another potential solution is to centralize the management and approval of permits within a single department of ministry. This would help to ensure that the permitting process is more coordinated and consistent and would reduce the risk of delays or complications resulting from the involvement of multiple ministries or agencies. By centralizing the permitting process, Indonesia can create a more streamlined and efficient system that is better able to support the development of geothermal projects.

Ultimately, the key to simplifying the permitting process in the geothermal industry in Indonesia is to prioritize renewable energy development and create a regulatory framework that encourages investment in this sector. By creating a supportive regulatory environment, Indonesia can unlock the potential of its abundant geothermal resources and move towards a more sustainable and secure energy future. Through a combination of regulatory reform, investment in renewable energy infrastructure, and the adoption of innovative technologies, Indonesia can become a leader in the development of sustainable energy solutions, paving the way for a cleaner, more prosperous future.

2. GOVERNMENT ACCELERATION PROGRAM

The acceleration program related to geothermal investment in Indonesia refers to the government's efforts to promote and facilitate the development of geothermal projects in the country. This includes initiatives such as the Geothermal Finance Aid, Geothermal Resource Risk Mitigation (GREM), and Government Drilling programs, which are designed to lower exploration risk and attract investors to geothermal project development in Indonesia. The government is also working to simplify the permitting process for geothermal projects and create a regulatory framework that prioritizes renewable energy development. These efforts are aimed at unlocking the potential of Indonesia's abundant geothermal resources and moving towards a more sustainable and secure energy future.

2.1 Geothermal Resource Risk Mitigation (GREM)

Geothermal Resource Risk Mitigation (GREM) is a government program aimed at lowering exploration risk and attracting investors and developers to invest in geothermal project development in Indonesia through PT Sarana Multi Infrastructure (SMI). The unique feature of GREM pertains to the presence of a de-risking mechanism or a risk-sharing arrangement, whereby the developer is not solely responsible for the risks and expenses associated with exploration in the event of an unsuccessful outcome. The primary issue facing geothermal developers is exploration risk, which the GREM facility incorporates a de-risking feature for upstream development. The GREM facility is designed to cater to two distinct

groups, namely, developers and subsidiaries of State-Owned Enterprises (SOEs) who can avail themselves of the GREM Public window and private developers who can access the GREM Private Window. The mechanism can be seen in Figure 1 below.

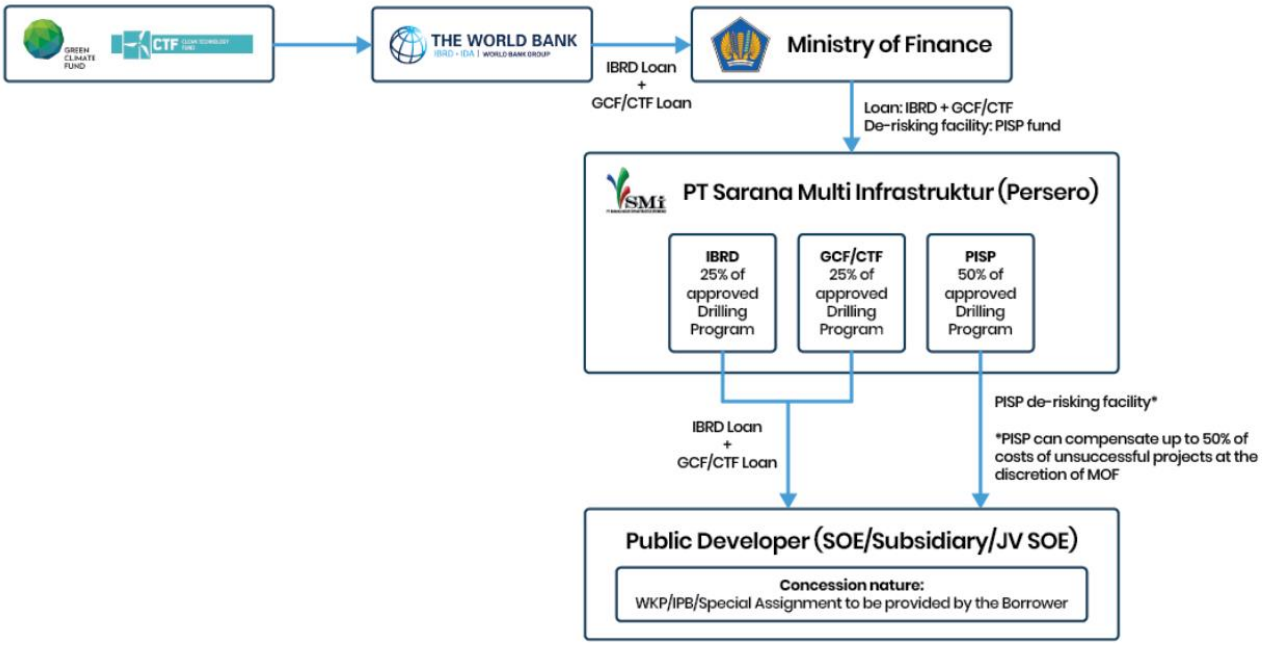


Figure 1: Government Resource Risk Mitigation (GREM) Flowchart.

2.2 Government Drilling

Government drilling is a program by the Indonesian government to explore geothermal potential in the country. The program is designed to reduce the risk of exploration failure by the private sector, which has been a major obstacle to investment in geothermal energy in Indonesia. Under the government drilling program, the government will conduct preliminary slim hole drilling in areas with potential geothermal resources. This type of drilling is relatively inexpensive and can provide valuable data about the size and quality of the geothermal resource. The private sector can then use this information to determine whether building a geothermal power plant in the area is feasible. The government's drilling program is being implemented by the Ministry of Energy and Mineral Resources (MEMR). The MEMR has allocated a budget of Rp 1.2 trillion (US$84 million) for the program in 2023. The program is expected to be completed by 2024.

The government's drilling program has been welcomed by the geothermal industry in Indonesia. The industry has long argued that the high risk of exploration failure has been a major obstacle to investment in geothermal energy in the country. The government's drilling program is seen as a way to reduce this risk and make geothermal energy more attractive to investors. The government drilling program is just one of the measures that the Indonesian government is taking to promote the development of geothermal energy. The government is also providing tax incentives and other financial support to the geothermal industry. The government is also working to improve the regulatory environment for geothermal development. The government's drilling program is a significant step forward for the development of geothermal energy in Indonesia. The program has the potential to reduce the risk of exploration failure and make geothermal energy more attractive to investors. If the program is successful, it could lead to a significant increase in geothermal power generation in Indonesia.

The following is a list of some of the advantages of drilling by the government:

- Reduce the risk of exploration failure for the private sector.
- Provide valuable data about the size and quality of the geothermal resource.
- Make geothermal energy more attractive to investors.
- Lead to a significant increase in geothermal power generation in Indonesia.

However, there are also some challenges associated with government drilling:

- It can be expensive.
- It takes a long time to complete.
- The results of the drilling may not be conclusive.

Overall, government drilling is a promising initiative that has the potential to boost the development of geothermal energy in Indonesia. However, it is important to be aware of the challenges associated with the program.

2.3 Tax Holiday

The Indonesian government offers a tax holiday for geothermal projects that meet certain criteria. The tax holiday exempts the project from corporate income tax for a period of 10 years. The project must also meet the following criteria:

- Located in an area with a geothermal resource potential of at least 50 megawatts.
- Have a minimum investment of IDR 1 trillion (US$67 million).
- Create at least 1,000 jobs.

The tax holiday is a significant incentive for geothermal projects in Indonesia. It can help reduce the cost of capital for these projects and make them more attractive to investors. In addition to the tax holiday, the Indonesian government also offers other financial incentives for geothermal projects. These include:

- Investment tax credits (ITCs)
- Accelerated depreciation
- Reduced import duties (RKBI)
- Exemption from value-added tax (VAT)

These incentives can help further reduce the cost of geothermal projects and make them more competitive with other forms of energy generation. The Indonesian government is committed to developing geothermal energy as a source of clean and renewable energy. The tax holiday and other financial incentives are part of the government's efforts to attract investment in geothermal projects and boost the development of this promising energy source.

The advantages of a tax holiday for geothermal projects are as follows:

- Reduce the cost of capital for these projects.
- Make geothermal energy more attractive to investors.
- Lead to a significant increase in geothermal power generation in Indonesia.

2.4 Presidential Decree 112/2022

Presidential Decree No. 112 of 2022 on the Acceleration of Renewable Energy Development for the Provision of Electricity was issued on September 13, 2022. The decree provides a number of incentives for the development of geothermal energy in Indonesia, including:

- Financing for geothermal projects. The decree provides for the provision of financing for geothermal projects through a variety of mechanisms, including loans, grants, and equity investments.

- Tax breaks for geothermal projects. The decree provides for a number of tax breaks for geothermal projects, including a reduction in the corporate income tax rate and an exemption from import duties on geothermal equipment.
- Government support for geothermal projects. The decree provides for government support for geothermal projects, such as the provision of technical assistance and the development of infrastructure.

The decree also sets out a number of other measures to accelerate the development of geothermal energy in Indonesia, such as streamlining the permitting process and providing support for research and development. The decree is seen as a significant step forward in the development of geothermal energy in Indonesia. The decree's incentives should encourage investment in geothermal projects and advance the development of this promising energy source.

Overall, Presidential Decree 112/2022 provides a number of attractive incentives for geothermal investment. These incentives are expected to attract investment in geothermal projects and boost the development of this promising energy source in Indonesia.

Additional information about Indonesian business permits related to revenue for geothermal developers:

- **Mining Business Permit (IUP)**: This permit is required for the exploration and exploitation of geothermal resources. The Ministry of Energy and Mineral Resources (MEMR) is responsible for issuing it.
- **Power Purchase Agreement (PPA)**: This agreement is between the geothermal developer and the state-owned electricity company, PLN. It lays out the terms and conditions for the sale of the geothermal plant's electricity.
- **Commercial Operation Date (COD)**: This is the date on which the geothermal plant is officially commissioned and begins commercial operation. The COD is a key milestone for geothermal developers, as it is the point at which they begin to generate revenue.
- **Environmental Permits** must be acquired from the Ministry of Environment and Forestry (MoEF) to ensure the project impacts are managed in an environmentally friendly manner.
- **Forestry permits** are also required for geothermal development projects in Indonesia, as most geothermal resources are located in protected forests. The Ministry of Environment and Forestry (MoEF) is responsible for issuing the Forestry Permit (*Persetujuan Penggunaan Kawasan Hutan*, PPKH).

Geothermal developers face the following difficulties in acquiring a permit:

- **Complex permit process**: The IPH is a complex permit that requires a detailed assessment of the environmental and social impacts of the geothermal project. The permit process can take several years to complete.
- **High costs**: The cost of obtaining a forestry permit can be high, as it requires the services of lawyers, consultants, and other experts.
- **Environmental challenges**: Geothermal development can have a significant impact on the environment, and geothermal developers must carefully manage these impacts to obtain a forestry permit.

By understanding the challenges of obtaining a forestry permit, geothermal developers can better prepare for the permit process and increase their chances of success.

The revenue that geothermal developers can generate depends on a number of factors, including the size of the geothermal resource, the efficiency of the geothermal plant, and the price of electricity. However, in general, geothermal developers can expect to generate a significant amount of revenue from their projects. Here are some of the benefits of obtaining these business permits for geothermal developers:

- **Legal certainty**: The IUP and PPA provide legal certainty for geothermal developers as they guarantee their rights to explore, exploit, and sell geothermal resources.
- **Access to finance**: The IUP and PPA can be used to secure financing for geothermal projects.
- **Revenue generation**: The COD marks the start of revenue generation for geothermal developers.

3. BINARY POWER PLANT

Conventional geothermal power plants that use a large steam turbine generator require a steam gathering system with a high steam flow rate. This condition forces the developer to drill more production and reinjection wells before it can start generating electricity. On the other hand, binary power plants do not require many wells, thus speeding up electricity generation. Binary power plants are flexible. It can be used for geothermal wells that have resource temperatures of 180°C (356°F) and higher. In other words, binary power plants can be used in fields that are often referred to as "medium-enthalpy" to “high-enthalpy” systems.

A binary power plant is a type of geothermal power plant that uses a secondary working fluid to generate electricity. The primary working fluid is geothermal water (brine) or steam, which is used to heat the secondary working fluid. The secondary working fluid then vaporizes and expands through a turbine to generate electricity. Binary power plants are used in areas where the geothermal resource is not hot enough to produce steam directly. The secondary working fluid is typically an organic compound with a low boiling point, such as isobutane or propane, and refrigerant. These compounds have a much lower boiling point than water, so they can be vaporized at lower temperatures. This makes binary power plants a good option for geothermal resources that are too hot for direct steam generation but not hot enough for conventional flash steam power plants. Binary power plants are also more efficient than direct steam generation power plants. This is because the secondary working fluid is not heated to the same temperature as the primary working fluid. The lower temperature of the secondary working fluid means that less energy is lost as heat; we called it the waste energy conversion by the exergy calculations.

Low-temperature geothermal resources have the potential to provide large amounts of clean electricity. And it’s the modularity of our heat-power systems that can make it a reality. They have huge potential to deliver a stable supply of clean electricity. But traditionally, it’s been very expensive to build geothermal power plants. With a great deal of financial risk involved and a long wait for profitability. With the Binary Power Plant's innovative incremental model, the geothermal power plant can start small and expand step by step. Build decentralized power plants and bring clean electricity to off-grid places. When the power plants need to produce more electricity, simply add more modules. With modular power plants, the potential of geothermal heat power can be fully realized. Delivering a stable supply of clean electricity day in and day out throughout the year (Negara, 2022)

Binary power plants are a relatively new technology, but they are becoming increasingly popular. This is because they are an extremely efficient and environmentally friendly way to generate electricity from geothermal resources. Binary power plants utilize waste energy: wet steam (condensate) and brine fluid (hot water). In conventional geothermal, usually the waste of steam and brine will go directly to the reinjection system; the waste heat cannot be converted to electricity because the plant technology is not sufficient to accept the low temperature level.

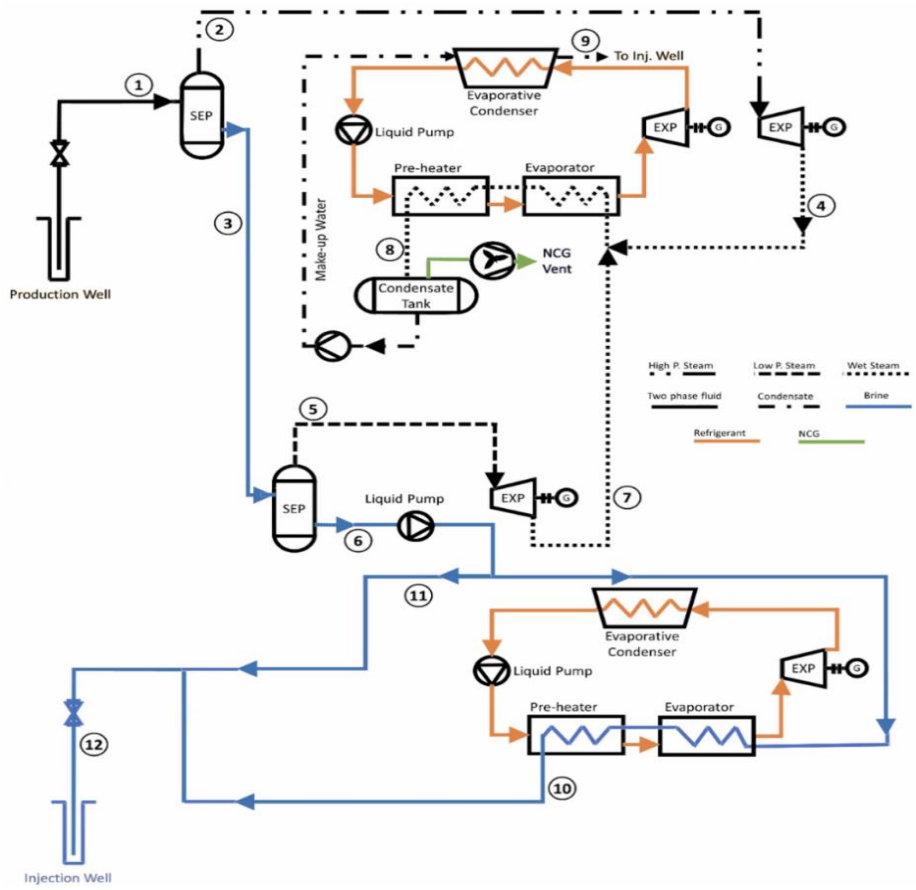


Figure 2: Binary Power Plant.

Binary power plants work by using a secondary fluid to extract heat from the geothermal reservoir. The secondary fluid is typically a non-toxic, low-boiling-point fluid such as isopentane, propane, or refrigerant. The heated secondary fluid is then used to drive a turbine to generate electricity. Binary power plants are more efficient than traditional flash steam plants for generating electricity from low-temperature geothermal resources. They are also more environmentally friendly, as they do not produce any emissions. As the demand for renewable energy continues to grow. They are a cost-effective and environmentally friendly way to generate electricity from geothermal resources. Here are some of the reasons why binary power plants are suitable for low-temperature geothermal resources:

- The secondary fluid used in a binary power plant has a lower boiling point than water, so it can be heated to a higher temperature by the geothermal reservoir. This means that more heat can be extracted from the reservoir, which results in higher efficiency.
- Binary power plants are less complex than traditional flash steam plants, so they are less expensive to build and operate.
- Binary power plants do not produce any emissions, so they are environmentally friendly.
- Binary power plants can be utilized nearby production well pads, which require less pipe line material. It can reduce the project's cost.
- The high-end technology, binary plants, can probably be developed with extra energy power output with advanced brine treatment technology. So, it is applicable for the future of Indonesia with low- to medium-temperature resources.

Some of the most promising areas for binary power plants in Indonesia include:

- Dieng Plateau (Central Java): PT Geo Dipa Energi
- Kamojang Plateau (West Java): PT Pertamina Geothermal Energy
- Wayang Windu Geothermal Field (West Java): Star Energy Geothermal (Wayang Windu) Limited

- Ulubelu Geothermal Field (Lampung): PT Pertamina Geothermal Energy
- Sarulla Geothermal Field (North Sumatra): Sarulla Operation Ltd. (a joint venture between PT Pertamina Geothermal Energy and Ormat Technologies)
- Ijen Geothermal Field (East Java): PT Medco Cahaya Geothermal, a joint venture between Medco Power Indonesia and Ormat Technologies
- Gunung Salak Geothermal Field (West Java): PT Star Energy Geothermal
- Sibayak Geothermal Field (North Sumatra): Star Energy Geothermal
- Hululais Geothermal Field (South Sumatra): PT Pertamina Geothermal Energy
- Lumut Balai Geothermal Field (South Sumatra): PT Pertamina Geothermal Energy
- Sungai Penuh Geothermal Field (Jambi): PT Pertamina Geothermal Energy

3.1 Incremental Development Plan

This model involves developing the power plant in stages rather than all at once. This can significantly shorten the time it takes to generate revenue, and it can also make the project more affordable for investors. A study by Aditya et al. (2022) found that the incremental development model could reduce the time to commercial operation (COD) by up to four times. This means that a project that would normally take 8 years to complete could be completed in just 2 years using the incremental development model. The incremental development model also has the advantage of making the utilization of geothermal power plants more efficient and orderly over time. This is because the power plant can be gradually brought online as each stage is completed. This helps to ensure that the power plant is always operating at its full capacity, which maximizes the return on investment for the project.

Overall, the incremental development model is a promising new approach to geothermal power plant development. It has the potential to significantly shorten the time to commercial operation, make the project more affordable for investors, and improve the efficiency of geothermal power plants. The incremental development model is a complex and challenging approach to geothermal power plant development. However, it has the potential to make geothermal energy a more attractive and viable option for investors as shown in figure 3.

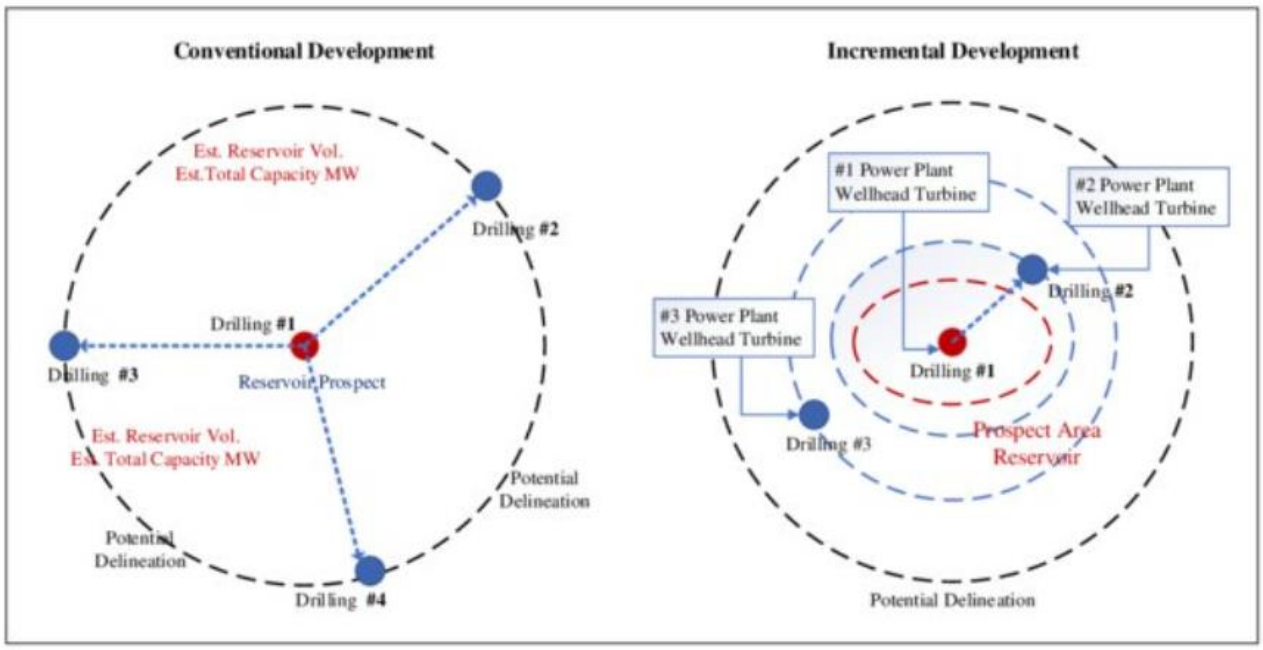


Figure 3: Diagram Conventional Development and Incremental Development.

The conventional approach involves developing the power plant all at once. This is the traditional way of developing geothermal power plants, and it is the most common approach. However, it can take several years to complete a conventional geothermal power plant, and this can make it difficult for investors to get a return on their investment.

The incremental development model involves developing the power plant in stages. This means that the power plant is brought online gradually as each stage is completed. This can significantly shorten the time it takes to generate revenue, and it can also make the project more affordable for investors. The investors can push the risk down, get the revenue faster, and support the next stage of construction with the initial revenue.

The new technology can produce electricity even though we find a very low-pressure well. With extremely flexible technology, investors can still earn revenue without any waste wells. It is a new era to have more confidence in geothermal development at medium to low enthalpy.

The diagram shows that the incremental development model can reduce the time to commercial operation by up to four times. This means that a project that would normally take 8 years to complete could be completed in just 2 years using the incremental development model (Onny Idianto, 2020)

3.2 Adaptive Project Management

Adaptive project management is a set of principles and practices that emphasize flexibility and adaptability. This makes it a good fit for geothermal development, which is a complex and dynamic process. Adaptive project management is a more flexible and adaptable approach to project management. This type of approach can be helpful for projects with changing requirements or uncertain environments. However, adaptive project management can also be more complex and challenging to implement than other project management approaches.

The advantages of geothermal development using adaptive project management:

- Reduce the risk of project failure.
- Make the project more flexible and adaptable to changes in the market.
- Help manage the environmental impact of the project.
- Improve communication and collaboration between team members.

Geothermal development is ideally suited to adaptive project management. It can reduce the risk of project failure, increase the project's flexibility and adaptability, and enhance team communication and collaboration. However, it is important to be aware of the challenges of using adaptive project management and to manage them effectively.

3.3 Geothermal Development Project Management

The most suitable geothermal development project management for binary power plants is one that takes into account the specific characteristics of these plants. Binary power plants are typically smaller and less complex than traditional steam power plants, but they still require careful planning and execution.

Here are some key considerations for geothermal development project management for binary power plants:

- **The geothermal resource**: The first step is to assess the geothermal resource and determine if it is suitable for a binary power plant. This will involve drilling test wells and collecting data on the temperature and flow rate of the geothermal fluid.
- **The binary cycle**: The next step is to select the appropriate binary cycle for the project. There are a number of different binary cycles available, each with its own advantages and disadvantages. The specific cycle that is selected will depend on the characteristics of the geothermal resource and the desired output of the power plant.

- **The plant design**: The plant design should take into account the specific characteristics of the binary cycle and the geothermal resource. The design should also be optimized to minimize costs and maximize efficiency.
- **The construction process**: The construction process for binary power plants is typically less complex than for traditional steam power plants. However, it is still important to carefully manage the construction process to ensure that the plant is built on time and within budget.
- **The commissioning process**: The commissioning process is the process of testing and adjusting the plant to ensure that it is operating as designed. This is an important step in ensuring that the plant is reliable and efficient.

By taking into account the specific characteristics of binary power plants, project managers can develop a project management plan that will increase the chances of success for these projects.

- **Use a project management tool**: A project management tool can help track progress, manage tasks, and communicate with stakeholders.
- **Set clear goals and objectives**: Having clear goals and objectives will help keep the project on track.
- **Break down the project into smaller tasks**. This will make the project seem less daunting and help identify potential risks.
- **Establish a communication plan**. This will ensure that everyone involved in the project is on the same page.
- **Be flexible**. Things don't always go according to plan, so it's important to be flexible and adaptable.
- **Celebrate successes**. This will help keep the team motivated and focused.

By following these tips, project managers can improve efficiency and increase the chances of success for geothermal development projects using binary power plants.

3.4 Increase Revenue

There are a number of ways to increase revenue using binary power plants. Some of these methods include:

- **Optimizing the plant design:** By optimizing the plant design, it is possible to increase the efficiency of the plant and generate more power. This can be done by using a more efficient binary cycle, choosing the right working fluid, and optimizing the heat exchangers and cooling water systems.
- **Improving the operating efficiency**: By improving the operating efficiency of the plant, it is possible to generate more power from the same amount of geothermal fluid. This can be done by optimizing the plant's control system, reducing downtime, and improving maintenance programs and procedures.
- **Expanding the plant capacity**: By expanding the plant capacity, it is possible to generate more power. This can be done by adding new generating units or by upgrading existing units.
- **Selling the excess power**: If the plant generates more power than is needed, the excess power can be sold to the grid. This can be a significant source of revenue, especially if the plant is located in an area with high demand for electricity.
- **Developing new applications**: Binary power plants can be used for a variety of applications, such as district heating, desalination, and industrial process heat. By developing new applications for binary power plants, it is possible to increase the demand for power and generate more revenue.

By following these methods, it is possible to increase revenue using binary power plants. Power plant design also must have high flexibility to maintain and increase revenue due to natural resources that are sometimes unpredictable. A fully integrated system is the key to increasing revenue.

4. INTEGRATION GEOTHERMAL BUSINESS PROCESS

Integration of a geothermal business process is the process of integrating all aspects of the geothermal business, from exploration and development to power generation and operations. This includes integrating the technical, financial, and operational aspects of the business. The goal of an integrated geothermal business process is to create a more efficient and effective geothermal business. Cost-cutting measures, increased productivity, and higher profits can all help with this.

Integrating geothermal business processes has a variety of advantages:

- **Reduced costs**: Integration can help reduce costs by eliminating duplication of effort and streamlining business processes.
- **Improved productivity**: Integration can help improve productivity by providing a more efficient and effective way to manage the business.
- **Increased profits**: Integration can help increase profits by reducing costs and improving productivity.

There are a number of challenges to integration of geothermal business processes. These include:

- **Complexity**: Integration can be a complex process, and it can be difficult to get all of the stakeholders involved to agree on the best way to integrate the business.
- **Cost**: Integration can be a costly process, and it can be difficult to justify the cost if the benefits are not clear.
- **Resistance to change**: There may be resistance to change from employees who are used to working in a certain way.

Despite the challenges, an integrated geothermal business process can be a valuable tool for improving the efficiency and effectiveness of the geothermal business.

There are a number of solutions that can be implemented to simplify the permit process in Indonesia's geothermal industry. These include:

- **Streamlining the permitting process:** The permitting process for geothermal projects in Indonesia is complex and time-consuming. It can take several years to obtain all of the necessary permits, and this can be a major obstacle for investors. Streamlining the permitting process would make it easier for investors to obtain the necessary permits and bring projects to fruition.
- **Establishing a one-stop shop for permits**: Currently, geothermal developers need to obtain permits from a number of different government agencies. This can be a complex and time-consuming process. Establishing a one-stop shop for permits would make it easier for geothermal developers to obtain the necessary permits and bring projects to fruition.
- **Providing clear and concise information on the permitting process** The information on the permitting process for geothermal projects in Indonesia is often unclear and difficult to understand. This can make it difficult for investors to know what is required and how to obtain the necessary permits. Providing clear and concise information on the permitting process would make it easier for investors to navigate the process and bring projects to fruition.
- **Training government officials on geothermal permitting**: Government officials who are responsible for issuing permits for geothermal projects often lack the necessary training on geothermal technology and the permitting process. This can lead to delays and misunderstandings. Training government officials on geothermal technology and the permitting process would help to ensure that they are able to issue permits in a timely and efficient manner.

By implementing these solutions, the government of Indonesia can simplify the permit process for geothermal projects and make it easier for investors to bring these projects to fruition. This would help boost the development of geothermal energy in Indonesia and contribute to the country's energy security.

In addition to the above, the government could also consider:

- **Establishing a public-private partnership**: A public-private partnership (PPP) could be established to streamline the permitting process for geothermal projects. This would involve the government working with private companies to develop a more efficient and effective permitting process.
- **Using technology to improve the permitting process**: Technology can be used to improve the efficiency of the permitting process in a number of ways. For example, online permitting systems can make it easier for investors to submit applications and track the progress of their applications.
- **Encouraging cooperation between government agencies**: The government could encourage cooperation between different government agencies that are involved in the permitting process for geothermal projects. This would help to ensure that the process is coordinated and efficient.

By taking these steps, the government of Indonesia can simplify the permit process for geothermal projects and make it easier for investors to bring these projects to fruition. This would help boost the development of geothermal energy in Indonesia and contribute to the country's energy security.

5. CONCLUSION

The Indonesian government is committed to developing geothermal energy as a source of clean and renewable energy. The government is implementing a number of acceleration programs to lower exploration risk and attract investment in geothermal projects. These programs include the Geothermal Resource Risk Mitigation (GREM) program, the Government Drilling Program, and the simplification of the permitting process. The government is also working to create a regulatory framework that prioritizes renewable energy development. These acceleration programs are seen as a significant step forward for the development of geothermal energy in Indonesia. The programs have the potential to reduce the risk of exploration failure and make geothermal energy more attractive to investors. If the programs are successful, it could lead to a significant increase in geothermal power generation in Indonesia.

The government's acceleration programs are in line with the country's commitment to achieving net-zero emissions by 2060. Geothermal energy is a major source of renewable energy in Indonesia, and the government's acceleration programs are essential to unlocking the potential of this resource. The government's acceleration programs are also in line with the global trend towards the development of renewable energy. As the world transitions to a low-carbon economy, geothermal energy is becoming an increasingly important source of energy.

The government's acceleration programs will help to ensure that Indonesia is at the forefront of the global development of geothermal energy.

REFERENCES

AF Sidik,R.B: Strategi Pengembangan Bisnis Panas Bumi di Indonesia (2018)

Aditya Negara: Construction Of The Fastest Geothermal Power Plant, Sorik Marapi, IIGCE (p. 8). Jakarta.(2022)

Onny Idianto, N. M., ITB International Geothermal Workshop, Incremental Development Strategy of Geothermal Field Using Wellhead Technology: Case Study Ulumbu Geothermal Field (2020)

Presidential Decree No. 112 of 2022: Acceleration of Renewable Energy Development for the Provision of Electricity

Introducing the Business Model Approach to Manage and Handle Complexity during EPC Lumut Balai Project Unit 2 Development

Erwandi Yanto, Rury Zonta Kusumah, Firman Johannes Simanullang,
Hadi Suranto, Gatot Yudoko, and Meditya Wasesa

PT Pertamina Geothermal Energy, Grha Pertamina, Pertamax Tower, 7th Floor, Gambir, Jakarta, Indonesia

erwandi.yanto@pertamina.com

Keywords: Business Model, Lumut Balai Geothermal Field, EPC Power Plant Project, Consortium Scheme, Project Management

ABSTRACT

The Lumut Balai geothermal field in Indonesia, operated by PT Pertamina Geothermal Energy Tbk, faced challenges during the EPC (Engineering, Procurement, Construction) Power Plant project of Unit 1 from 2014 to 2019, which was significantly different from the Power Plant and FCRS development of Unit 2 from 2022 to 2024. Despite facing different challenges, effective project management is crucial for the successful execution of the project. This study aims to introduce a business model for project management in the consortium scheme of the EPC Lumut Balai Geothermal Power Plant Unit 2. The consortium comprises three contractors with expertise in EPC project construction. The business model focuses on the simplified business process, command chain, and the relationships among authority, stakeholders, shareholders, media, communities, and reporting procedures between the owner and the consortium. The results are based on lesson learned and an understanding of the actual conditions from the project's initiation to the current phase of execution and control. The business model framework has been developed to address the uniqueness, complexity, challenges, and strategies of handling the EPC project profile of Lumut Balai Power Plant development.

1. INTRODUCTION

In today's dynamic and rapidly evolving business landscape, Engineering, Procurement, and Construction (EPC) projects have become increasingly complex and challenging to manage. These projects involve intricate coordination of various stakeholders, technologies, resources, and timelines. As the scale and complexity of EPC projects continue to grow, traditional project management approaches may fall short in effectively handling the intricacies involved.

Introducing the business model approach to manage and handle complexity during EPC project development offers a new perspective and methodology to address the evolving project management needs. Traditionally, project management has focused on planning, execution, and control, often overlooking the broader business context. The business model approach seeks to bridge this gap by integrating strategic thinking, business goals, and stakeholder interests into the project management process.

Lumut Balai Geothermal Field Overview

Lumut Balai is one of the most promising geothermal field prospective in Indonesia which is operated by PT Pertamina Geothermal Energy. The exploration had been started since 1993 until 2007 through a lot of efforts to conduct the surveys, then continue with exploitation and development from 2007-2019 by the first plant construction with the installed capacity 55 MWe. In Figure 1, there is shown the specific milestone of Lumut Balai development from the plant and facilities construction in 2014 till the commercial date in 2019, then the current situation has reached the stage of the second plant project development with the capacity 55 MWe.

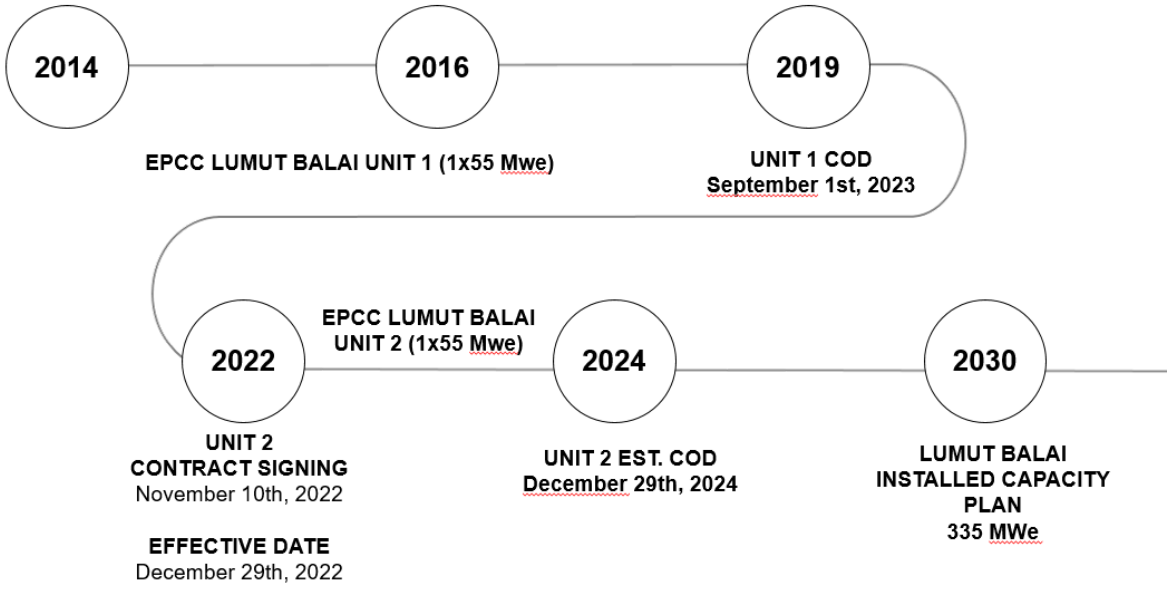


Figure 1: The Milestone of Lumut Balai Geothermal Project Development by Consortium Scheme and Funded by Loan (JICA).

As the future business growth plan of PT. Pertamina Geothermal Energy to add 600 MWe installed capacity in all of geothermal field. Lumut Balai become one of the most potential fields to grow since the resources of this field is really promising from the subsurface characterization. Lumut Balai will plan to be developed until 335 MWe which is more than half capacity from the overall PGE's future plan as shown in Figure 2 below.

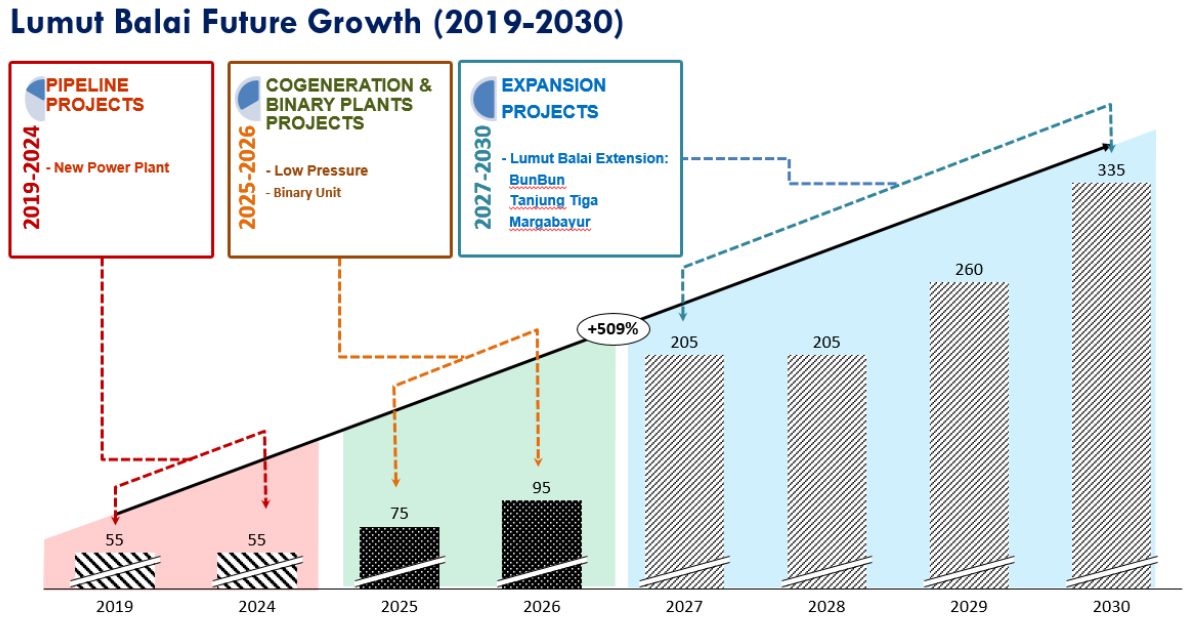


Figure 2: Future Business Growth Plan of Lumut Balai Geothermal Field from 2019 – 2030 (source: PGE's Business Plan 2030).

2. THEORETICAL FRAMEWORK

At its core, the business model approach recognizes that EPC projects are not isolated endeavors but integral parts of a larger business ecosystem. It emphasizes the alignment of project objectives with overall business objectives, ensuring that the project's outcomes contribute positively to the organization's long-term vision and profitability.

The business model In Figure 3 approach entails a systematic analysis of the following key aspects during EPC project development:

- Business Model Alignment: At the core of the conceptual framework is the alignment of the EPC project with the overall business model of the organization. This involves understanding the organization's strategic goals, financial objectives, and long-term vision. The business model approach ensures that the EPC project's objectives and outcomes are in sync with the broader business strategy, contributing to the organization's growth and profitability.
- Complexity Analysis: The conceptual framework recognizes the inherent complexity in EPC project development. It involves a thorough analysis of the project's intricacies, including technological requirements, stakeholder involvement, regulatory compliance, environmental considerations, and resource allocation. This step enables a comprehensive understanding of the challenges and opportunities associated with the project.
- Stakeholder Integration: The business model approach emphasizes stakeholder integration as a crucial element in project development. Identifying and engaging with relevant stakeholders, such as clients, contractors, suppliers, local communities, and regulatory authorities, is essential. The framework outlines strategies to effectively communicate with and manage diverse stakeholder interests to ensure a collaborative and supportive project environment.
- Risk Management and Contingency Planning: Managing risks is critical in complex EPC projects. The conceptual framework includes a systematic risk assessment to identify potential threats and opportunities. It involves developing risk mitigation strategies and contingency plans to address uncertainties proactively and ensure project resilience.
- Technology Integration and Innovation: EPC projects often involve cutting-edge technologies and innovations. The business model approach promotes the integration of appropriate technologies aligned with the organization's business goals. It encourages leveraging innovation to enhance project efficiency, reduce costs, and deliver value to stakeholders.
- Flexibility and Adaptability: Recognizing the dynamic nature of the business environment, the conceptual framework emphasizes flexibility and adaptability during project development. It encourages iterative planning and a willingness to adapt to changing circumstances and emerging challenges.
- Sustainable Practices: The business model approach places a strong emphasis on sustainability. Integrating environmentally friendly solutions, adopting responsible business practices, and engaging with local communities are key components of the framework. It ensures that the EPC project not only meets immediate needs but also contributes to the long-term well-being of the environment and society.
- Business Impact Evaluation: The conceptual framework includes an evaluation mechanism to assess the business impact of the EPC project. It measures project success against predefined business objectives and key performance indicators. This evaluation ensures that the project delivers tangible business value and aligns with the organization's overarching vision. The business model approach represents a paradigm shift in EPC project management. By integrating strategic thinking, stakeholder alignment, risk management, technology integration, flexibility, and sustainability into project development, this approach provides a holistic and forward-thinking framework to navigate complexity effectively. Embracing the business model approach can empower organizations to achieve successful project outcomes that align with their overarching business objectives, ensuring sustainable growth and competitive advantage in an ever-changing market.

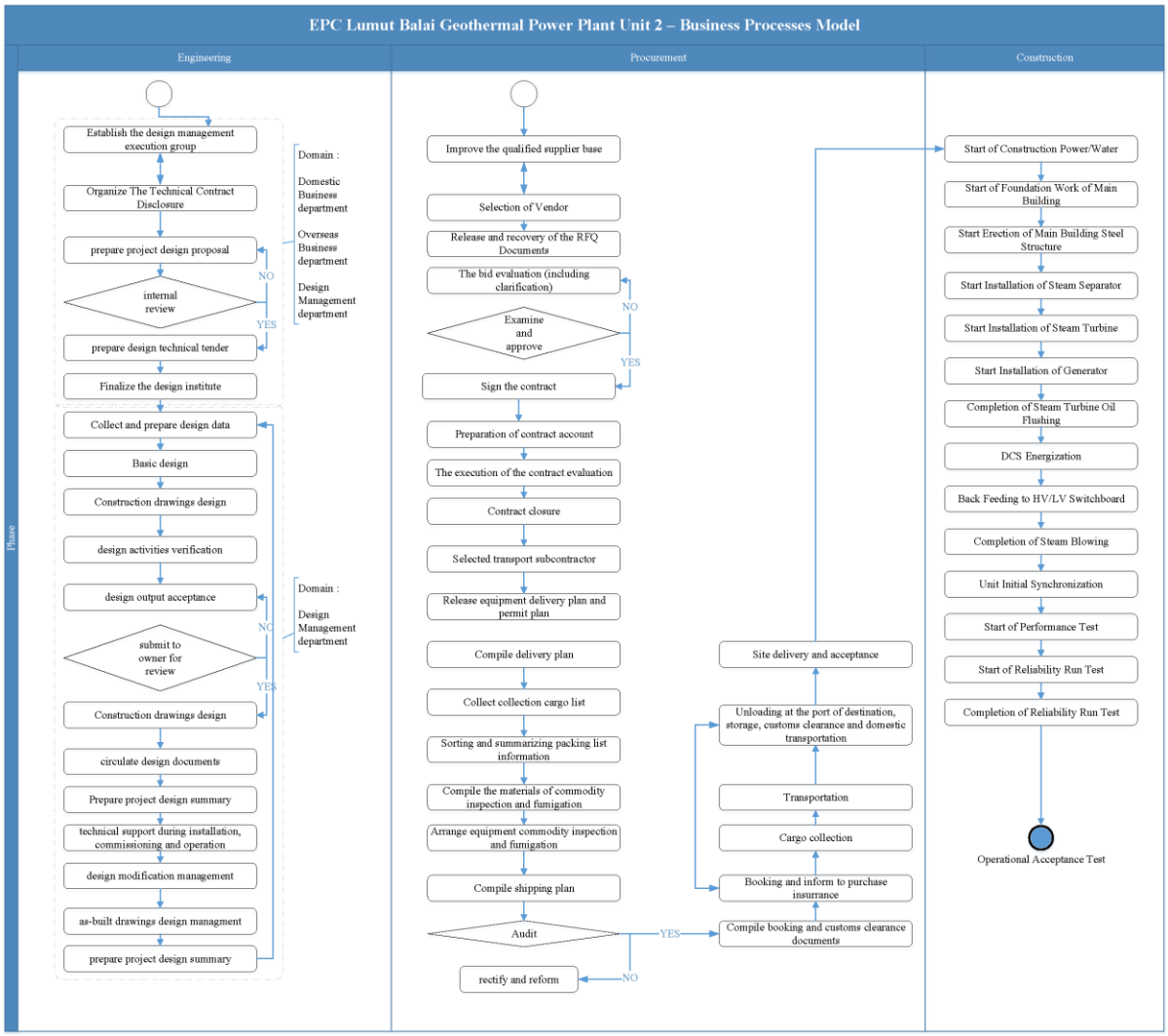


Figure 3: Business Process Model of Lumut Balai Project Unit 2 (Engineering, Procurement, Construction, and Commissioning) Project Development.

3. CHALLENGES AND STRATEGIES

Manpower, Manpower refers to the total number of people, employees, or workers available and engaged in a particular workforce or organization. It is a term commonly used to describe the human resources or labor force available to perform tasks, projects, or operations within a company or industry.

Challenges:

- Multi-task personnel to handle operational and project,
  One of the challenges faced by the organization is the need for personnel to handle multiple tasks simultaneously. In many cases, employees may be required to juggle between their regular operational duties and project-related responsibilities. This can lead to a strain on their productivity and focus, potentially affecting the quality of work on both fronts.
- Personnel availability (57) and schedule limitations (on-off)
  The availability of personnel can be a significant challenge for the organization. Some team members may have limited working hours due to part-time employment or other commitments. Additionally, there could be on-off or rotating shift schedules in certain roles, leading to potential gaps in coverage and coordination issues.
- Overwork and fatigue risk potential
  With multi-tasking and limited personnel availability, there is a higher risk of overworking

certain individuals. Overworking can lead to fatigue, decreased motivation, and burnout, impacting both the individual's well-being and overall team performance.

Strategies:

- Collaboration work-scheme with HQ personnel
  To address the challenge of multi-tasking, the organization can implement a collaboration work-scheme with personnel from the headquarters (HQ). This approach involves involving HQ staff in specific projects or tasks, allowing them to share the workload and expertise. Collaboration can lead to increased efficiency, as different team members bring diverse skills and perspectives to the table.
- Multi-personnel assignment in 1 task or position
  Instead of relying solely on one person to handle a specific task or position, the organization can adopt a multi-personnel assignment strategy. By assigning multiple individuals to the same task or role, they can divide the responsibilities and workloads more effectively. This not only reduces the burden on each individual but also provides a backup in case someone is unavailable due to leave or other reasons.
- Maintain the working schedule of personnel
  To tackle personnel availability and schedule limitations, the organization must carefully manage and maintain the working schedule of its employees. This may involve creating flexible work arrangements, such as staggered shifts or part-time options, to ensure adequate coverage throughout the day. By optimizing schedules, the organization can maximize productivity and minimize potential disruptions.

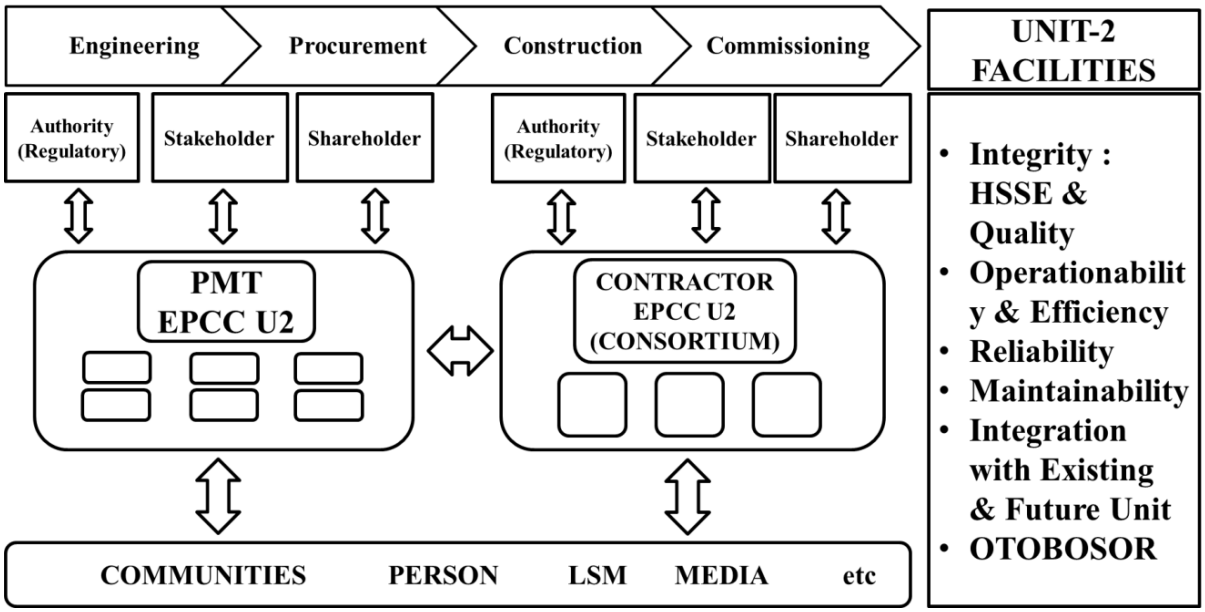


Figure 4: Managing & Handling Strategy of EPCC Complexity and Challenges of Lumut Balai Project Development Unit 2 and Existing Operational Sustainability.

Stakeholder Management, is the process of identifying, analyzing, and engaging with individuals, groups, or organizations (stakeholders) who have an interest in or are affected by a project, initiative, or organization. The goal of stakeholder management is to understand and address their needs, concerns, and expectations to ensure a positive relationship and achieve successful project outcomes.

Challenges:

- Multi stakeholder (PLN, EBTKE, LSM, Media, Communities, etc.) have different culture, habit, policy, and characters
  Stakeholders involved in a project come from diverse backgrounds, including government agencies (PLN, EBTKE), non-governmental organizations (LSM), media, local communities,

and more. Each stakeholder group has its own unique culture, habits, policies, and characteristics. Managing such a diverse group can be challenging as their expectations, priorities, and approaches to the project may differ significantly. Effective communication and understanding between stakeholders with distinct backgrounds become essential for successful collaboration.

- Conflict of Interest
  Stakeholders often have different interests and objectives related to the project. These varying interests can lead to conflicts of interest, where the goals of one stakeholder might be in opposition to those of another. Managing these conflicts requires careful negotiation, compromise, and finding win-win solutions to ensure the project's progress isn't hindered by internal disagreements.
- Social turmoil surround project location
  Some projects might face social turmoil or resistance from local communities or activist groups due to concerns about environmental impact, displacement of communities, or other socio-economic factors. Addressing and managing such turmoil requires sensitivity and open dialogue with affected communities to address their concerns and find sustainable solutions.

Strategies:

- Conduct an early approach/communication to the upper level stakeholder
  Engaging upper-level stakeholders (such as government agencies or higher management) early in the project planning phase is crucial. It helps in gaining their support and buy-in for the project. By involving key decision-makers from the beginning, the project is more likely to receive necessary approvals and resources, making it easier to navigate through potential challenges later on.
- Socialize the project program and all the risks to the communities
  Effective communication with all stakeholders, especially the local communities, is essential. Socializing the project program involves sharing information about the project's goals, benefits, and potential risks openly and transparently. This communication allows communities to understand how they might be affected, voice their concerns, and be involved in the decision-making process. By being transparent, the project can build trust and credibility with the communities, reducing the likelihood of resistance and enhancing cooperation.
- Ensure the policy compliance
  Adhering to relevant policies and regulations is crucial in stakeholder management. Stakeholders often have their own policies and guidelines that need to be followed. Ensuring compliance with these policies helps to build trust with stakeholders and demonstrates the project's commitment to meeting legal and ethical standards. Moreover, compliance with regulations can minimize the risk of legal disputes and negative reputational impacts.

Production Stability, refers to the consistent and uninterrupted output of steam and electricity of existing process. It involves maintaining a steady and reliable level of production with minimal disruptions or fluctuations to meet customer demands, achieve operational efficiency, and sustain profitability.

Challenges:

- The interconnection pipeline from Unit 1 to 2 will affect the existing productions
  The interconnection of pipelines between two units in a production facility can lead to disruptions in the existing production processes. During the interconnection process, there may be downtime or modifications required, which could temporarily impact the overall production output and efficiency. Ensuring a smooth transition during the interconnection phase is critical to minimizing production disruptions.
- The simultaneous operation Unit 1 and 2 will be potentially lack of steam supply.
  Operating two units simultaneously in a geothermal or steam-based production facility requires a stable and sufficient steam supply. If the steam supply is insufficient to meet the

demands of both units, it can result in a decline in production rates, reduced efficiency, or even complete shutdowns. Balancing the steam supply between the units is crucial to maintain production stability.

- Facilities reliability harmness
  The reliability of production facilities, including geothermal power plants or steam-driven processes, can impact production stability. If the facilities experience frequent breakdowns, equipment failures, or unplanned maintenance issues, it can lead to unplanned downtime and negatively affect production stability and output.

Strategies:

- Optimization steam consumption
  To address the challenge of potential steam supply shortages, optimizing steam consumption becomes essential. Conducting a thorough analysis of steam usage in different processes and identifying opportunities for efficiency improvements can help in reducing steam wastage and ensuring an adequate supply for simultaneous operation of both units.
- Ensure the plant reliability
  To tackle the harmness caused by facilities' reliability issues, it's crucial to focus on preventive maintenance, regular inspections, and monitoring of critical equipment. Implementing a robust maintenance program can help identify and address potential issues proactively, reducing the likelihood of unexpected breakdowns and downtime.
- Plan the make up well
  To address the impact of interconnecting pipelines between Unit 1 and 2, meticulous planning and coordination are necessary. A detailed plan should be developed to manage the interconnection process with minimal disruptions to the existing production processes. Temporary workarounds or alternative supply arrangements can be considered during the transition to maintain production stability.
- Close monitoring of geothermal operation
  Continuous monitoring of geothermal operations is crucial to ensure stable and reliable production. Monitoring parameters such as steam flow, pressure, and temperature can help in identifying any deviations or potential issues early on, enabling prompt corrective actions to maintain stable production.

Consortium Scheme, is a collaborative arrangement where multiple companies or entities join forces to work together on a specific project, venture, or business initiative. In a consortium, each member contributes its expertise, resources, and capabilities to achieve common objectives, share risks, and mutually benefit from the collaboration. Consortium schemes are often used in large-scale projects that require diverse expertise and significant investment.

Challenges:

- Multi-nations contractors in consortium result the longer decision making
  In a consortium with contractors from different countries or regions, decision-making processes can become more complex and time-consuming. Differing perspectives, cultural nuances, and time zone differences may lead to delays in making critical project decisions, potentially affecting project timelines and efficiency.
- Unpreparedness of consortium delay the execution
  When consortium members are not adequately prepared for their roles and responsibilities, it can lead to delays in project execution. Lack of clarity on roles, responsibilities, and expectations among the consortium partners can cause confusion and inefficiencies, hindering progress.
- Unexperienced contractors may harm the projects
  Incorporating inexperienced contractors in the consortium can pose risks to the project's success. Lack of expertise and familiarity with the project domain may result in subpar work quality, cost overruns, or safety concerns.

Strategies:

- Conduct routine meetings to equalize the perception
  To address decision-making challenges and ensure effective communication among consortium members, it is essential to conduct routine meetings. Regular meetings provide a platform for all parties to share their perspectives, align their understanding of project objectives, and collectively make informed decisions. These meetings also facilitate the resolution of any misunderstandings or conflicts that may arise.
- Be an arbiter to get win-win solution of the issues
  As the project owner or facilitator, it's crucial to act as an arbiter when conflicts or disagreements arise within the consortium. Strive to find win-win solutions that address the concerns of all parties involved. Facilitating open and transparent discussions and encouraging a collaborative approach can foster a sense of trust and cooperation among consortium members.
- Embrace to work in collaboration
  Encouraging a culture of collaboration among the consortium members is vital for the project's success. Foster an environment where knowledge sharing, collective problem-solving, and mutual support are valued. Emphasize the importance of the shared project goals and how each member's expertise contributes to achieving those objectives.

4. KEY TAKEAWAYS

Lesson Learned

- Ensure the Project Management Plan to tackle the risks and issues, having a well-defined and comprehensive Project Management Plan is crucial for addressing risks and issues that may arise during the project. The plan should include risk assessment, mitigation strategies, and contingency plans to proactively manage potential challenges.
- Ensure the contract clearness and contractors experience/expertise in handing the similar project, ensuring clear and well-defined contracts and thoroughly evaluating contractors' experience and expertise are essential steps. Selecting experienced contractors with a successful track record in handling similar projects increases the likelihood of project success.
- Reliability assurance is a must to guarantee the operational sustainability, reliability is key to ensuring the smooth and sustainable operation of the project. Regular maintenance, quality assurance, and adherence to industry standards are essential to achieve operational excellence and minimize disruptions.
- Intense Communication and collaboration will be needed for the consortium project scheme. A consortium project involves multiple stakeholders working together. Effective communication and collaboration are vital for aligning objectives, resolving conflicts, and fostering a cohesive working environment among all parties involved.

Best Practices

- Agile and adaptive project management cycle is totally worth for complex project, adopting an agile and adaptive project management approach is highly beneficial for managing complex projects. It allows for flexibility and responsiveness to changing circumstances, enabling teams to adjust and optimize project execution as needed.
- Multi-personnel assignment in 1 task/position is helpful for the simultaneous project and operational activities, assigning multiple personnel to a single task or position can help balance the workload between projects and operational activities. This ensures efficient and effective execution of both aspects without compromising on quality or timelines.
- Interconnection steam supply for multiple power plant can be a good choice to anticipate the reservoir decline, implementing an interconnection steam supply strategy between multiple power plants can be a strategic move to optimize resources and anticipate potential reservoir decline. It ensures continuous and stable power generation while utilizing resources efficiently.

Challenges

- Rooster type of Working schedule in Lumut Balai become the most challenge in terms of project and operational handling simultaneously, involves rotating shifts, presents a significant challenge in coordinating project and operational activities effectively. Managing work shifts, team availability, and seamless transitions become crucial for successful execution.
- Stakeholder response is unpredictable should be tackled and registered prior to the project execution, making proactive engagement and recording of their concerns and expectations essential. Addressing stakeholders' needs and concerns early on helps prevent potential conflicts and ensures a smoother project execution.
- Interconnection steam supply strategy is really challenging for operational excellence, implementing an interconnection steam supply strategy demands meticulous planning and management. Ensuring optimal steam supply distribution and pressure balancing is essential to achieve operational excellence across multiple power plants.
- Unexperienced of contractor will need more attention in monitoring the project, monitoring and supporting inexperienced contractors are crucial to ensure they meet project requirements and deliver quality results. Close monitoring helps identify potential challenges early, allowing for timely intervention and corrective actions.

5. CONCLUSION

- Addressing manpower challenges is crucial for maintaining a productive and efficient workforce. By implementing strategies such as collaborating with HQ personnel, adopting multi-personnel assignments, and optimizing working schedules, the organization can overcome these challenges and create a more resilient and successful workforce.
- Effective stakeholder management is essential for the success of any project. By understanding and addressing the challenges posed by diverse stakeholders, conflicts of interest, and social turmoil, and by implementing strategies such as early engagement, transparent communication, and policy compliance, the project can build strong relationships with its stakeholders and create a positive impact in the community.
- Production stability is critical for the smooth operation of any industrial facility, especially in geothermal or steam-based processes. By addressing challenges related to pipeline interconnection, steam supply, and facility reliability, and implementing strategies like steam optimization, preventive maintenance, well-planned interconnection, and close monitoring, the production facility can achieve consistent and reliable production output.
- Consortium schemes offer a way to pool resources and expertise for large-scale projects, but they also come with specific challenges. By addressing decision-making delays, unpreparedness, and potential risks associated with inexperienced contractors, and implementing strategies such as routine meetings, arbitration for win-win solutions, and fostering a collaborative mindset, the consortium can overcome these challenges and effectively work together to achieve project success.

REFERENCES

Alexander Osterwalder &Yves Pigneur. (2010). Business Model Generation: A Handbook for Visionaries, Game Changers, and Challengers, John Wiley and Sons

Anastasi, G., Corucci, F., & Marcelloni, F. (2011). An Intelligent System for Electrical Energy Management in Buildings. International Conference on Intelligent Systems Design and Applications, ISDA, Nov 2011, 702–707. https://doi.org/10.1109/ISDA.2011.6121738.

Auth, G., Jokisch, O., & Dürk, C. (2019). Revisiting automated project management in the digital age – a survey of AI approaches. Online Journal of Applied Knowledge Management, 7(1), 27–39. https://doi.org/10.36965/ojakm.2019.7(1)27-39.

Batselier, J., and Vanhoucke M., 2017, Improving project forecast accuracy by integrating earned value management with exponential smoothing and reference class forecasting, International Journal of Project Management, 35 (2017), 28-43.

Barber, C., Dacre, N. & Dong, H. 2021. Reframing project management process paralysis: an autoethnographic study of the UK Fire Service. Advanced Project Management, 21.

Bicheno, J., & Holweg, M. (2009). The Lean Toolbox: The Essential Guide to Lean Transformation. Picsie Books.

Bjorvatn, T. & Wald, A. 2018. Project Complexity And Team-Level Absorptive Capacity As Drivers Of Project Management Performance. International Journal of Project Management, 36, 876–888.

Brookes, N., Lattuf Flores, L., Dyer, R., Stewart, I., Wang, K., & Dacre, N. 2020. Project Data Analytics: The State Of The Art And Science [APM Research]. Association for Project Management (APM).

Cleland, D. I., & King, W. R. (1983). Systems analysis and project management (3rd ed.). New York: McGraw-Hill.

Crawford, L. H., Hobbs, J. B., & Turner, J. R. (2005). Project categorization systems: Aligning capability with strategy for better results. Newtown Square: Project Management Institute.

Daniel, P. A. & Daniel, C. 2018. Complexity, uncertainty and mental models: From a paradigm of regulation to a paradigm of emergence in project management. International Journal of Project Management, 36, 184–197.

Flyvbjerg, B. 2014. What you should know about megaprojects and why: An overview. Project Management Journal, 45, 6–19.

Foreman, S. (1996). Internal marketing. In J. R. Turner, K. V. Grude, & L. Thurloway (Eds.), The project manager as change agent (pp. 116–125). London: McGraw-Hill.

Galbraith, J. R. (1973). Designing complex organizations. Boston: Addison-Wesley Longman.

Gates, B., Myhrvold, N., Rinearson, P. & Domonkos, D. 1995. The Road Ahead, Viking.

Hennings, R.-D., & Munter, H. (1985). Artificial Intelligence 1. Expertensysteme. 3(3), 351.

Kockum, F. & Dacre, N. (2020). Towards an Adaptive Approach to Managing Complexity in Projects: A Literature Review. Proceedings of the 20th International Conference on Product-Focused Software Process Improvement, 295–311.

Kulkarni, S., & Shirasgaonkar, S. (2017). Predictive Analytics for Project Performance Improvement using Machine Learning. Procedia Computer Science, 108, 799–808.

Laguna, M., & Marklund, J. (2013). Business Process Modeling, Simulation and Design (2nd ed.). Pearson Education.

Larson, E. W., & Gray, C. F. (2014). Project Management: The Managerial Process (6th ed.). McGraw-Hill Education.

Liu, L., & Shtub, A. (2005). Project Risk Management in the Chinese Construction Industry: A system dynamics simulation model. International Journal of Project Management, 23(6), 477–484.

Lock, D. (2007). Project Management (9th ed.). Gower Publishing.

Maier, M. W., & Rechtin, E. (2009). The Art of Systems Architecting (3rd ed.). CRC Press.

Maylor, H. (2010). Project Management (4th ed.). Pearson Education.

Miller, R., & Lessard, D. (2000). Understanding and Managing Risks in Large Engineering Projects. International Journal of Project Management, 18(8), 437–448.

Mir, F. A., & Pinnington, A. H. (2014). Exploring the Value of Project Management: Linking Project Management Performance and Project Success. International Journal of Project Management, 32(2), 202–217.

Mir, F. A., & Pinnington, A. H. (2017). Project Management and Organizational Performance: A Theory Based Meta-Analysis. International Journal of Project Management, 35(8), 1695–1709.

O'Sullivan, D., & Dooley, L. (2009). Applying AI to Project Management. IEEE Intelligent Systems, 24(2), 49–53.

Oyedele, L. O., Owolabi, H. A., Alaka, H. A., Bilal, M., Ajayi, S. O., Akinade, O. O., & Bello, S. A. (2018). A Systematic Review and Critical Analysis of Sustainable Construction Research in Nigeria: Past, Present, and Future. Journal of Cleaner Production, 172, 3793–3812.

PMBOK Guide (Project Management Institute). (2021). A Guide to the Project Management Body of Knowledge (7th ed.). Project Management Institute.

Patanakul, P., & Shenhar, A. J. (2012). What Project Strategy Really Is: The Fundamental Building Block in Strategic Project Management. Project Management Journal, 43(1), 4–20.

Pinto, J. K. (2016). Project Management: Achieving Competitive Advantage (4th ed.). Pearson.

Project Management Institute (PMI). (2017). PMI's Pulse of the Profession: Success Rates Rise: Transforming the High Cost of Low Performance. Project Management Institute.

Rajkumar, S. (2013). Project Management Knowledge and Skills for Green Project Management. In I. Management Association (Ed.), Sustainable Green Technologies for Environmental Management (pp. 1-20). IGI Global.

Schwalbe, K. (2019). Information Technology Project Management (9th ed.). Cengage Learning.

Shenhar, A. J., Dvir, D., Levy, O., & Maltz, A. C. (2001). Project Success: A Multidimensional Strategic Concept. Long Range Planning, 34(6), 699–725.

Shtub, A., Bard, J. F., & Globerson, S. (2005). Project Management: Processes, Methodologies, and Economics (2nd ed.). Prentice Hall.

Söderlund, J. (2004). Building theories of project management: past research, questions for the future. International Journal of Project Management, 22(3), 183–191.

Taylor, J. E., & Levitt, R. E. (2004). Economics of Standards in Information Networks. Journal of Management Information Systems, 20(2), 41–70.

Turner, J. R. (1999). The Handbook of Project-Based Management: Improving the Processes for Achieving Strategic Objectives. McGraw-Hill.

Turner, J. R., & Müller, R. (2005). The Project Manager's Leadership Style as a Success Factor on Projects: A Literature Review. Project Management Journal, 36(2), 49–61.

Wang, X., Lu, Y., Zhang, H., & Liu, W. (2017). Green Project Management: A Structured Literature Review. International Journal of Project Management, 35(7), 1404–1421.

Ward, J. L., & Chapman, C. B. (2003). Transforming Project Risk Management into Project Uncertainty Management. International Journal of Project Management, 21(2), 97–105.

Whitten, N. E., & Bentley, L. D. (2007). Systems Analysis and Design Methods (7th ed.). McGraw-Hill Education.

Winch, G. M. (2010). Managing Construction Projects (2nd ed.). Wiley-Blackwell.

Zwikael, O., & Smyrk, J. (2012). A General Framework for Gauging the Performance of Initiatives to Improve Project Planning and Control. Project Management Journal, 43(3), 5–2

Assessing the Impact of Carbon Trading to Indonesia Geothermal Project Economic

Serina Andiani Pongtuluran, Triwening Larasati, Ferdino R. Fadhillah, Johanes Timoty Jeremi Terok, Daniel Adityatama, Astri Indra Mustika, and Muhammad Ghassan Jazmi Shalihin

PT Geoenergi Solusi Indonesia

serina.pongtuluran@geoenergis.com

Keywords: geothermal, carbon trading, Indonesia

ABSTRACT

Indonesia possesses abundant geothermal potential, ranking among the world's leading countries with total reserve of 23.36 Gigawatts; however, only 2.29 Gigawatts are currently exploited. Unfortunately, geothermal projects in Indonesia frequently encounter difficulties in reaching the production phase due to a complex interplay of economic, technical, and social factors. To address the economic challenges associated with the projects, maximizing the revenue potential of geothermal derivative products, such as carbon trading, alongside electricity sales has emerged as potential approach. This paper aims to assess the implications of carbon trading on geothermal power plant projects in Indonesia. The research draws upon literature review related to economic components of geothermal projects, carbon trading schemes, and case studies of carbon trading. Through scenario analysis, the study compares the economic returns of geothermal projects with and without carbon trading. Additionally, the paper identifies the challenges and opportunities that carbon trading presents for geothermal power plants in Indonesia. Preliminary results indicate that carbon trading has a positive impact on enhancing the returns of geothermal projects. Furthermore, the integration of carbon trading offers additional benefits, including generating supplementary state revenue, improving the environmental perception of geothermal power plants, and fostering sustainable development. By embracing carbon trading, Indonesia's geothermal sector can potentially overcome economic hurdles and create a more favorable investment environment, unlocking the full potential of its geothermal resources.

1. INTRODUCTION

1.1 Background information on carbon trading

Climate change is one of the concerns for every country that has destructive impacts on various sectors. One of the consequences of climate change is threatening the economic stability worldwide. This phenomenon is because the rise in the average temperature on Earth's surface leads to heat waves, adversely affecting the human capacity to work, resulting in reduced productivity. According to the Swiss Re Institute (2021), climate change can cause a global Gross Domestic Product (GDP) decline of 11-18%, equivalent to approximately US$ 23 trillion by the year 2050, if the global temperature increases by 3.2°C.

Based on the Climate Change Risk Profile report for Indonesia by the World Bank (2021), Indonesia ranks 97th out of 181 countries facing climate change impacts. This assessment is based on the ND-GAIN (Notre Dame Global Adaptation Initiative) index, which considers a country's vulnerability to climate change through political, geographical, and social factors. Most projections indicate that the rate of average temperature increase in Indonesia is potentially lower than the global average increase (1.5 - 2.0 °C), estimated to be around 0.8 to 1.4°C by the year 2050. Indonesia is highly vulnerable to rising sea levels, which can threaten the country's food security in the agricultural sector, water availability, disaster risk management, development level, health and nutrition, and their implications for poverty and inequality.

The risks of climate change have driven various conventions and agreements carried out by many countries, with the Kyoto Protocol and the Paris Agreement serving as references for taking steps to mitigate the impacts of climate change. Both agreements have encompassed commitments from all nations to reduce emissions and collaborate on climate change mitigation. The Kyoto Protocol set a target of reducing emissions by 5% from the 1990 levels, and the Clean Development Mechanism

(CDM) was used to achieve this goal. The Paris Agreement aims to reduce global greenhouse gas emissions to limit the average temperature increase to 2 degrees Celsius, aiming to reach net-zero emissions. The Paris Agreement established a new carbon trading platform called the Sustainable Development Mechanism (SDM).

Carbon trading is one of the potential approaches to address economic challenges in geothermal projects. It involves trading the right to emit carbon. When a country or project contributes to carbon reduction through clean energy sources like geothermal, they can earn carbon credits that can be sold to other countries or companies exceeding their allowable carbon emissions limits. By utilizing carbon trading, geothermal projects can boost their income by selling additional carbon credits in addition to the revenue generated from electricity sales. It can provide economic support to make geothermal projects more appealing to investors and governments. Carbon trading also positively impacts the environment and sustainable development, contributing to global carbon emission reduction and enhancing a positive perception of environmental sustainability from geothermal power plants. Implementing carbon trading in geothermal projects in Indonesia can yield dual benefits - increasing income and contributing to efforts in mitigating the impacts of climate change, aligning with global commitments to achieve carbon emission reduction targets.

1.2 Overview of Indonesia's geothermal potential and challenges

Indonesia possesses abundant geothermal potential, ranking among the world's leading countries with total reserve of 23.36 Gigawatts; however, only 2.29 Gigawatts are currently exploited. Unfortunately, geothermal projects in Indonesia frequently encounter difficulties in reaching the production phase due to a complex interplay of economic, technical, and social factors. Setiawan (2014) divides Indonesia's geothermal challenges into three parts, namely upstream side problems, downstream side problems, and supporting side problems.

1.2.1 Upstream side problems

Geothermal development faces challenges due to a lack of information on available reserves during auctions, causing uncertainty for investors and leading to uneconomical prices for geothermal power. The high initial investment of approximately US$25 million and the risk of exploration failure make the projects unbankable and challenging to secure financing. Additionally, about 41.6% of the geothermal potential overlaps with protected forests or conservation areas, hindering development due to regulations prohibiting mining activities in those locations.

1.2.2 Downstream side problems

The downstream side problems in geothermal development are the unattractive geothermal electricity price, with fixed tariffs set by the government, especially for remote areas, and the market structure characterized by a single buyer (monopsony market), which weakens the bargaining position of sellers.

1.2.3 Supporting side problems

The supporting side problems in geothermal development are the complex bureaucracy system in Indonesia, which hinders the ease of doing business and leads to lengthy licensing processes, particularly due to the authority delegation to local governments. Additionally, there has been a lack of national commitment and strong leadership to promote geothermal development in the past, both at the central and local government levels. Furthermore, consumers and society lack awareness about the importance of renewable (green) energy development, including geothermal.

One potential approach to address the challenges, particularly in the economic aspect, is to maximize the revenue potential of geothermal derivative products, such as carbon trading and electricity sales. Engaging in carbon trading alongside selling electricity allows geothermal projects to access an extra income stream. This approach leverages the reduction of greenhouse gas emissions associated with geothermal energy production, providing them with an additional source of revenue. Geothermal projects have a promising opportunity to enhance their financial returns by exploring carbon trading alongside electricity sales. Not only does this approach offer economic incentives for investing in

geothermal energy, but it also contributes to efforts in combating climate change by reducing carbon emissions.

1.3 Purpose and significance of the study

The purpose of this study is to evaluate the potential impacts of integrating carbon trading mechanisms into geothermal projects in Indonesia. Specifically, the study aims to assess the implications of carbon trading on geothermal power plant projects in Indonesia. The study will delve into the various aspects and consequences of incorporating carbon trading within the context of geothermal energy development in the country. It will investigate the potential benefits, challenges, and opportunities that arise from participating in carbon markets alongside traditional electricity sales in geothermal power plants. The findings of this study could potentially guide decision-makers, investors, and policymakers in understanding the feasibility and significance of adopting carbon trading as a part of geothermal energy development strategies in Indonesia.

1.4 Research design and approach, Data collection methods, Scenario analysis for economic comparison

The research is centered on the economic aspects of geothermal projects and how carbon trading influences the geothermal power plants in Indonesia. Data collection methods draw upon a literature review of the economic components of geothermal projects, carbon trading schemes, and case studies of carbon trading. Through scenario analysis, the study compares the economic returns of geothermal projects with and without carbon trading. Additionally, the paper identifies the challenges and opportunities carbon trading presents for geothermal power plants in Indonesia.

2. CARBON TRADING SIGNIFICANCE IN GEOTHERMAL ENERGY

2.1 Geothermal projects in Indonesia: Economic challenges and opportunities

The economic aspect poses a significant challenge for geothermal projects in Indonesia, encompassing several key issues such as high initial investment and uncertain revenue streams.

2.1.1 High initial investment

In the early stages of geothermal exploration, high initial investment refers to a substantial amount of funds needed to initiate exploration activities. This includes the costs of conducting various studies and surveys to assess the geothermal potential in the target area. The high level of uncertainty is related to the inherent uncertainty or risks associated with the geothermal exploration phase. Geothermal exploration involves studies in geology, geochemistry, and geophysics. The high risks in geothermal exploration stem from the lack of direct confirmation that the project will successfully discover economically viable geothermal sources for further development. All these studies require significant costs as they involve expensive equipment, expert teams, and in-depth analysis. Moreover, the high risks in geothermal exploration require companies and investors to carefully consider the risks and potential returns before deciding to proceed with further project development.

2.1.2 Uncertain revenue streams

Uncertain revenue streams refer to the uncertainty related to geothermal projects' income or cash flow. This uncertainty is caused by fluctuating electricity prices, regulatory changes, weather and climate variability, and unstable energy demand. As a result, geothermal projects need to assess risks and conduct careful financial analysis to ensure profitability and sustainability amidst economic uncertainty.

2.2 Carbon trading schemes and their implications

Carbon trading schemes refer to market-based mechanisms that allow countries, companies, or projects to trade carbon credits as a way to reduce greenhouse gas emissions. The primary goal of these schemes is to incentivize emission reduction efforts by assigning a monetary value to carbon dioxide (CO_2) and other greenhouse gas emissions. The key carbon trading schemes are Clean Development Mechanism (CDM) under the Kyoto Protocol and Sustainable Development Mechanism (SDM) under Paris Agreement.

CDM and SDM are two carbon trading mechanisms that play different roles in addressing greenhouse gas emissions. Based on the Kyoto Protocol, developing countries do not have emission reduction targets, and CDM serves as an offset mechanism to compensate for emissions. However, CDM provides less beneficial incentives to businesses as it tends to encourage emission growth in the same business-as-usual (BAU) patterns. Additionally, CDM's commitment to sustainable development remains unclear.

On the other hand, SDM has a more significant contribution to overall emission reduction mitigation. As part of the Paris Agreement, SDM considers mitigation targets, including future developments. SDM also plays a role in promoting ambition and driving climate policy implementation. Unlike CDM, SDM focuses more on contributing to sustainable development by encouraging a transition from fossil fuel use to more environmentally friendly energy sources.

2.3 Case studies of carbon trading in the energy sector

Carbon trading in the energy sector was already gaining momentum as a market-based approach to mitigate greenhouse gas emissions. Some case studies of carbon trading in the energy sector consist of:

2.3.1 European Union Emissions Trading System

In 2005, the European Union Emissions Trading System (ETS) was established as the world's first emissions trading system involving electricity generation, intensive industries like cement, and aviation sectors. The ETS underwent four developmental phases. Phase 1 (2005-2007) served as a pilot phase, covering electricity generation and energy-intensive industries, where a significant portion of emission allowances was given free to businesses with a penalty of €40 per ton for non-compliance. Despite an increase in carbon trading volume, incomplete emission data resulted in a surplus of allowances, causing the price to drop to zero in 2007. Phase 2 (2008-2012) coincided with the commitment period of EU countries under the Kyoto Protocol, leading to reduced allowance caps and higher penalties for non-compliance. During Phase 3 (2013-2020), the ETS underwent reforms, introducing auctioning as the method for allocating allowances and expanding its coverage to more sectors. In Phase 4 (2021-2030), the ETS faced a proposed revision to the EU Climate Law, targeting a 43% emissions reduction compared to 2005, with an annual allowance reduction of 2.2% starting in 2021.

2.3.2 China Emissions Trading System

The China Emissions Trading System (ETS) was established in 2013 as a regional pilot to incentivize investors and market participants to support China's decarbonization and energy transition efforts. The ETS covers a significant portion of emissions from the energy sector. In July 2021, the national ETS was launched, involving 2,225 power generation companies required to submit quotas to offset emissions from 2019 and 2020. The national carbon market serves as a tool to drive China's commitment to achieve a carbon peak before 2030 and carbon neutrality before 2060. This ETS is expected to become the world's largest carbon market, covering approximately 4.5 billion tons of CO2 annually, or around 40% of China's total emissions.

2.3.3 South Korea’s Emission Trading Scheme (KETS)

The Korean government signed and ratified the UNFCCC and Kyoto Protocol to address climate change and incorporated the goal of reducing national greenhouse gas emissions by 30% from the BAU projection in 2020 into the Framework Act on Low Carbon, Green Growth. The Act established the Target Management System (TMS) to regulate emissions and energy efficiency in various sectors, including energy. The TMS operates command and control, setting reduction targets for controlled entities. In parallel, the Act on the Allocation and Trading of Greenhouse Gas Emission Allowances (ETS Act) was implemented, establishing the Emission Trading Scheme (ETS) starting in 2015. The ETS targets compliance entities based on their emission levels. Both TMS and ETS will work together from 2015 onwards. However, some issues remain unresolved, including allowance allocation, market stabilization measures, the role of the power sector, and offset programs. The government aims to cover seven sectors in the ETS, targeting a reduction of 233MtCO_{2e} by 2020 (Park and Hong, 2014).

3. IMPLICATIONS OF CARBON TRADING ON GEOTHERMAL POWER PLANT PROJECTS IN INDONESIA

3.1 Economic assessment of geothermal projects with and without carbon trading

Geothermal projects can experience a positive impact on producing renewable energy with low greenhouse gas emissions when engaging in carbon trading. By selling carbon credits, geothermal developers can generate additional revenue, enhancing the financial viability of their projects. Moreover, carbon trading drives higher demand for renewable energy, particularly geothermal, as companies strive to meet emission reduction targets. This increased demand may result in more favorable power purchase agreements (PPAs) or feed-in tariffs for geothermal electricity, creating a stable and appealing revenue stream for project developers. Carbon trading's impact can also be harnessed for public relations and branding efforts, attracting potential investors and customers who prioritize sustainability and eco-friendly initiatives.

Meanwhile, without carbon trading geothermal projects may face financial challenges. The lack of additional revenue from carbon credits can make the project economics less attractive, especially when compared to fossil fuel-based power generation sources that do not incur carbon costs. Geothermal projects without carbon pricing incentives may heavily rely on government support like subsidies or tax incentives to compete with conventional energy sources, which can vary in availability and stability across regions, affecting project feasibility. The absence of carbon pricing could also reduce pressure on conventional energy producers to cut emissions, making it challenging for geothermal projects to compete on equal footing. In contrast, carbon trading can offer crucial financial support and market demand, making geothermal projects economically more viable and encouraging renewable energy investment to combat climate change.

3.2 Analysis of the challenges and opportunities presented by carbon trading

The challenges for implementing carbon trading may result in a potential decline in Indonesia's exports, estimated to reach USD 141 million annually. One of the primary challenges in carbon trading lies in determining the price of carbon, highlighting the importance of establishing robust regulations and mechanisms and implementing effective carbon pricing. These measures are essential to achieving the Nationally Determined Contributions (NDC) target and ensuring that the income generated from carbon trading is directed towards sustainable emission reduction programs, fostering Indonesia's commitment to combat climate change.

Implementing an effective carbon pricing mechanism is crucial for reducing greenhouse gas emissions and achieving the NDC target. Price regulation and a well-designed carbon trading mechanism can incentivize stakeholders to actively participate in emission reduction efforts and ensure that revenues from carbon trading are invested in sustainable programs. Before designing the carbon trading mechanism, it is essential to determine the specific GHG reduction target. This involves calculating the emissions to be reduced and identifying the sectors that contribute the most to these emissions. Understanding the abatement cost allows for calculating an ideal floor price, enabling effective carbon pricing and successful emission reduction strategies.

3.3 Additional benefits of integrating carbon trading in geothermal projects

Indonesia has implemented emission reduction solutions based on market mechanisms such as the Clean Development Mechanism (CDM) of the Kyoto Protocol, the Joint Crediting Mechanism (JCM), and the Verified Carbon Standard (VCS). The CDM has been successfully applied to approximately 215 projects in Indonesia, with 37 of them receiving Certified Emission Reduction (CER) credits. As a result of these efforts, the CDM has successfully reduced greenhouse gas emissions by approximately 10.1 thousand tons of CO_2. In comparison, the JCM has contributed to a reduction of about 329.5 thousand tons of CO_2 emissions.

Carbon trading through the commodity exchange has several benefits, namely transparency, buyers and sellers can see prices transparently and there is also direct access so there is no confusion in finding sellers or buyers of carbon credits. In addition, trading through the stock exchange can also provide the

best price, because carbon trading through the carbon exchange will use an auction system, where buyers and sellers can bid and ask according to the wishes of each party

4. CONCLUSION

Carbon trading has a positive impact on enhancing the returns of geothermal projects. The integration of carbon trading offers additional benefits, including generating supplementary state revenue, improving the environmental perception of geothermal power plants, and fostering sustainable development. By embracing carbon trading, Indonesia's geothermal sector can potentially overcome economic hurdles and create a more favorable investment environment, unlocking the full potential of its geothermal resources. However, challenges lie in determining the price of carbon and establishing effective regulations and mechanisms to achieve the Nationally Determined Contributions (NDC) target and direct income from carbon trading towards sustainable emission reduction programs.

REFERENCES

GUO, Jessie; KUBLI, Daniel; SANER, Patrick. The economics of climate change: no action not an option. Swiss Re Institute, 2021.Setiawan, Hadi. Geothermal energy development in Indonesia: Progress, challenges and prospect. Gas, (2014), 1: 280.

ICDX Group. Challenges and Opportunities for Carbon Trading in Indonesia https://www.icdx.co.id/news-detail/press-release/challenges-and-opportunities-for-carbon-trading-in-indonesia, (2021).

PARK, Hojeong; HONG, Won Kyung. Korea′ s emission trading scheme and policy design issues to achieve market-efficiency and abatement targets. Energy Policy, 2014, 75: 73-83.

World Bank. Carbon Pricing for Climate Action. Accesss from https://openknowledge.worldbank.org/handle/10986/36080, (2021).

Biodiversity Awareness at Geothermal Power Plant: Preliminary Study on Fauna around Geothermal Area

Ryski D. Busta, Erwin P. Floris, and Muhammad A. Tarunaprawira

Supreme Energy

ryski-busta@supreme-energy.com, erwin-patrisa@supreme-energy.com, arief-tarunaprawira@supreme-energy.com

Keywords: Geothermal, Biodiversity, Fauna

ABSTRACT

Indonesia has a huge potential for geothermal energy in the world with about 40% of potential geothermal energy. However, most geothermal power plants are located in remote areas and close to or within conservation areas. The consequences, geothermal activities have negative impact on biodiversity, including fauna diversity. Therefore, we need mitigation and sustainability effort to maintain the diversity of fauna around geothermal area. Fauna inventory is one of the initial stages to study and fauna conservation. The objective of this study specifically to inventory fauna diversity especially mammals around PT. SEML geothermal project area. The study conducted on May 2020 until March 2022 using five camera traps operated along forest paths where those predicted as regular tracks of the animals. We successfully identified sixteen species that consist of fourteen species of mammals and two species of avifauna. Four of those mammal species are categorized as threatened species according to the IUCN, namely Long-tailed Macaque (EN), Southern Pig-tailed Macaque (EN), Sambar Deer (VU), and Mainland Serow (VU). One mammal species, the Sumatran Striped Rabbit (DD) is categorized to critical habitat trigger. The results of this study can be used to develop programs for biodiversity conservation for the exact purpose of flora and fauna around geothermal areas can coexist with geothermal development activities.

1. INTRODUCTION

Indonesia is located in the ring of fire in volcano line that makes Indonesia has huge of geothermal potential (Pambudi, 2018). World Bank reports claims that Indonesia possesses 40% of the world's geothermal resources (Meier, Randle, Lawless, 2015). Furthermore, Ministry of Energy and Mineral Resources of the Republic of Indonesia has published data on geothermal sites in Indonesia. There are 252 geothermal potential site that located in Indonesia. Almost 80% (201) of geothermal sites in Indonesia located in isolated active volcanic systems such in Sumatra, Java, Bali and Nusa Tenggara, Maluku, and North Sulawesi. The rest, about 20% (51) geothermal sites located in regions with active non-volcanic environment such as Sulawesi, Bangka Belitung, Kalimantan, and Papua (Dipayana and Ramadhan, 2022).

Geothermal energy counts among renewable energies sources, environmental friendly and have great potential for the future (John, 2018). However, most of the geothermal power plants are located close to or within conservation areas. The consequence, presence of geothermal power stations associated with negative impacts on habitats and species (Ng, White, Katariya and, Pollard, 2021). Rehbein, Watson, Lane, Sonter, Venter, Atkinson, and Allan (2020) reported spatial distribution of geothermal development is moving from developed regions towards more biodiverse developing regions such as Southeast Asia and sub-Saharan Africa, where the consequences for global biodiversity conservation will be more intense. John (2018) reported geothermal activities have negative impact on avifauna species richness in Hell's Gate National Park, Kenya due to development of geothermal. Therefore, we need mitigation and sustainability effort to maintain the diversity of fauna around geothermal area.

PT Supreme Energy Muara Laboh (SEML) is a company engaged in geothermal development. PT SEML operating a Geothermal Power plant project located in Liki Pinangawan, Muaralaboh with altitude between 450-1,500 meters above sea level. SEML located adjacent to a UNESCO World Heritage Site, the Kerinci Seblat National Park (KSNP). Therefore, as a company which concern to

environmental protection especially biodiversity conservation, PT. SEML carried out efforts to monitor biodiversity by installing camera traps around the SEML work area. The objective of the study is to specifically to inventory fauna diversity especially mammals around PT. SEML geothermal project area.

2. MATERIAL AND METHOD

2.1 Data Collection

We deployed 5 camera traps around SEML project site during in 2015 and 2020 to 2022 in various location as described in Figure 1. Two types of camera traps were used: Bushnell Trophy Cam infrared and Trail Camera HC-801A. Cameras were set to operate 24 h/day with 3 images per trigger. We used 1 min delay interval to distinguish individuals. Camera traps deployed on the ridge or forest floor where there is a suspected or path using by animals. The coordinates of the camera installation location are taken by GPS and can be seen in Table 1. Each camera was placed on relatively flat terrain 50 cm off the ground on a tree (Cheyne et al., 2012) and positioned facing toward trails at 2.5 m distance. All vegetation and debris were cleared from the field of view for better opportunity to be captured.

Table 1: Camera Trap coordinate and days effort.

No	Camera Traps Code	Coordinate (UTM)		Elevation	Start Date	End Date	Duration (Days)
		Easting	Northing				
1	CT 011	736885	9818908	1632	8 May 2020	11 April 2021	339
2	CT 013	736952	9818982	1609	7 January 2015	5 November 2020	178
3	CT 015	736796	9818988	1674	8 June 2020	3 October 2020	118
4	CT 023	735742	9821730	1266	23 March 2021	1 January 2022	285
5	CT 024	735698	9822181	1143	1 December 2020	21 September 2022	660
Total Days Efforts							1580

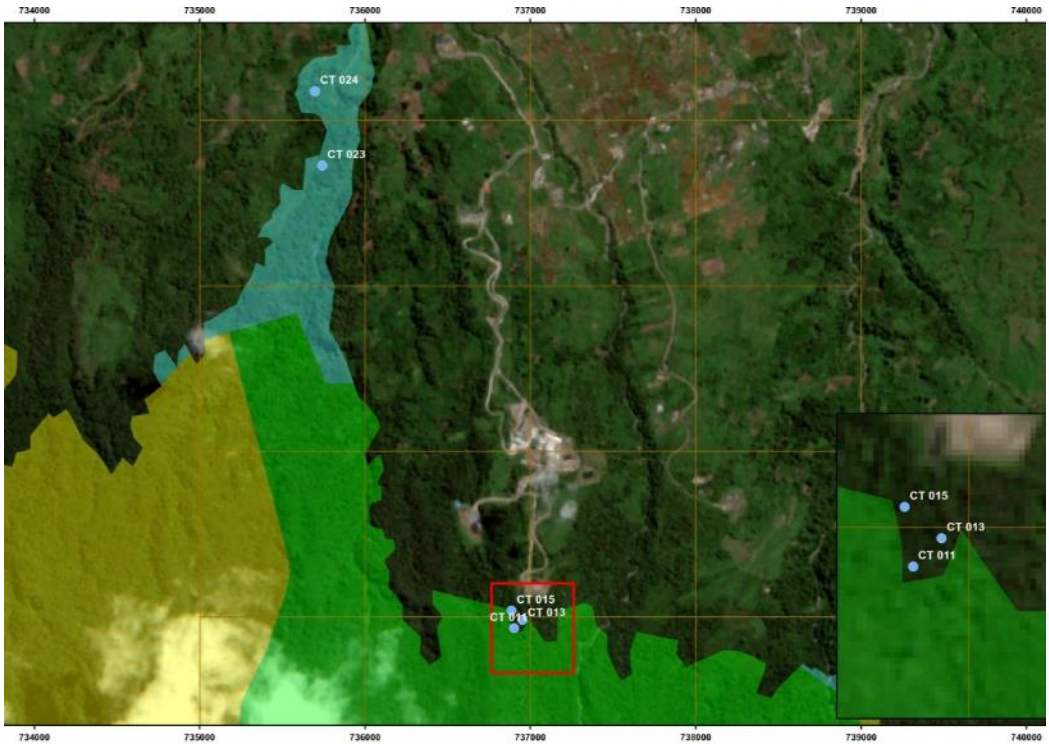


Figure 1: Camera Traps Installation Location.

2.2 Data Analysis

Captured photo of a photographed animal identified using Francis (2008) A Field Guide to the Mammals of Thailand and South-East Asia and Payne and Francis (1985) A Field Guide to the Mammals of Borneo for identification mammals. For avifauna, we used Mackinnon, Phillipps and van Balen (2010) A Field Guide to the Birds of Borneo, Sumatra, Java, and Bali.

2.2.1 Relative Abundance Index

The study used camera trap results to identify species relative abundance (Jenks et al., 2011). We are convinced by hypothesis that rate of independent photo detection indicates animal abundance. Moreover, relative abundance index (RAI) is determined as number of events divided by sampling effort and multiplied by 100 as shown in formula below (Rovero et al., 2014).

$$RAI = \frac{ni \times 100}{\sum ED}$$

Note: RAI = Relative Abundance Index; ni = number of independent photograph of species – i; ∑ED = Total Active Day

2.2.2 Species Occupancy

One of the Key Performance Indicators (KPI) in monitoring using camera traps is occupancy indicator. Species occupancy is analyzed through PRESENCE software released by USGS. PRESENCE software identified camera trap data as discrete numbers of 1 and 0. If the camera traps data records species, then it will have number 1 and if no species is recorded, it will have number 0. Species occupancy and species detection probabilities were analyzed using a single-season model approach (Mackenzie, *et al*., 2006). However, priory, raw data requires preparation like cleaning and increasing its capabilities by grouping data from 5 consecutive days of effort into one event. If the camera trap results do not meet the 5-day event, it will be ignored (Gibbs et al., 2022).

3. RESULT AND DISCUSSION

Five camera traps that deployed during 2015 and 2020 to 2022 with total 1580 camera trap effort. It generated 1855 photos as result. 205 photos amongst were independent photos. We identified 16 species that consist of 14 species of mammals and 2 species of avifauna. Four of those mammal species are categorized as threatened species according to the IUCN, namely Long-tailed Macaque (EN), Southern Pig-tailed Macaque (EN), Sambar Deer (VU), and Mainland Serow (VU). One mammal species, the Sumatran Striped Rabbit (DD) is categorized to critical habitat trigger. The result showed in table 2.

14 species of mammals consist of 6 orders. Most of mammals captured by camera trap belongs to Carnivora order (4 species) and Cetartiodactyla (4 species). Two species avifauna that recorded in camera trap are belong to Galliformes order. Galliformes order is one of order in Aves class that most member of the order is ground dwelling and only can fly for short distance (Tran, Anu Piazza, Granatosky, 2020), that's why we record *Arborophila rubrirostris* and *Polyplectron chalcurum* in this study.

The most captured species in this study is Southern Red Muntjak (*M. muntjak*) with number of independent photo is 37 photos and Bronze-tailed Peacock-pheasant (*P. chalcurum*) with number of independent photo is 26. Vinitpornsawan and Fuller (2023) also reported that Southern Red Muntjak in one of common species that captured in Thung Yai Naresuan Wildlife Sanctuary, Thailand. The high independence photo of Sambar Deer and Bronze-tailed Peacock-pheasant indicated the habitat of the study is still good habitat because Southern Red Muntjak commonly found at dipterocarp forest (Francis, 2008) and Bronze-tailed Peacock-pheasant dweller of primary forest at sub-montane forest.

Table 2: List of species found in camera traps.

No	Class	Order	Species	Common Name	English Name	Protection Status		
						IUCN	GOI	CITES
1	Mamalia	Carnivora	*Catopuma temminckii*	Kucing Emas	Asiatic Golden Cat	NT	P	I
2		Carnivora	*Martes flavigula*	Musang leher kuning	Yellow Throated Marten	LC		III
3		Carnivora	*Prionodon linsang*	Linsang	Banded linsang	LC	P	II
4		Carnivora	*Paguma larvata*	Musang bulan	Masked palm civet	LC		III
5		Cetartiodactyla	*Cervus unicolor*	Rusa sambar	Sambar Deer	VU	P	
6		Cetartiodactyla	*Capricornis sumatraensis*	Kambing gunung sumatra	Mainland Serow	VU	P	I
7		Cetartiodactyla	*Muntiacus muntjak*	Kijang muncak	Southern Red Muntjac	LC	P	
8		Cetartiodactyla	*Sus scrofa*	Babi hutan	Wild Boar	LC		
9		Lagomorpha	*Nesolagus netscheri**	Kelinci Sumatra	Sumatran Striped Rabbit	DD	P	
10		Primates	*Macaca fascicularis*	Monyet ekor panjang	Long-tailed macaque	EN		II
11		Primates	*Macaca nemestrina*	Beruk	Southern Pig tailed Macaque	EN		II
12		Rodentia	*Hystrix brachyura*	Landak	Malayan Porcupine	LC		
13		Scandentia	*Tupaia sp.*	Tupai	Treesrew	LC		
14		Scandentia	*Tupaia javanica*	Tupai kekes	Horsfield's Treeshrew	LC		
15	Aves	Galliformes	*Arborophila rubrirostris*	Puyuh Gonggong Sumatera	Red-billed partridge	LC		
16		Galliformes	*Polyplectron chalcurum*	Kuau kerdil	Bronze-tailed Peacock pheasant	LC	P	

* = Critical Habitat Trigger; P = Protected; LC=Least Concern, NT=Near Threatened, VU =Vulnerable, EN=Endangered

Figure 2. Camera Trap Result: A. Malayan porcupine; B. Sumatran Rabbit; C. Sambar Deer; D. Bronze-back Peacock-Pheasant; E. Asian Golden Cat; F. Southern Red Munjtak; G. Pig-tailed Macaque; H. Pig-tailed Macaque; I. Yellow-Throated Marten; J. Tree shrew; K. Empty camera trap result; L. Human captured in camera trap.

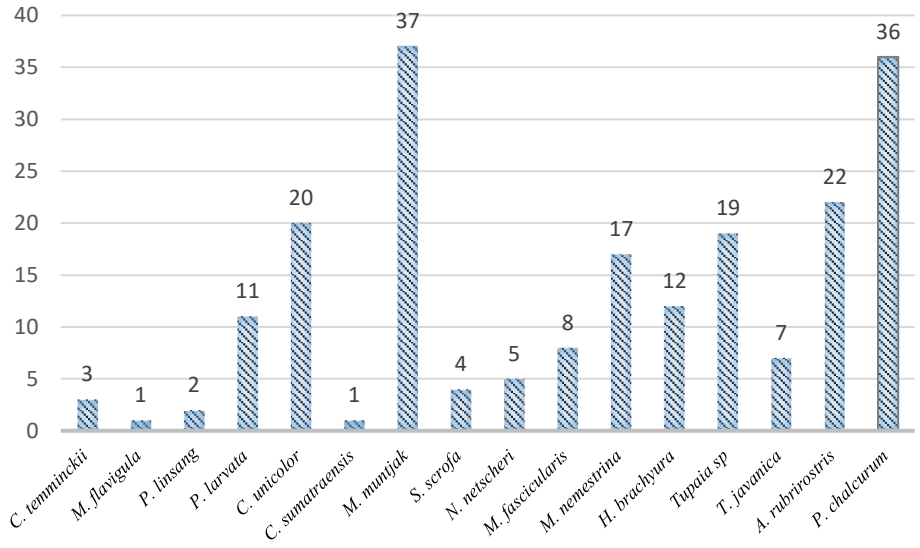


Figure 3: Number of independent photo for species.

Table 3: Relative Abundance Index (RAI) of Camera Trap record and Naive Occupancy Proportion.

No	Species	RAI	Naïve Occupancy	
			Number of locations Occupied	Fraction of locations Occupied
1	*Catopuma temminckii*	0.19	1	20%
2	*Martes flavigula*	0.06	1	20%
3	*Prionodon linsang*	0.13	1	20%
4	*Paguma larvata*	0.70	3	60%
5	*Cervus unicolor*	1.27	3	60%
6	*Capricornis sumatraensis*	0.06	1	20%
7	*Muntiacus muntjak*	2.34	5	100%
8	*Sus scrofa*	0.25	2	40%
9	*Nesolagus netscheri**	0.32	1	20%
10	*Macaca fascicularis*	0.51	4	80%
11	*Macaca nemestrina*	1.08	5	100%
12	*Hystrix brachyura*	0.76	2	40%
13	*Tupaia sp.*	1.20	2	40%
14	*Tupaia javanica*	0.44	2	40%
15	*Arborophila rubrirostris*	1.39	4	80%
16	*Polyplectron chalcurum*	2.28	3	60%

Table 3 shows the relative abundance index (RAI) of species captured through camera trap monitoring. RAI describes the number of independent photos in 100 working days of camera traps. Southern Red Muntjac, Bronze-tailed Peacock-pheasant, Red-billed partridge and Sambar Deer were the species with the highest abundance during monitoring activities.

Southern pig-tailed macaque (*M. nemestrina*) and Southern red muntjak (*M. muntjak*) are species with high occupancy. It captured in all camera trap which deployed in area of study. Furthermore, Sumatran Serow (*C. sumatraensis*), Sumatran Striped rabbit (*N. netscheri*), Golden cat (*C. temminckii*), Banded linsang (*P. linsang*), and Yellow Throated Marten (*M. flavigula*) only captured in one camera. Sumatran Striped rabbit (*N. netscheri*), Golden cat (*C. temminckii*) and Yellow Throated Marten (*M. flavigula*)

captured at CT 11; Banded linsang (*P. linsang*) captured at CT 23; and Sumatran Serow (*C. sumatraensis*) captured at CT 13.

Table 4: Occupancy Rate Probability of Critical Habitat Trigger and Key Species.

Species	Occupancy				
	Naïve Estimate	Modelled Estimate	SE	Lower 95% CI	Upper 95% CI
Nesolagus netscheri	33%	36%	29%	4%	87%
Macaca fasicularis	67%	82%	39%	3%	100%
Macaca nemestrina	67%	72%	30%	12%	98%

Note: SE = Standard Error; CI = Confidence Interval.

Calculation of occupancy rate and probability of detection of key species and critical habitat trigger species showed at table 4. The probability of detection can be influenced by the characteristics of the survey or the characteristics of the site. In this study the probability of occupancy only influenced by the characteristics of the site.

The Sumatran Rabit (*N. netscheri*) is one of the critical habitat trigger species, the model calculation results show a 36% occupancy probability with an occupancy range of 4-98% at a 95% confidence level. Although The Sumatran Rabit (*N. netscheri*) only captured by one camera, based on PRESENCE analysis, The Sumatran Rabit (*N. netscheri*) might occupancy two location in this study. Long-tailed Macaque (*M. fasicularis*) and the Pigtailed Macaque (*M. nemestrina*) were two species that listed as endangered. These two species have the highest occupancy rates than other key species. It probably widespread in this study. Long-tailed Macaque (*M. fasicularis*) and the Pigtailed Macaque (*M. nemestrina*) might occupy all monitoring location in this study.

4. CONCLUSION

The total number of fauna species documented in this study are sixteen species that consist of fourteen species of mammals and two species of avifauna. Four of those mammal species are categorized as threatened species according to the IUCN, namely Long-tailed Macaque (EN), Southern Pig-tailed Macaque (EN), Sambar Deer (VU), and Mainland Serow (VU). One mammal species, the Sumatran Striped Rabbit (DD) is categorized to critical habitat trigger. The most abundance species are Southern Red Muntjak and Bronze-tailed Peacock-pheasant while Long-tailed Macaque and the Pigtailed Macaque are most widespread species in this study area. The results of this study can be used to develop programs for biodiversity conservation for the exact purpose of flora and fauna around geothermal areas can coexist with geothermal development activities.

REFERENCES

Cheyne, S.M., Ripoll C. B, Adul, Macdonald, E. And Sastramidjaja, W.J.: Standard Operating Procedure (SOP) For Placing Camera Traps, *Project Report*, Orangutan Tropical Peatland, Palangkaraya, (2012).

Dipayana, G. F. and Ramadhan, R. A.: Geothermal energy in Indonesia. In H. Ardiansyah, & P. Ekadewi (Eds.), *Indonesia post-pandemic outlook: Strategy towards net-zero emissions by 2060 from the renewables and carbon-neutral energy perspectives*, 159–180. BRIN Publishing, Cibinong, (2022)

Francis, C. M.: *A Field Guide to the Mammals of Thailand and South-East Asia,* Asia Book co. ltd., Bangkok, (2008).

Gibbs, J. P., Hunter, M. L., Sterling, E. J.: *Problem-Solving in Conservation Biology and Wildlife Management: Exercises for Class, Field, and Laboratory (2nd Edition)*, Wiley-Blackwell, New Jersey, (2008).

Jenks, K. E., Chanteap, P., Damrongchainarong, K., Cutter, P., Redford, T., Lynam, A. J., Howard, J., Leimgruber, P.: Using relative abundance indices from camera-trapping to test wildlife

conservation hypotheses – an example from Khao Yai National Park, Thailand. *Tropical Conservation Science*, **4 (2)**, (2011), 113-131.

John, G. A.: *Impacts of Geothermal Power Station on Avifauna at Hell's Gate National Park, Nakuru County, Kenya (Thesis)*, Kenyatta University, Mombasa, (2018).

Mackenzie, D. I., Nichols, J. D., Royle, J. A., Pollock, K. H., Bailey, L. L., Hines, J. E.: *Occupancy estimation and Modelling: inferring patterns and dynamics of species occurrence*, Academic, London, (2006).

Mackinnon, J., Phillipps, K., and van Balen, B.: *A Field Guide to the Birds of Borneo, Sumatra, Java, and Bali*, Lembaga Ilmu Pengetahuan Indonesia, Cibinong, (2010).

Meier, P., Randle, J. B., Lawless, J. V.: *Unlocking Indonesia's Geothermal Potential*, Asian Development Bank and The World Bank (2015).

Ng, C., White, T., Katariya, V., Pollard, E.: Geothermal power generation and biodiversity: the business case for managing risk and creating opportunity, *Proceedings World Geothermal Congress*, (2020).

Pambudi, N. A.: Geothermal power generation in Indonesia, a country within the ring of fire: Current status, future development and policy, *Renewable and Sustainable Energy Reviews*, **81**, (2018), 2893-2901.

Payne, J. and Francis, C. M.: *A Field Guide to the Mammals of Borneo for identification mammals*, The Sabah Society, Kinabalu, (1985).

Rehbein, J.A., Watson, J.E., Lane, J.L., Sonter, L.J., Venter, O., Atkinson, S.C., Allan, J.R.: Renewable energy development threatens many globally important biodiversity areas, Global Change Biology, 26, (2020), 3040-51.

Rovero, F., Martin, E., Rosa, M., Ahumada, J. A., Spitale, D.: Estimating Species Richness and Modelling Habitat Preferences of Tropical Forest Mammals from Camera Trap Data, *PLoS ONE*, **9 (7)**, (2014).

Tran, L., Anu A., Piazza Z., and, Granatosky M.: Galliformes Locomotion, *Encyclopedia of Animal Cognition and Behavior*, (2020), 2853-2861.

Vinitpornsawan, S., Fuller T. K.: A Camera-Trap Survey of Mammals in Thung Yai Naresuan (East) Wildlife Sanctuary in Western Thailand. *Animals*, **13**, (2023).

Building Reputation to Obtain Social License to Operate in Patuha's Geothermal Area

Ilen Kardani, Rita Purwita I, Genny M Yudawinata, and Maria Rahmawati

PT GEO DIPA ENERGI

ilen.kardani@geodipa.co.id, rita_p@geodipa.co.id,
genny@geodipa.co.id, maria@geodipa.co.id

Keywords: Social License to Operate, Patuha's Geothermal Area, Community and Social Engagement, Stakeholders

ABSTRACT

This article will discuss the theory and best practices for managing social issues in rural areas to develop and sustain geothermal project. It will cover topics such as identifying key stakeholders, build a specific social map, developing effective communication strategies, creating effective partnerships with local organizations, and leveraging technology to improve social engagement. By understanding the challenges faced by rural communities and implementing best practices, we can make a real difference in improving their quality of life while maintaining the business continuity.

Having a strong social reputation is essential for any businesses especially in the geothermal industry, whereby mostly located in rural areas. Some content of this article will discuss how a geothermal business can build its social reputation to gain the trust of local communities and be successful in developing business. It will highlight the importance of building relationships with local communities in Patuha area, understanding their needs, and taking steps to ensure that their interests are taken into account. It will also discuss how companies can use different strategies such as corporate social responsibility initiatives, transparent communication, and engaging with stakeholders to build a strong social reputation as a license to operate in Patuha's geothermal area. By obtaining a social license, companies can start or maintain operations in geothermal areas without facing any resistance from local communities.

There are many cases where social license has been a factor in ceasing the process of initiating or commencing a project. For example, when a company wants to build a new geothermal power plant, they must ensure that they have obtained the necessary permits and approvals from local authorities before they can begin construction. Similarly, when planning to build a new geothermal projects, companies must consider any potential impacts on nearby wildlife and take steps to mitigate them before they can begin work. These are just some examples of cases where social license has been an important factor in halting the initiation or commencement of geothermal projects.

The practical aspects implemented in Patuha include initiatives such as creating job opportunities for the locals, providing access to quality education, nurture local business partners, and developing infrastructure projects. Local businesses can have a major impact on the local society and its economy. By providing jobs, goods, services, and other resources to the community, businesses can help to improve the quality of life for residents in the area. When businesses are successful, they also create opportunities for others to start their own companies or work with existing ones. This creates a cycle of mutual benefits that helps sustain business growth and development in a local area. In addition, businesses often invest in their local communities by sponsoring events or donating to charitable causes which can further strengthen relationships with customers and citizens alike. This will not only benefit the business but also help foster a sense of belonging within the local area.

1. INTRODUCTION

In today's complex and interconnected world, businesses are increasingly being held accountable for their impact on society. Addressing social issues has become not just a moral imperative, but also a strategic necessity for companies across all industries. A key concept in this realm is the social license

to operate, which refers to the level of acceptance and approval a company has from the local community and other stakeholders to conduct its operations.

Geothermal energy is a renewable source of energy that has many benefits for local societies. It is a clean, reliable and cost-effective way to produce electricity and heat. By investing in geothermal energy, local societies can create jobs, reduce air pollution and improve public health. In addition, geothermal businesses can benefit from the positive impacts they have on their local communities. Through the creation of jobs and new economic opportunities, geothermal businesses can help to sustain their business in the long term. Furthermore, by providing clean energy to local society, geothermal businesses can help reduce carbon emissions and contribute to global efforts against climate change. Therefore, it is clear that mutual benefits are gained when both local society and geothermal business invest in each other's success.

Having a strong social reputation is essential for any businesses especially in the geothermal industry, whereby mostly located in rural areas. Some content of this article will discuss how a geothermal business can build its social reputation to gain the trust of local communities and be successful in developing geothermal business. It will highlight the importance of building relationships with local communities in Patuha's geothermal area, understanding their needs, and taking steps to ensure that their interests are taken into account. By obtaining a social license, companies can start or maintain operations in geothermal areas without facing any resistance from local communities. This will also help them to create a positive reputation and build trust with their stakeholders, which is essential for long-term success.

Small social activities can include hosting events such as fundraisers, workshops, focus group discussions, sport events, culinary, or even just providing internet for local groups to work or study. By investing in these activities, businesses can create an environment of collaboration and mutual respect between themselves and the community they serve. This will not only benefit the business but also help foster a sense of belonging within the local area.

Sustainable business practices have become increasingly important for businesses in recent years. Not only do they benefit the environment, but they also have a positive impact on local societies. By engaging in sustainable practices that benefit local communities, businesses can ensure that their operations are mutually beneficial for both the company and its surrounding area. This can include investing in renewable energy sources, providing job opportunities to locals, and creating educational programs to support the community. By doing so, businesses can create a positive cycle of growth and prosperity that will ultimately help them sustain their operations in the long-term.

2. WHY IS SOCIAL LICENSE TO OPERATE IMPORTANT TO THE SUCCESS OF GEOTHERMAL BUSINESS?

The term "social license to operate" emerged in the mining industry in the 1990s in an effort to highlight the importance of community-industry relationships in mitigating risk (Gunningham et al. 2004; Thomson and Boutilier 2011; Lacey, Parsons and Moffat 2012; Dowd and James 2014; Moffat et al. 2016; Baines and Edwards 2018).

The social license to operate is a concept that recognizes the importance of public acceptance and support for a company's activities. It goes beyond legal requirements and regulations, encompassing the social and environmental impacts of a company's operations. Essentially, it is the unwritten contract between a company and society, granting the company permission to operate in a certain community or region.

Social license to operate is based on the belief that companies have a responsibility to be good corporate citizens and take in to account the interests and concerns of various stakeholders, including local communities, indigenous groups, non-governmental organizations (NGOs), employees, customers, and suppliers. These stakeholders can influence the success of a company through their support, activism, or opposition.

Why is social license to Operate important to the success of geothermal business, due to the numerous geothermal projects that are hindered in their construction due to community rejection, such as in Wae Sano area, geothermal project in Banten, and another project in West Sumatera area.

Some general reasons why community rejected the geothermal project:

1. **Environmental Concerns**. Geothermal projects can have environmental impacts, including land disruption, habitat destruction, and potential release of harmful gases.
2. **Health and Safety Concerns**. Geothermal energy production involves drilling into the Earth's crust, which can sometimes result in noise or the release of toxic substances.
3. **Cultural and Historical Concerns**. If the project area holds cultural or historical significance to the community, they might oppose the project out of fear that it could harm these important aspects of their identity.
4. **Lack of Consultation**. Communities often want to be involved in decision-making processes that affect their area. If the company did not adequately consult or involve the local community in the planning and decision-making for the geothermal project, this could lead to opposition.
5. **Economic Concerns**. Sometimes communities fear that the economic benefits of a project will not be shared fairly or that the project will lead to negative economic impacts in the long term.
6. **Disruption of Livelihoods**. Geothermal projects might require land acquisition or displacement of local communities, which can disrupt their livelihoods and ways of life.
7. **Perceived Lack of Transparency**. If the company's intentions or actions are perceived as lacking transparency, it can lead to suspicion and opposition.
8. **Negative Past Experiences**. If the community has had negative experiences with similar projects or companies in the past, they might be more inclined to reject new projects.

The rejection from the community will obstruct the project which could adversely affect the company. On the other hand, the company will also lose investors who would have supported the project's implementation. That's why social license to operate very important for geothermal business. However, companies are not the only party benefiting from the establishment of SLO— when granted, often both companies and communities gain (Hall et al. 2014; Dowd and James 2014; Moffat et al. 2016)

3. HOW TO BUILD COMPANY REPUTATION TO SECURE SOCIAL LICENSE TO OPERATE IN PATUHA

A company's reputation plays a crucial role in securing and maintaining its social license to operate. A positive reputation built on trust, transparency, and ethical practices enhances a company's credibility and fosters a sense of trust among stakeholders. On the other hand, a poor reputation can lead to resistance, protests, and even legal challenges that jeopardize a company's social license.

To build a solid reputation, companies must prioritize open and honest communication with stakeholders. This involves engaging in a dialogue and actively listening to the concerns and needs of the local community. By understanding the social map of the area which they operate, companies can tailor their strategies and initiatives to address specific social issues and build stronger relationships with stakeholders.

The methodology applied in Patuha to build reputation in order to gain social license support:

3.1 AMDAL and Social Mapping Documents

For this reason, an Environmental Impact Assessment (EIA) or AMDAL document is required to understand the Social Impact Analysis in the surrounding area. AMDAL analysis should be made at the initial planning stage of a project, before the project starts or takes place. This makes it possible to identify potential environmental impacts that may occur as a result of the project and take steps to reduce or manage these impacts. Ideally, an environmental impact analysis should be carried out before a final decision is made regarding the design, location and scale of the project.

By conducting an environmental impact analysis at an early stage, projects can be designed in such a way that negative impacts on the environment and society can be minimized. This analysis also helps

stakeholders such as government, local communities, and environmental organizations to have a better understanding of how the project will affect the environment and surrounding communities.

It is important to remember that environmental impact analysis is not only about complying with applicable regulations, but also about corporate social and environmental responsibility for the impacts caused by their activities. By starting an environmental impact analysis early on, companies can take the necessary preventive and mitigating actions to maintain a balance between environmental desires and project development.

In addition to having the EIA document, Geo Dipa also conducts Social Mapping studies by social consultant that are updated annually to identify suitable program recommendations to be implemented in Geo Dipa's geothermal area.

Figure 12: Social Mapping of Patuha Geothermal.

3.2 Public Consultation

Regarding open communication, Geo Dipa consistently engages in periodic public consultations with the local community, especially to facilitate direct communication, gather aspirations, and collectively seek solutions to social and environmental issues in the community. Beyond initiating contact and informing stakeholders of development plans, companies also need to provide ample opportunities for stakeholder feedback (Thomson and Boutilier 2011; Hall 2014; Voyer and van Leeuwen 2019), as studies have shown that active participation can build trust and promote compromise (De Cremer et al., 2005; Gouldson et al., 2007; Diez et al., 2015).

Overcoming resistances from local communities: Protests and how to facilitate dialogue

Despite a company's best efforts, there may still be resistances from local communities, including protests and opposition to their operations. It is crucial to address these concerns proactively and facilitate a constructive dialogue. Companies should listen to the grievances of the community and take them seriously, seeking common ground and mutually acceptable solutions.

Transparency and honesty are paramount in overcoming resistances. By providing accurate information and being open about potential risks and impacts, companies can build trust and credibility. Engaging with local leaders, community representatives, and other stakeholders can also help bridge the gap and find common solutions that address both the company's needs and the community's concerns.

Responsiveness: Companies demonstrate a willingness to address concerns and incorporate stakeholder feedback into their decision-making processes. They strive to be accountable for their actions and make changes or adjustments based on stakeholder input.

Collaboration and partnerships: Organizations collaborate with stakeholders, NGOs, and government agencies to address shared challenges and find mutually beneficial solutions. This fosters trust, builds relationships, and promotes positive outcomes for all parties involved.

In terms of information transparency, Patuha facilitates external parties who wish to obtain information about Patuha. Information can be accessed directly through the PT Geo Dipa Energi (Persero) website at www.geodipa.co.id, where there is information about the Annual Report and Sustainability Report

that may be needed by the public. Additionally, communication is also open through the HaloPatuha call center.

Figure 2: Call Centre of Patuha Geothermal.

Building relationships with stakeholders: Communication and social engagement

One of the key strategies for securing a social license to operate is building strong relationships with stakeholders. Effective communication and social engagement are essential in this process. Companies must actively engage with the local community, NGOs, and other organizations to understand their concerns, needs, and aspirations.

Partnerships with local NGOs and organizations can be particularly valuable. These partnerships not only help companies gain insights into local social issues but also demonstrate a commitment to addressing these issues collaboratively. By working together, companies and NGOs can develop innovative solutions that have a greater impact on the community.

In addition to routine public consultation activities, Geo Dipa also engages in other communication activities by conducting discussions for the development of the Strategic Plan, involving various stakeholders. This is done to gather aspirations from stakeholders related to suitable programs in the company's working area. Currently, Geo Dipa has a Strategic Plan document to be implemented over 5 years for sustainable programs, supported by the Work Plan document developed together with stakeholders, especially the beneficiaries, for each year.

The strategic plan and work plan complement each other and help the organization in planning, implementing, and managing CSR programs effectively, beneficially, and with precision. The strategic plan provides direction and long-term goals, while the work plan details operational steps to achieve these goals.

Furthermore, Geo Dipa also conducts Stakeholder Engagement studies to map out stakeholders and assess their level of engagement with Geo Dipa, which enables the organization to develop necessary strategies in approaching stakeholders to enhance their engagement. We have programs to create social mapping every 4 years, the latest one was conducted in 2021.

3.3 Corporate Social Responsibility (CSR) Initiatives

Corporate social responsibility initiatives are a powerful tool for addressing social issues and securing a social license to operate. Companies can contribute to the community in various ways, such as investing in education and infrastructure, supporting local businesses, and creating job opportunities. These initiatives not only improve the quality of life for the local community but also promote economic development and social progress.

Investing in local education is particularly important as it equips individuals with the skills and knowledge needed to thrive in the modern economy. By supporting local schools and educational programs, companies can empower the next generation and contribute to the long-term growth and sustainability of the community.

Geo Dipa has 4 aspects in CSR programs, including Empowerment, Infrastructure, Charity, and Capacity Building. These program's called Geo Dipa Peduli, Geo Dipa Maju, Geo Dipa Hijau and Geo Dipa Pintar. In Empowerment aspect Geo Dipa has carried out some programs such as Integrated Waste Management, Coffee Farmers Group, Multimedia Arts, Small-Medium Enterprise Snacks, and Village Tourism.

And then for Infrastructure aspect Geo Dipa has carried out infrastructure improvement program and electrical installation since 2016 and more than 1000 houses have installed electricity from Geo Dipa. The other of infrastructure improvement program, Geo Dipa always contribute to disaster mitigation and disaster response such as repairing the bridge and road access due to flooding. For next Charity program Geo Dipa has carried out food security program and supplies more than 3000 package every year, and compensation for underprivileged children 250 person every year. And the last for Capacity Building aspect, Geo Dipa has carried out geothermal goes to school and scholarship program for 75 students every year.

Investing in local education and infrastructure

Investing in local education and infrastructure is another effective strategy for addressing social issues and securing a social license to operate. By improving educational facilities and providing scholarships, companies can empower individuals and contribute to the development of a skilled workforce. Additionally, investing in infrastructure projects such as roads, healthcare facilities, and clean water supply can have a transformative impact on communities, improving their quality of life and overall well-being.

Geo Dipa provides opportunities for local residents to become part of the company and collaborates with the Department of Manpower in labor recruitment. Additionally, for non-skilled jobs, Geo Dipa always involves local residents in labor-intensive activities or other work. Our program in Geo Dipa such as training for local welders, photography training, scholarship supports, certifications for small business, High School Certification Program.

3.4 Run Business Process with Transparency and Integrity

Maintaining a positive social reputation requires good corporate governance (GCG) and transparency. Companies must adhere to ethical standards, comply with regulations, and be accountable for their actions. This includes transparent reporting on social and environmental performance, as well as engaging in regular dialogue with stakeholders to address any concerns or issues. Transparency and openness are essential to gaining legitimacy and building the trust required for SLO (Thomson and Boutilier 2011; Rooney et al. 2014).

By practicing good corporate governance and transparency, companies can build trust and credibility, which are vital for securing a social license to operate. Stakeholders need to see that companies are acting responsibly and are committed to addressing social issues in a genuine and meaningful way. Social License to Operate can be works if have legitimacy, credibility, and trust (Thomson and Boutilier 2011; Moffat and Zhang 2014).

The governance practices at Patuha have been consistently implemented with the existence of guidelines related to social and environmental aspects, such as Standard Operating Procedures (SOP) for CSR program implementation, SOP for CSR program's working relationship pattern, SOP for the selection of CSR program beneficiaries, and Occupational Health and Safety (K3LL) governance.

As per government regulation, this CSR has to reach 4% of net profit of the corporation. And this 4% of net profit distributed for the local people around Patuha's Area. On top of CSR budget, Geo Dipa put aside 0,5% of total revenue for the benefits of local government. Hence, the numbers of money distributed from Geo Dipa Patuha always monitored and reported transparently.

The mutual benefits of addressing social issues for business growth

Addressing social issues is not just about philanthropy or meeting regulatory requirements; it can also drive business growth. By proactively addressing social issues, companies can enhance their reputation, attract and retain top talent, and strengthen their relationships with customers and investors. Furthermore, companies that address social issues are often better positioned to identify and mitigate potential risks, ensuring long-term sustainability and profitability.

3.5 Creating Job Opportunities and Supporting the Local Economy

One of the most impactful ways companies can address social issues and secure their social license to operate is by creating job opportunities and supporting the local economy. By hiring locally and sourcing goods and services from local suppliers, companies can stimulate economic growth and improve the livelihoods of community members.

Furthermore, companies can invest in training and skill development programs to enhance the employability of local residents. This not only helps address social issues such as unemployment but also creates a sense of pride and ownership among community members.

Geo Dipa provides opportunities for local residents to become part of the company and collaborates with the Labor Offices in labor recruitment. Additionally, for non-skilled jobs, Geo Dipa always involves local residents in labor-intensive activities or other work. For non-skilled jobs such as cleaners, house keepers, security, drivers. Geo Dipa always give priority to local residences unless required personal are not available locally. Total numbers non-skilled labors in Geo Dipa Patuha reach 65% of Geo Dipa's employees.

By doing this initiatives, local people have interest to secure their jobs and helps Geo Dipa indirectly to prevent any social issues in Patuha's Area. And this is the highest level of social license to operate whereby they will protect their interest and Geo Dipa protect the business.

3.6 Monitoring and Evaluation

Environmental considerations and managing social impact

Addressing social issues goes hand in hand with environmental considerations. Companies must be mindful of the environmental impact of their operations and take proactive measures to minimize negative consequences. This can include adopting sustainable practices, reducing carbon emissions, and protecting natural resources. Managing social impact requires ongoing monitoring and evaluation. Companies should regularly assess the social and environmental impact of their operations and take corrective actions when needed. By being proactive in managing social impact, companies can demonstrate their commitment to sustainability and responsible business practices. Patuha is committed to addressing environmental impacts by conducting periodic monitoring of the Environmental Management and Monitoring Plans (RKL RPL) in every quarter, biodiversity monitoring, integrated domestic waste management, disaster mitigation, reforestation, and seedling activities, as well as participating in the annual PROPER assessment. The high commitment of Patuha towards environmental and social impacts is evidenced by the achievements and awards received by Patuha, including Safe Working Hours since 2014, Proper Green on 2021-2022, Subroto Award for Occupational Health and Safety (K3LL) with Aditama K3 and Utama for the LL category, Assessment of Occupational Safety and Health Management System (SMK3 PP50) with Satisfactory results, ISO 14001:2015 certified, West Java Governor's Award for Platinum category in OHS (P2K3), West Java Governor's Award for Zero Accident category, and CSR Award in the Electricity Installation category.

Utilization of available technology can greatly support social license to operate in the Patuha Geothermal Area. Technologies such as environment monitoring software, remote CCTV, noise reductions, early warning systems, gas detection system, public announcement system, water treatment technology, and digital display system can be used to monitor environmental impact and ensure compliance with regulations. Digital platforms and social media can also be utilized to engage with local communities, providing transparency and promoting positive relationships. Furthermore, advanced drilling technologies can minimize environmental disruption, while renewable energy technologies can assist in harnessing the geothermal potential effectively. These technologies not only

facilitate operational efficiency but also contribute to the establishment and maintenance of a social license to operate.

Figure 3: Achievements and Awards.

4. CONCLUSION

Addressing social issues is not just a moral obligation; it is also a strategic imperative for businesses. A solid company reputation plays a pivotal role in securing a social license to operate, which is essential for long-term success and sustainability. By actively engaging with stakeholders, investing in the community, and being transparent and accountable, companies can build trust, foster goodwill, and create a positive social impact that benefits both the business and the local community. Ultimately, addressing social issues is not just about doing the right thing; it is about securing a sustainable future for all.

The absence of a social license can result in opposition, protests, reputational damage, legal challenges, and difficulties in obtaining permits or approvals for future projects. On the other hand, companies that actively seek and maintain a social license to operate can benefit from enhanced reputation, increased stakeholder support, improved risk management, and long-term sustainability.

Overall, the concept of social license to operate recognizes that a company's legitimacy and success depend not only on financial performance but also on its ability to operate in a socially and environmentally responsible manner while addressing the concerns and expectations of its stakeholders.

REFERENCES

Baines J and Edwards P. 2018. The role of relationships in achieving and maintaining a social licence in the New Zealand aquaculture sector. Aquaculture. 485(1):140-146.

Boutilier R and Thomson I. 2011. Modelling and measuring the social license to operate: fruits of a dialogue between theory and practice. Queensland (Australia): International Mine Management.

Dowd AM and James M. 2014. A social license for carbon dioxide capture and storage: how engineers and managers describe community relations. Soc Epistemol. 28(3-4):364-384.

Gunningham N, Kagan RA, Thornton D. 2004. Social license and environmental protection: why businesses go beyond compliance. Law Soc Inq. 29:307-41.

Hall NL. 2014. Can the "social license to operate" concept enhance engagement and increase acceptance of renewable energy? A case study of wind farms in Australia. Soc Epistemol. 28(3-4):219-238.

Lacey J, Parsons R, Moffat K. 2012. Exploring the concept of a social license to operate in the Australian minerals industry: results from interviews with industry representatives. CSIRO. 1-26.

Moffat K and Zhang A. 2014. The paths to social license to operate: an integrative model explaining community acceptance of mining. Resour Policy. 39:61-70

Moffat K, Lacey J, Zhang A, Leipold S. 2016. The social license to operate: a critical review. Forestry. 89:477-488.

Moffat K and Zhang A. 2014. The paths to social license to operate: an integrative model explaining community acceptance of mining. Resour Policy. 39:61-70.

Prospect : Patuha's Document of Stakeholders Engagement Reports (2022)

Prospect : Patuha's Document Monitoring Evaluation and Community Satisfaction Index (2022)

Rooney D, Leach J, Ashworth P. 2014. Doing the social in social license. Soc Epistemol. 28(3-4):209-218.

Universitas Gajah Mada : Patuha's Document of Social Mapping Report (2011)

Direct Large Scale Geothermal Field Development vs Smaller Staged Development: Considerations, Risk, and Impact to the Project Feasibility

Daniel Adityatama[1], Ferdino R. Fadhillah[1,2], M. Rizqi Al Asy'ari[1],
Agung W. Mukti[4], Dorman Purba[3], Nadya Erichatama[1], and V. Adven Brilian[4]

[1]Geoenergi Solusi Indonesia (GEOENERGIS), Jakarta, Indonesia
[2]ITB School of Business and Management, Graha Irama 12th floor, Jakarta, Indonesia
[3]ENERKA Bhumi Pratama, Cibis Nine 11th floor , Jakarta Selatan, Indonesia
[4]PT Geo Dipa Energi (Persero), Jakarta, Indonesia

daniel.adityatama@geoenergis.com

Keywords: geothermal, Indonesia, development scenario, project economic, risk

ABSTRACT

Indonesia plans to increase the geothermal power plant installed capacity to 5,700 MW in 2030, more than double the current capacity. This accelerated development plan will put geothermal stakeholders in a dilemma, whether to directly develop the field on a large scale or staged manner.

Directly developing geothermal fields on a large scale generally yields a lower overall cost per MW but will require a longer time to construct and missed opportunity to generate revenue earlier. Direct large-scale development also exposes the developers to resource risks, such as rapid production decline due to a lack of understanding of the field characteristics required for resource management. A staged development, on the other hand, can generate revenue earlier due to a shorter development duration and provides the developer time to properly assess the resource characteristics of the geothermal field to devise a proper field management strategy such as reinjection and production strategies. However, smaller staged development tends to have a higher cost per MW developed compared to direct large-scale development. Those two scenarios may have different impacts on the whole project's economics.

This study evaluated the impact of different development strategies to project economics and feasibility. The development history of geothermal fields in Indonesia and worldwide, such as Ohaaki and Geysers, are used to identify the development strategies employed and their outcomes. The strategies identified were then used as the basis for developing the various scenarios of geothermal development. A project financial model was then used to assess the impact of those scenarios on the whole project economics and feasibility. Finally, this study is expected to provide guidelines or considerations for geothermal stakeholders in Indonesia in determining the proper geothermal development strategy.

1. INTRODUCTION

The geothermal development strategy is currently confronted by a challenging decision. One option is to pursue immediate large-scale development, which promises a lower cost per MW. However, this path comes with the drawback of potential resource-related complications during the production phase. Alternatively, an incremental staged approach offers the advantage of further understanding of resource characteristics, albeit at a higher cost per MW.

Choosing the full-size development route requires a longer timeline, resulting in delayed revenue generation. In contrast, opting for smaller, phased development stages allows for revenue streams upon the completion of each unit. These contrasting approaches hold the potential to yield differing impacts on the overall project economics—a vital aspect that will be thoroughly assessed in this paper. This objective dilemma of geothermal development is shown in Figure 1.

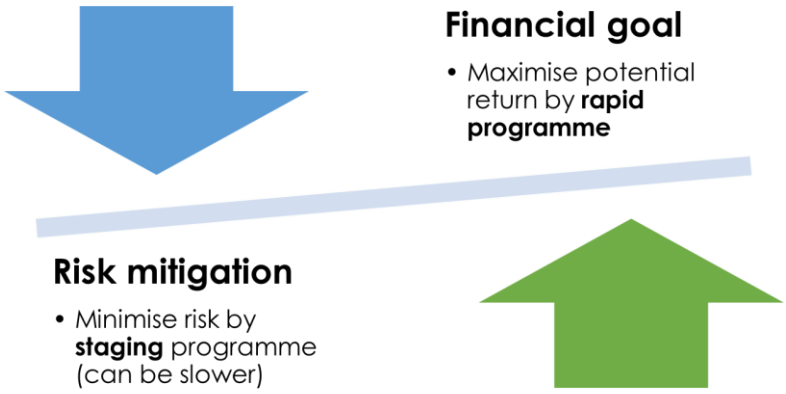


Figure 1: Objective dilemma of geothermal development (modified from Lawless, 2015; Jacobs, 2022).

Objective of the Study

The objectives of the paper are as follow:

- Advantages and Disadvantages Evaluation: The research will conduct a comprehensive assessment of the pros and cons associated with various geothermal development strategies. By analyzing the strengths and weaknesses of each approach, the study aims to provide a well-rounded understanding of the potential benefits and challenges.
- Global Case Discussions: The research intends to draw insights from international experiences, exemplified by cases like the Geysers and Ohaaki developments. By discussing these cases, the study seeks to highlight real-world instances of geothermal field expansion and the lessons that can be gleaned from them.
- Financial Simulation Case Study: The research proposes to present a detailed case study involving financial simulation. This case study will focus on the geothermal development assessment of a specific field in Indonesia. Through this simulation, the study aims to offer a practical demonstration of how different development strategies influence the financial aspects of a project.
- Factor Identification for Decision-Making: The research aims to identify crucial factors that should be taken into consideration when selecting geothermal development scenarios. By pinpointing these factors, the study intends to provide a structured framework for stakeholders to assess and compare various strategies effectively.

In summary, the proposed methods involve a comprehensive evaluation of development approaches, discussions of international cases, a practical financial simulation case study, and the identification of key decision-making factors. Through these methods, the study aims to provide valuable insights and guidance for stakeholders engaged in geothermal development projects in Indonesia.

2. METHODOLOGY

The methodology employed in this study comprises the following steps:

- Literature Review and Conceptual Framework:
  Conduct an in-depth review of relevant literature on geothermal development strategies, their advantages, disadvantages, and economic implications. Formulate a conceptual framework that outlines the key factors influencing the selection of development approaches.
- Case Selection and Analysis:
  Identify and analyze global geothermal development cases, such as the Geysers and Ohaaki developments. Examine these cases to understand the strategies employed, the outcomes

achieved, and the lessons learned. This analysis will provide valuable insights into the effectiveness of different approaches.

- Scenario Development:
  Based on the insights gained from case analyses and the conceptual framework, develop a range of geothermal development scenarios. These scenarios will encompass both direct large-scale and staged approaches, taking into account various factors such as development timeline, costs, revenue generation, and resource management strategies.
- Financial Simulation:
  Select one geothermal field in Indonesia as a case study for financial simulation. Utilize historical data, projected costs, revenue projections, and the identified scenarios to create a detailed financial model. This simulation will quantify the financial implications of each scenario, including capital expenditures, operational costs, revenue streams, and potential returns on inveDeveloperent.
- Economic and Feasibility Assessment:
  Evaluate the financial simulation results to assess the economic viability and feasibility of each geothermal development scenario. Analyze key metrics such as net present value (NPV), internal rate of return (IRR), payback period, and sensitivity analysis to understand the project's robustness under various conditions.
- Factor Identification and Decision Framework:
  Analyse the findings from the case analyses, financial simulation, and economic assessment to identify critical factors that influence the choice of development strategies. Develop a decision-making framework that outlines considerations such as resource characteristics, development costs, revenue potential, and risk mitigation.
- Guidelines and Recommendations:
  Based on the synthesized results and decision framework, formulate practical guidelines and recommendations for geothermal stakeholders in Indonesia. Provide insights into how to navigate the trade-offs between large-scale direct development and staged approaches, considering both financial and resource-related factors.
- Conclusion and Implications:
  Summarize the study's findings, highlighting the implications for geothermal development in Indonesia. Discuss the broader significance of the research outcomes for sustainable and economically viable geothermal projects.

3. GEOTHERMAL DEVELOPMENT APPROACH

Developing a power plant within a geothermal field is a process that can consume a considerable amount of time. In accordance with Indonesian government regulations, the entire journey from the exploration phase to the Commercial Operation Date (COD) of the power plant is expected to be completed within a span of 5 years. There's also a provision for a potential extension of an additional 2 years. However, it's worth noting that the actual timeline for development, starting from the drilling of the initial exploration well, often exceeds this baseline. This extended period is depicted in Figure 2. In some instances, the development timeline has even stretched beyond a decade. Although, it's important to acknowledge that in recent years, there have been instances of achieving faster development timelines, as indicated by the red boxes in Figure 2.

However, it's essential to recognize that the graph presented only captures a portion of the overall scenario. In the period from 2010 to 2021, numerous exploration drillings were conducted within Geothermal Working Areas (known as *Wilayah Kerja Panas Bumi* or WKP). Nevertheless, among these, only a total of 4 fields have successfully advanced to the production phase. This reality underscores the considerable challenges and complexities associated with the development of geothermal projects.

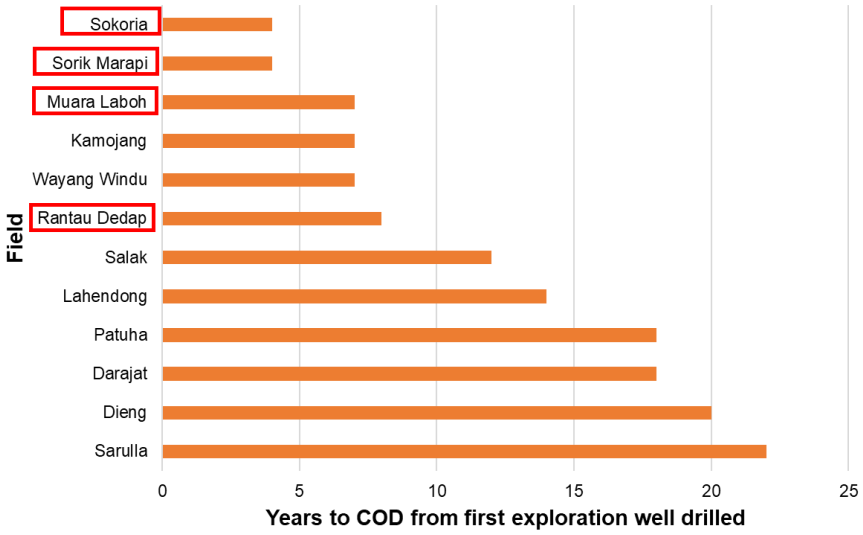


Figure 2: Duration to the power plant COD from the first exploration well drilling (Modified from Jacobs, 2022).

The prolonged duration leading up to the Commercial Operation Date (COD) directly translates into an extended period before developers can start earning revenue. This, in turn, significantly impacts the overall project economics. Conversely, when pursuing a staged development approach, there's a trade-off involving relatively smaller revenue streams and higher initial capital expenditures (CAPEX), which can be attributed to the economy of scale principle. This interplay between revenue and CAPEX constitutes a critical challenge in the context of geothermal development. Striking the right balance amidst these factors is indeed a noteworthy challenge in the field of geothermal energy projects.

The extended timeframe also implies that the developer must continually invest capital (typically sourced from its equity) over a prolonged duration before they can generate revenue. This particular problem is illustrated in Figure 3. Considering this issue, developers face the task of not only maximizing power plant capacity (through direct large scale development), but also considering strategies to expedite the exploration phase. However, pursuing such acceleration carries the risk of substantial capital expenditure (for instance, drilling multiple full-size or significant diameter wells) while resource uncertainty remains notably high.

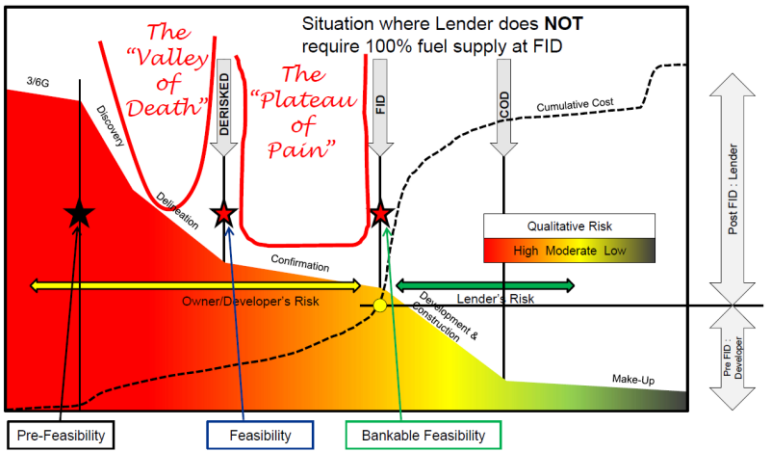


Figure 3: Geothermal project phase risk profile (modified from Jacobs, 2022).

3.1 Accelerated Exploration or Staged Exploration?

As shown in Figure 3 previously, the geothermal exploration drilling typically has three objectives:

- Discover the resource
- Delineate the resource
- Confirm the resource

Going through those objectives in stages (Figure 4) can minimize risk and reduce the potential cost of abandonment if the desired resource size and characteristics are not met. However, that may mean longer exploration time, thus longer "plateau of pain" as shown in Figure 3. Consequently, some developers may opt for an accelerated process, despite the associated higher risk of increased abandonment costs, as illustrated in Figure 5.

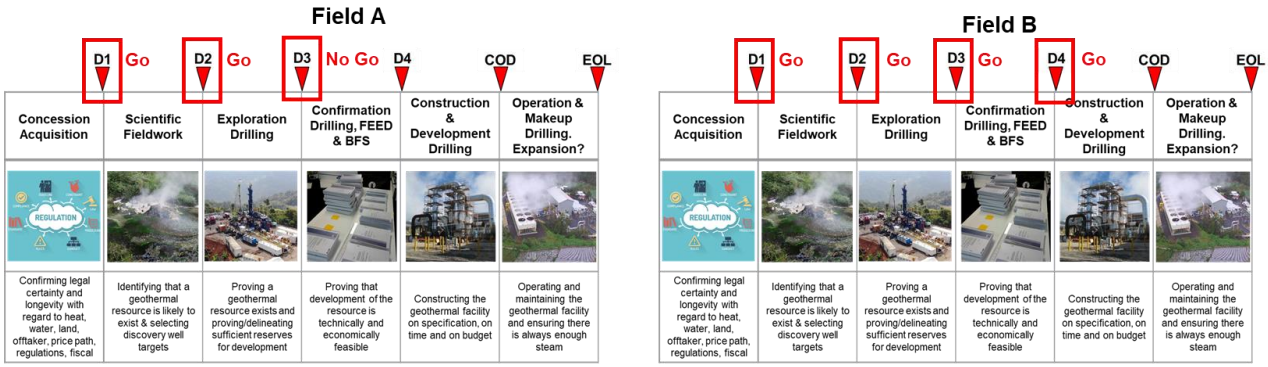


Figure 4: Illustration of geothermal project stages and decision gate prior deciding to proceed to next phase.

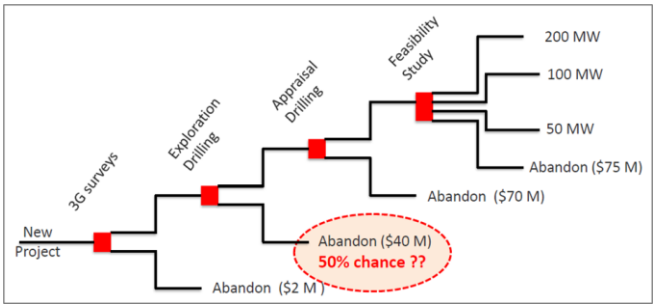


Figure 5: Illustration of cost of abandonment in geothermal project (modified from Jacobs, 2022).

The expedited exploration involves a drilling campaign that typically focuses on discovering, outlining, and at times confirming the availability of steam (a critical factor for bankable feasibility, often requiring around 50% verification of the anticipated power plant capacity) within a single campaign, as illustrated in Figure 6.

This approach stands in contrast to the staged exploration strategy, where each step is conducted sequentially, and the outcome of each phase is assessed before making a decision to move forward. The primary objectives of this strategy usually revolve around minimizing the expenses associated with project abandonment, particularly in cases where resource uncertainty remains high or confidence levels are relatively low. This approach is illustrated in Figure 7.

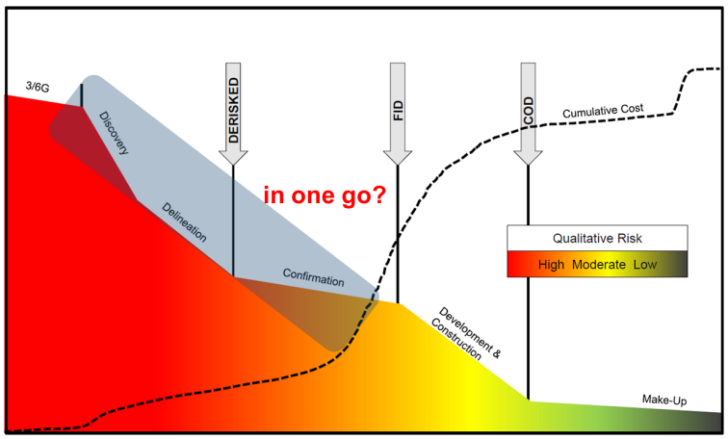


Figure 6: Illustration of accelerated exploration, aims to discover, delineate, and confirm the steam availability in one go.

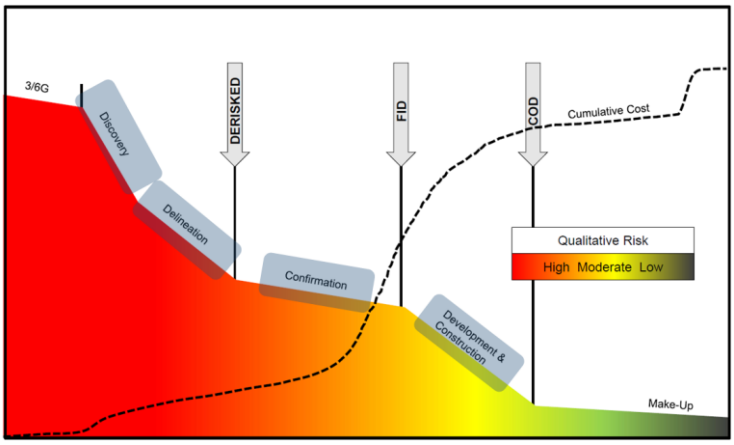


Figure 7: Illustration of staged exploration, typically aims to minimize cost of abandonment.

3.2 Direct Large Scale Development

Direct large-scale geothermal development involves the immediate and extensive development of geothermal fields to achieve a substantial increase in installed capacity, often directly maximizing the available resource in the area. This approach is characterized by the construction of single or multiple power plants and infrastructure on a significant scale within a relatively short timeframe. The emphasis is on maximizing production output and harnessing economies of scale to achieve a lower cost per megawatt (MW) generated.

4. INTERNATIONAL CASE OF GEOTHERMAL DEVELOPMENT

4.1 The Geysers, USA

4.1.1 Geysers Background:

The Geysers, located in the Mayacamas Mountains of Northern California, holds the distinction of being one of the world's oldest and most significant geothermal power plants. Its history traces back to the 1960s when initial exploration and development activities began. The site's rich geothermal resources were harnessed for electricity generation, making it a pioneering venture in the field of renewable energy.

4.1.2 Development of The Geysers:

The Geysers' development journey was marked by innovative engineering and technical advancements. In the early stages, exploratory drilling revealed a vast reservoir of steam and hot water beneath the

earth's surface. Pioneering techniques were employed to tap into this resource, including the concept of "flash steam" power plants that converted high-pressure geothermal steam into electricity.

Over time, the field's potential became increasingly evident, leading to substantial expansion efforts. The development of various power plants and the establishment of a complex network of wells, pipelines, and infrastructure turned The Geysers into a significant energy-producing hub. The collaborative efforts of geothermal companies and scientific researchers contributed to enhancing the field's productivity and shaping its future direction.

4.1.3 Production Challenges and Overproduction:

While The Geysers achieved remarkable success in electricity generation, it also encountered challenges that provided valuable insights for the geothermal industry. One of the most notable challenges was the issue of overproduction. As the field's productivity increased, there were instances where the extraction of steam exceeded the natural replenishment rate of the reservoir. This led to a decline in reservoir pressure and a subsequent reduction in steam production.

The issue of overproduction underscored the delicate balance between energy generation and reservoir sustainability. Overcoming this challenge required the implementation of sophisticated reservoir management strategies. These strategies included practices such as reinjecting produced fluids to maintain reservoir pressure, optimizing production rates, and adopting measures to enhance overall resource longevity.

4.2 Ohaaki, New Zealand

The Ohaaki geothermal power plant is a facility that uses steam from the Ohaaki geothermal field to generate electricity. It is owned and operated by Contact Energy, and it has a distinctive 105 m high natural draft cooling tower, the only one of its kind in New Zealand.

The Ohaaki geothermal power plant was commissioned in 1988 with an initial capacity of 104 MW. However, the production has declined over time due to the ingress of shallow groundwater from the overlying Ohaaki Rhyolite Formation, which lowers the enthalpy and pressure of the steam. This has also caused an increase in calcite scaling, which requires antiscalant dosing systems.

The production decline has been observed since the late 1960s and early 1970s, when field testing showed a rate of 14% per annum. The decline rate was expected to be higher when the power plant was at full production.

In 1995, a deep exploration programme was undertaken to drill three deep wells to cross the regional structural trend and locate permeable fractures and zones within the greywacke below the volcanic formations. The wells encountered temperatures up to 300°C in the volcanic formations above the greywacke.

As of 2011, the maximum net capacity of the Ohaaki geothermal power plant was about 65 MW with an annual output of around 400 GWh pa1 The Waikato Regional Council granted resource consents for a term of 35 years and for a take of 40,000 tonnes per day of geothermal fluid.

The Ohaaki geothermal power plant is an example of how geothermal energy can be used to generate electricity, but also how it faces challenges such as resource depletion, environmental impacts, and technical difficulties.

5. FINANCIAL MODELLING RESULT

In NPV calculation, WACC discount rate is assumed to be 7.42% for IPP scenario and 7.6% for own use scenario. The NPV value per scenario comparison is illustrated in Figure 8. The NPV value ranges from -81 MUSD to -173 MUSD. From the NPV projection result, no scenario is identified to have a positive NPV. All scenarios seem to have an NPV value below zero, indicating the project still does not meet financial feasibility standards. The highest value of NPV is possessed by 1x15 MW; 1x45 MW plan for both IPP and own use scenario.

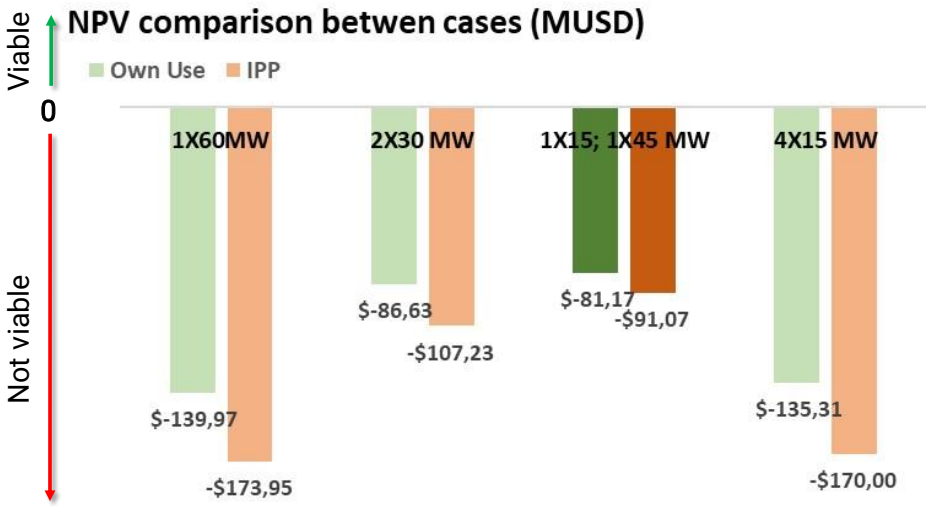


Figure 8: NPV projection of each scenario.

The value of IRR project for own use scenario is 3.5-4.7% while IPP scenario is 2.3-4.4% (Figure 9). These values still do not reach or even exceed the WACC discount rate margin. However, the IRR project value of this project is still in a typical IRR project range for power plant in Indonesia (4-7%). The 1x15 MW; 1x45 MW from IPP scenarios has the highest IRR project value among other scenarios.

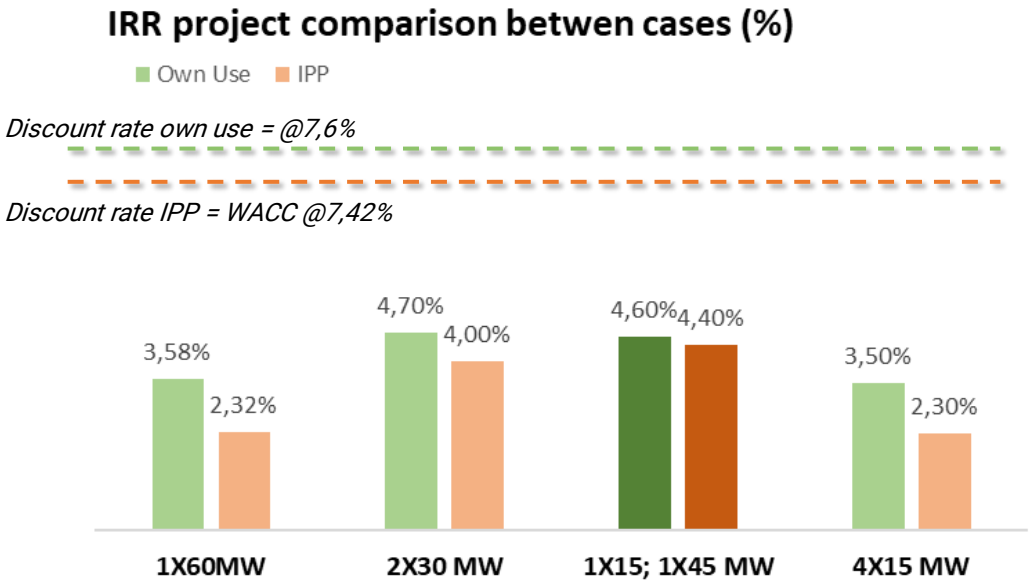


Figure 9: IRR Project projection of each scenario.

Aside from IRR project, financial feasibility also can be achieved if the IRR equity reaches at least 12% value. From IRR equity projection in Figure 10, it is known that the IRR equity of this project has a range of -0.7% to 4.7%, meaning the IRR equity is still below the expected value. If compared, the own use scenario generally has a higher IRR equity value than IPP scenario. This might be caused by the difference of debt ratio, debt interest, depreciation method, and applied carbon trading mechanism.

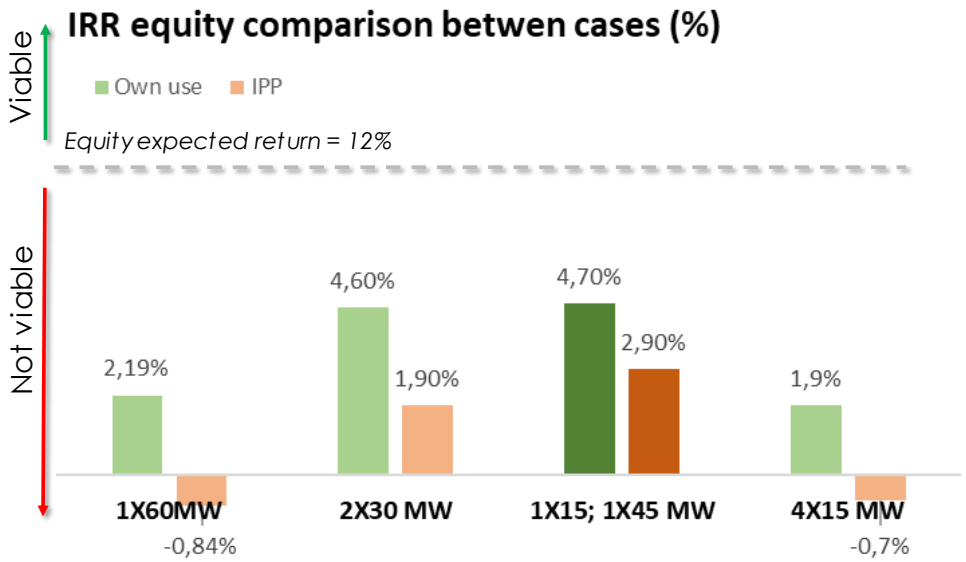


Figure 10: IRR Equity projection of each scenario.

6. SUMMARY AND CONCLUSION

In conclusion, geothermal development faces a pivotal crossroads between immediate large-scale and staged approaches. The chosen path must reconcile financial feasibility, resource sustainability, and timelines. International cases like the Geysers and Ohaaki provide valuable insights, emphasizing the importance of balance. The paper's proposed methodology encompasses holistic evaluation, practical simulations, and targeted decision-making frameworks.

While direct large-scale development maximizes production and economies of scale, staged approaches ensure enhanced resource comprehension and minimized risk. Striking equilibrium between revenue generation and capital investment remains the central challenge. The study, driven by its objectives, aims to guide geothermal stakeholders in Indonesia towards strategic decision-making and sustainable project development in the complex energy landscape.

REFERENCES

Clearwater, S., & Burnell, J. (2003). Ohaaki Geothermal Field: A Review of Production History and Reservoir Engineering Studies. In Proceedings World Geothermal Congress 20032

Clearwater, S., & Burnell, J. (2011). Ohaaki Geothermal Field: A Review of Production History and Reservoir Engineering Studies. In Proceedings Thirty-Sixth Workshop on Geothermal Reservoir Engineering3

Contact Energy. (2011). Ohaaki Geothermal Power Station1

EBTKE. (2022). Pengembangan Panas Bumi Di Indonesia. Jakarta, Indonesia: Ministry of Energy and Mineral Resources.

Gehringer, M., & Loksha, V. (2012). Geothermal handbook: planning and financing power generation.

Jacobs. (2022). Geothermal 101: Resources, exploration, drilling, power development, energy evaluation, feasibility, development stages.

Jacobs. (2022). Geothermal Business Model: Module 2 - Part 1. The geothermal lifecycle. PT. SMI Geothermal Training.

NREL. (2021). Energy Technology and Market Risk Reduction. Retrieved from NREL.gov: https://www.nrel.gov/energy-solutions/risk-reduction.html

Purwanto, E. H., Suwarno, E., Hakama, C., Pratama, A. R., & Herdiyanto, B. (2020). An Updated Statistic Evaluation of Drilling Performance, Drilling Cost and Well Capacity of Geothermal Fields in Indonesia. In Proceedings World Geothermal Congress (p. 1).

Purwanto, E. H., Suwarno, E., Lukman, R. F., & Herdiyanto, B. (2018). Geothermal Drilling in Indonesia: A Review of Drilling Operation, Evaluation of Well Cost and Well Capacity. In Proceedings, The 6th Indonesia International Geothermal Convention & Exhibition, Jakarta, Indonesia.

Ussher, G. (2021). Exploration strategy and risk. Ministry of Foreign Affair and Trade New Zealand.

Evaluating the Impact of Tariff Regulations on the Economic Performance of the "XYZ" Geothermal Project: An Analysis from Equity, Lender, and Government Perspectives

Ferdino R. Fadhillah[1,2,3], Nadya Erichatama[1,2],
William Jhanesta[1,2], Daniel W. Adityatama[1,2], and Dorman Purba[2]

[1]Geoenergi Solusi Indonesia (GEOENERGIS), Jakarta, Indonesia
[2]ENERKA Bhumi Pratama, Cibis Nine 11th floor , Jakarta Selatan, Indonesia
[3]ITB School of Business and Management, Graha Irama 12th floor, Jakarta, Indonesia

ferdino.rf@geoenergis.com, rfferdino@gmail.com

Keywords: Geothermal, Investment, DSCR, NPV, IRR

ABSTRACT

Indonesia is ranked as the second-largest geothermal energy producer globally, with a potential resource of 29 GW. However, the country has only utilized a meager 2356 MW, equivalent to roughly 8% of its total potential. In line with this, the Government of Indonesia has set a target to significantly increase its geothermal utilization for power generation to 5.799 MW by 2030. The Government of Indonesia has launched a new tariff scheme to support the country's efforts in promoting renewable energy sources, including geothermal. The latest Presidential Regulation 112/2022 has changed the tariff scheme from a ceiling to a ceiling with a staging scheme. This regulatory shift is expected to impact revenue projections and, consequently, the economic outcomes of geothermal projects in Indonesia.

The objective of this research is to analyze the economics of the "XYZ" geothermal project under the new tariff regulation from the perspectives of equity, lender, and government. To achieve this objective, the study utilizes secondary data related to project capital and operational expenditures, financing strategies, revenue projections, and depreciation-tax. The capital budgeting approach analyzes the data and determines the project's economic performance. The critical parameters analyzed from the net cash flow include the net present value (NPV), internal rate of return (IRR), debt service coverage ratio (DSCR), and government take.

The analysis reveals that the "XYZ" geothermal project does not provide adequate compensation to the equity, as evidenced by a negative NPV and an IRR below the discount rate. The lender requirement also could not be fulfilled by the project due to lower minimal DSCR of project in compared to lender requirement.

1. INTRODUCTION

1.1 Current and Expected Geothermal Installed Capacity.

Indonesia boasts significant geothermal potential, estimated at around 23 gigawatts of electricity generation capacity (GWe). This places Indonesia among the world's leading geothermal energy producers, second only to the United States and surpassing the Philippines (Darma, Imani, Shidqi, Riyanto, & Daud, 2021; ADB, 2018; ThinkGeoenergy, 2023). However, despite this promising potential, Indonesia currently utilizes only 9% of its geothermal capacity for energy production (Fadhillah, et al., 2022; ThinkGeoenergy, 2023). Indonesia's geothermal sector encompasses 16 power plants managed by state-owned enterprises (SOEs) and Independent Power Producers (IPPs). Additionally, there have been exploration and development efforts in 63 geothermal working areas. Furthermore, there are 15 preliminary survey and exploration areas in the pre-exploration phases (MEMR, 2022).

Indonesia has established an ambitious goal of reaching a geothermal utilization capacity of 5,799 megawatts (MW) by the year 2030. This represents a remarkable 259% increase from the current capacity (PLN, 2021) as shown in Figure 1. This strategic direction aligns with Indonesia's commitment to bolstering its green energy portfolio, as it aims to derive 23% of its energy from renewable sources

by 2025 and an additional 21% by 2030 (DEN, 2022a). Achieving this utilization target will necessitate substantial additional efforts in accelerating the development of geothermal resources.

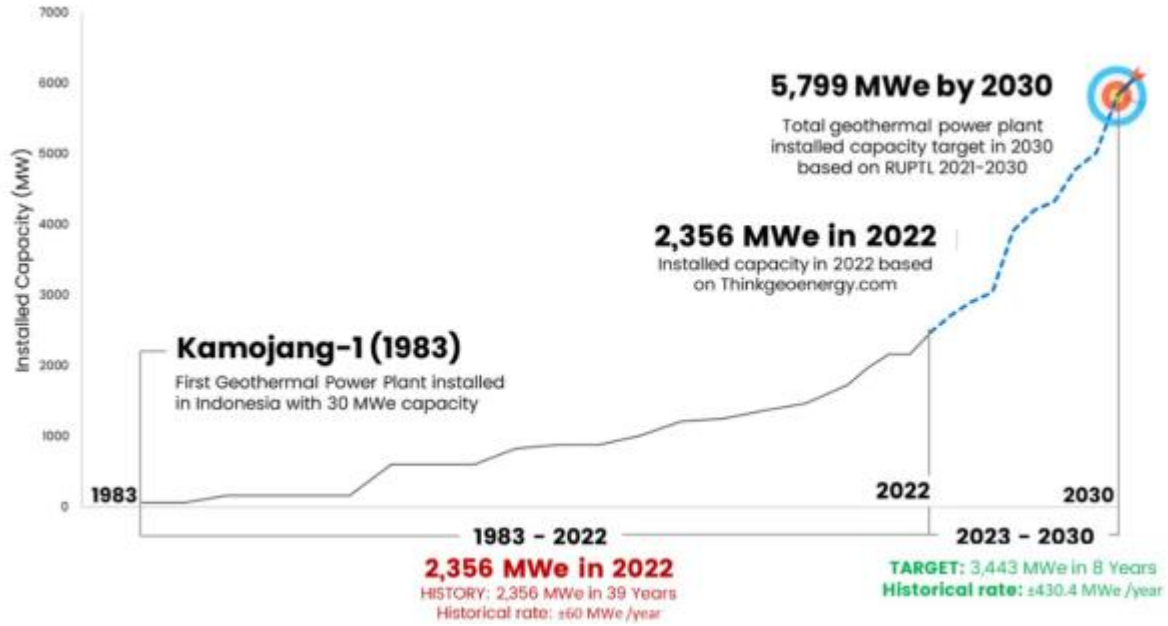


Figure 1: The installed capacity of geothermal power plants in Indonesia (ESDM, 2022).

1.2 The Potential and Challenges of Indonesia Geothermal Development.

The geothermal sector holds significant market potential due to the concentration of current reserves primarily in Sumatra and Java, where there is substantial demand for electricity. Moreover, these regions are still reliant on coal-fired power plants, which are subject to an early phasing-out program initiated by the Government of Indonesia (GoI). This coal phase-out strategy opens up opportunities for geothermal electricity generation to serve as a viable substitute for the fossil fuel power plants. Geothermal is also expected to be baseload of electricity that replaces coal's primary power generation in Indonesia (World bank, 2011).

Despite of promising potential, geothermal industry encountered challenges in attracting investors. This is primarily due to the high risks that not compensate by fair return to the investor. Development geothermal projects to the production phase frequently encounters impediments stemming from unfavorable economic conditions, limited resource availability, and social concerns. The industry is significantly influenced by a complex interplay of political, economic, social, and technical factors (Komendantova, Patt, Barras, & Battaglini, 2012; IRENA, 2022). Figure 2 shows the general problem of Indonesia geothermal project with explanation as below.

1.3 Research Question and Objective.

The primary business issue faced by the XYZ geothermal project in this research is the uncertainty surrounding regulation changes related to the tariff scheme. Any alterations to the tariff scheme could directly impact the project's revenue, and consequently, its economic performance. The revenue fluctuations resulting from these changes will have a direct effect on the project's cash flow. However, despite the significance of the tariff changes, the exact financial impact on the XYZ geothermal project remains unknown.

The research question that addressed in this study: How is the project economic performance under the ceiling with staging tariff mechanism?

The primary objective of the research is to analyze the XYZ project's performance from financial perspective after implementation of ceiling with staging tariff scheme. The financial evaluation

performed by evaluating the key parameters from equity, lender, and government perspectives. Those stakeholders have difference financial feasible criterion that need to be fulfilled since each of them has importance role to ensure the development geothermal project.

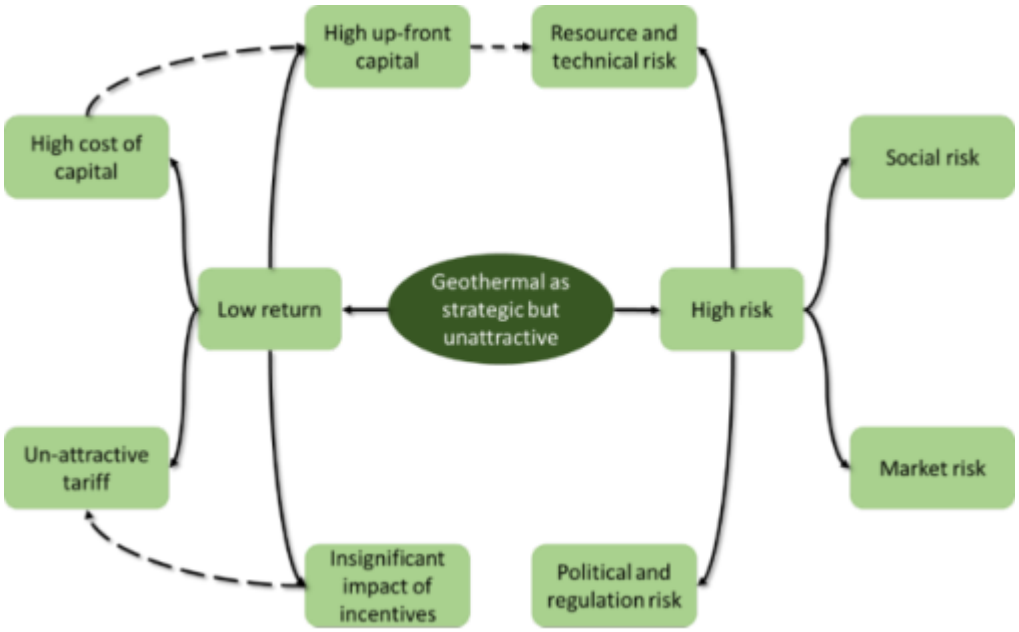


Figure 2: The problem tree of general Indonesia geothermal project.

1.4 Research Methods.

The research on the XYZ geothermal project relied on information gathered through a thorough literature review, which encompassed various aspects related to the project's financial aspects. The reviewed literature included data on project capital, technical-financial assumptions, operating expenses, depreciation, and tax rates. To assess the economic viability of the XYZ project, a financial model was developed and employed for analysis.

2. INDONESIA GEOTHERMAL PROJECT OVERVIEW

2.1 Geothermal Project Stages

The geothermal business process, especially for electricity generation, mainly consisted of preliminary survey, exploration, test drilling, project review, field development, power plant construction, commissioning, and production phases (ESMAP, 2012; IGA, 2014) A geothermal company in Indonesia is eligible to perform preliminary survey until feasibility study for 7 years maximum. The company that successfully reaches commercial operation date (COD) would obtain 30 years of license, Conversely, in cases where an area is found unpromising for geothermal development during the preliminary survey and feasibility study phase, the company is obliged to relinquish the rights to that specific area to the government (Purba et al., 2021; GoI, 2014). The summary of Indonesia geothermal project stages shown in Figure 3.

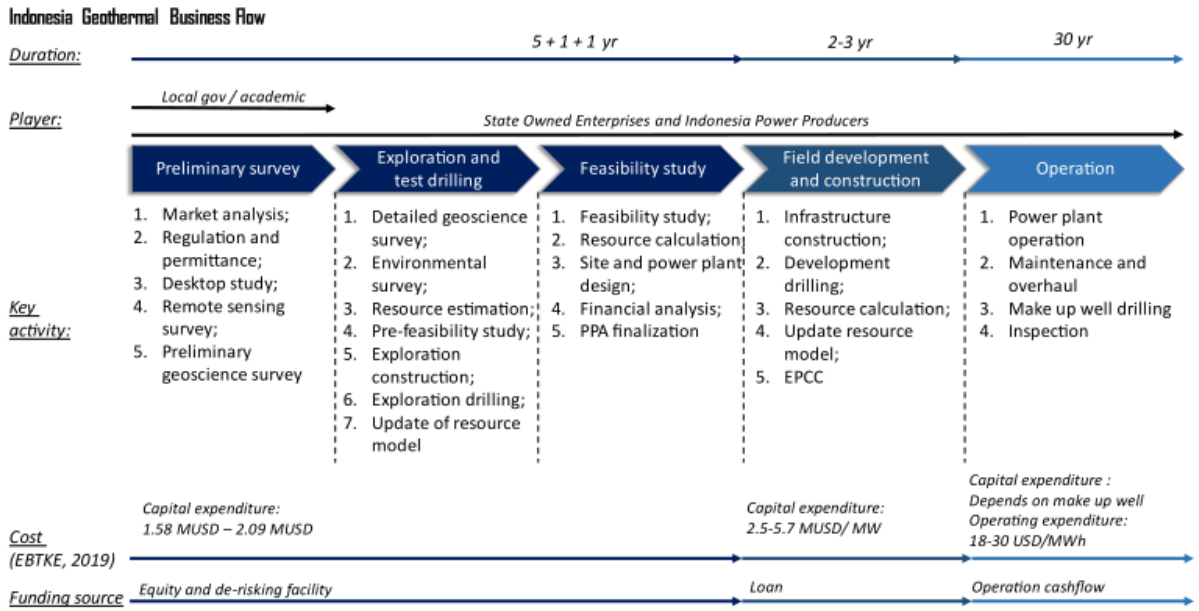


Figure 3: Indonesia geothermal business flow modified from GoI (2014), Purba (2021), and ESDM (2022).

2.2 Indonesia Geothermal Fiscal Regime

As outlined by EBTKE (2022), the geothermal fiscal regime in Indonesia is distinguished by two primary regimes, each defined by Indonesian law 21/2014. These regimes encompass the net operating income scheme for the existing working area (*Wilayah Kerja Eksisting*) and the royalty system for the geothermal area with a business license working area (*Wilayah Kerja Panasbumi Izin Panas Bumi*). The details of each regime as below:

2.2.1 Existing "net operating income" regime

Net Operating Income (NOI) scheme in Indonesia employs a profit-sharing mechanism based on the net operating income derived from the geothermal project's revenue after deducting operating expenses. Under this scheme, the government is entitled to receive a share of 34% of the net operating income, which includes all corporate taxes such as income taxes, Value Added Tax (VAT), Land tax, import tax, and other applicable taxes. Figure 4 shows the schematic of NOI "Existing" scheme. Based on EBTKE (2022), the net operating income (NOI) scheme was implemented in the existing geothermal working area with the following criteria:

- Field of the Entity with Geothermal Resource Utilization Rights: The NOI scheme applies to geothermal working areas operated by entities that hold the right to utilize geothermal resources, known as Kuasa Pengusahaan Sumber Daya Panas Bumi (KPSP). Notable examples of such entities include Pertamina Geothermal Energi and Geodipa Energi..
- Joint Operating Contract (JOC) Schemes: Geothermal working areas operating under the Joint Operating Contract (JOC) scheme are eligible for the NOI regime. Notable geothermal projects utilizing the JOC scheme include Wayang Windu, Darajat, Salak, Sarulla, and Bedugul.
- The entity that holds permit to utilize geothermal resources (Izin Pengusahaan Panas Bumi) such as Tulehu, PLN

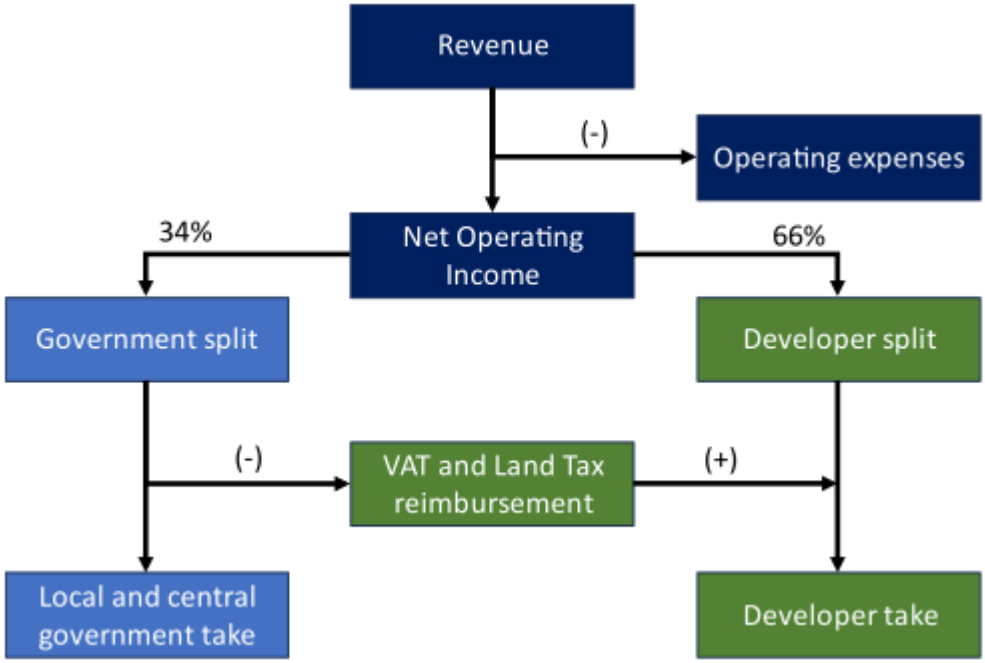


Figure 4: The schematic of NOI "Existing" scheme (modified from EBTKE, 2022).

2.2.2 Royalty regime

IPB Scheme is implemented in geothermal areas that hold the geothermal license (Izin Panas Bumi). The IPB scheme uses royalty system from gross revenue consisting of production fee, fixed fee, and production bonus. The government takes total of royalties-fees and corporate income tax. In comparison, the developer takes revenue deducted from government take, OPEX, and interest expenses. It is important to note that although the IPB scheme operates with a calculation similar to a concession, it is designed to ensure that the resources involved remain the property of the state. The scheme upholds the principle that the geothermal resources are owned by the state, while allowing developers to utilize and generate revenue from those resources in accordance with the terms and conditions of the geothermal license. Figure 5 shows the schematic of royalty scheme.

2.3 Various Available Incentives in the Current Geothermal Industry

The Government of Indonesia offers various fiscal incentives to promote investment and profitability in the geothermal industry. These incentives aim to create a favorable investment climate by reducing business costs and risks for investors. The incentives are provided through different government programs, encouraging businesses to invest in geothermal projects to maximize benefits. (Chalk, 2001) (UNCTAD, 2000). Based on EBTKE (2022; 2021), Lesmana et al (2020), Winofa et al (2020), Abidin (2020), and Fadhillah (2023), current fiscal incentives implemented for the geothermal industry as shown in Table 1.

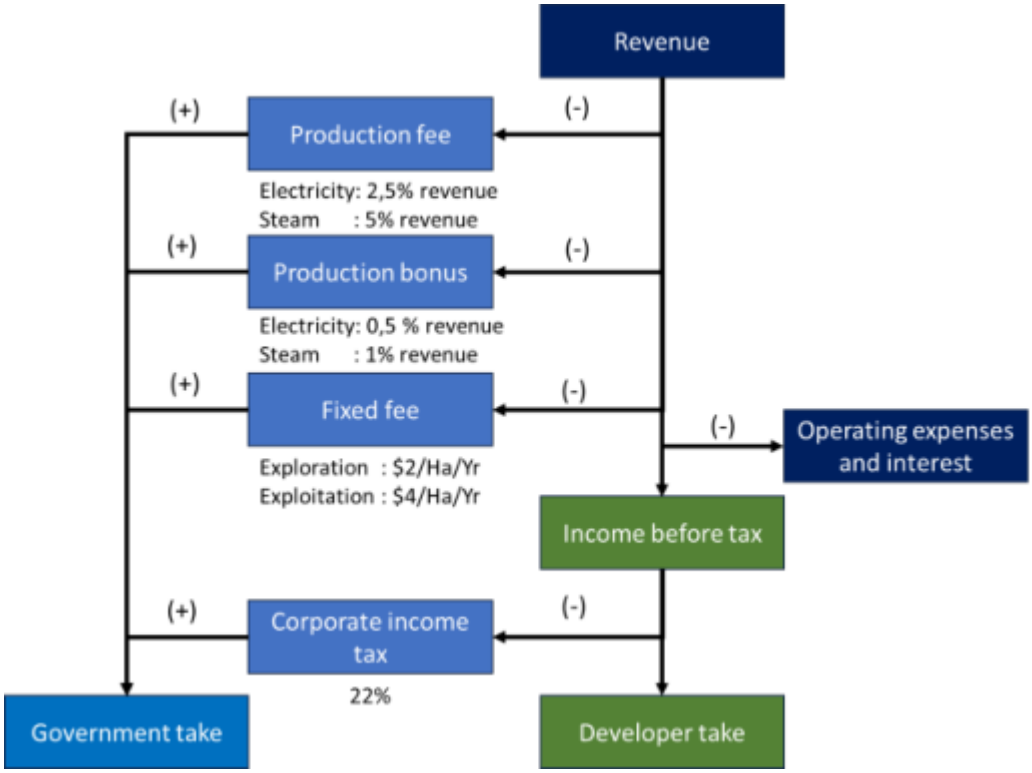


Figure 5: The schematic of Royalty "IPB" scheme (modified from EBTKE, 2022).

Table 1: Current fiscal incentives for geothermal.

Fiscal incentives	Remarks	Effective period of project stage
Tax holiday (PMK 130 / 2020)	The geothermal industry with an investment of more than 0.5 trillion USD would be eligible to obtain 5 years tax holiday. The detail of the tax holiday period as below: - 5 years for 0.5 to 1 trillion IDR investment - 7 years for 1 to 5 trillion IDR investment - 10 years for 5 to 15 trillion IDR investment - 25 years for 15 to 30 trillion IDR investment - 20 years for >30 trillion IDR investment	Operation
Tax allowance (GR 78/2019)		
- Investment allowance	Reduction of taxable income equals 5% per year of the total investment for the 6-year period and 30% of the total investment for the full period. The investment should be owned by the main business entity and not transferred during the period (Abidin, Rosdiana, & Salomo, 2020; Lesmana, Winofa, Pratama, Ashat, & Saptadji, 2020)	Operation
• Accelerated depreciation amortization	Geothermal classified as "class 3" use the double declining balance method with the 8-year period for tangible and intangible asset	Operation
• Loss carry over	Geothermal industry is eligible to perform loss carry forward for 5 year period with maximum no longer than 10 year. Geothermal as new and renewable energy also eligible to obtain 1 yr additional of the facility.	Operation

Fiscal incentives	Remarks	Effective period of project stage
Land tax exemption (PMK 172/2019)	The land tax for geothermal industry is extempted during the exploration phases (MoF, 2016). The land tax is charged on production phases with guidance to directorate general of tax regulations No. PER-45/PJ/2013.	Exploration
Import tax and value added tax exemption (PMK 172/2016)	Geothermal industry is 100% exempted from import tax for the equipment that not available / adequately produced in Indonesia (Abidin, Rosdiana, & Salomo, 2020; Lesmana, Winofa, Pratama, Ashat, & Saptadji, 2020). Geothermal industry is not imposed to VAT (Abidin, Rosdiana, & Salomo, 2020)	Exploration and development

As indicated by Kristina (2018) and Nugraha et al. (2017), the current tax incentives for geothermal projects in Indonesia have not demonstrated significant impact in enhancing project attractiveness or reducing the cost of electricity generation. The incentives, as per IRENA (2022) and IESR (2022), include a tax holiday that allows for 100% tax reduction for corporate income tax (PPh) for a period of 5 to 20 years. However, this particular incentive has not been effectively utilized, mainly because most renewable energy (RE) developers do not generate taxable profits during the initial five years of project implementation. Therefore, Fadhillah (2023) provide the case example of ineffective tax holiday period.

2.4 Geothermal Tariff Scheme: Ceiling with Staging

Indonesia's geothermal tariff scheme adopts the ceiling with staging scheme based on the location and power plant capacity. This implementation is outlined in Presidential Regulation 112/2022, which amends the previous ceiling tariff scheme. The ceiling with staging scheme divides the operation period of a geothermal power plant into two distinct stages: stage 1 (from year 1 to year 10) and stage 2 (after year 10). Each phase has different ceiling for the base tariff that the developer could obtain during the negotiation with PLN (GoI, 2022). Furthermore, the location factor is multiplier index for the base tariff during stage 1 to accommodate the variation of development cost due to different infrastructure conditions among the region (MEMR, 2022b). Figure 6 shows the distribution of base tariff and location factor. The calculation of the applied base tariff as below.

$$Tariff\ stage\ 1 = agreed\ tariff\ x\ location\ factor$$

$$Tariff\ stage\ 2 = agreed\ tariff$$

Geothermal Power Plant – electricity price

Capacity (MW)	Ceiling Price (HPT)							
	s.d 10 MW		>10 MW s.d. 50 MW		>50 MW s.d 100MW		>100 MW	
	Stg thn 1-10	Stg thn 11-30	Stg thn 1-10	Stg thn 11-30	Stg thn 1-10	Stg thn 11-30	Stg thn 1-10	Stg thn 11-30
Staging Price (cent $/kWh)	9,76 x F	8,30	9,41 x F	8,00	8,64 x F	7,35	7,65 x F	6,50
Levelized Price (cent $/kWh)	9,25		8,92		8,19		7,25	

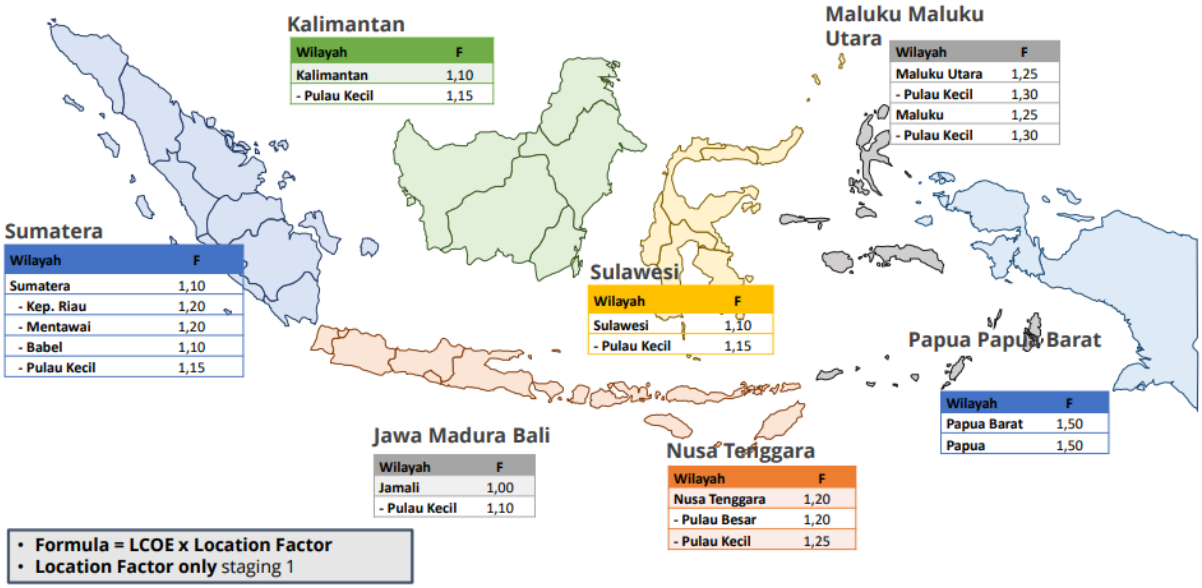


Figure 6: The base tariff and location factor of geothermal tariff under presidential regulation 112/2022.

ADB (2014) explained the Indonesia geothermal tariff adopts an escalation approach over the years, utilizing a partial percentage of tariff (α) to adjust the tariff values. The escalation factor used for this purpose is based on the United States Producer Price Index (US PPI) since the contract is denominated in USD. The calculation as below

$$P(t) = [(1 - \alpha)P(0)] + [\alpha P(0)USPPI(t)/USPPI(0)]$$

Where

P(t) = Tariff in year t, in US¢/kWh
P(0) = (base) tariff at COD = Tariff bid at time of tender, in year (0)
USPPI(t) = United States Producer Price Index for year (t)
USPPI(0) = United States Producer Price Index for year (0)
α = Coefficient (determined by ad-hoc discussion with range 0.25-0.4)

2.5 Geothermal Financial Model

The financial model is an essential tool for capital budgeting and financial analysis, enabling the assessment of a project's economic feasibility. It utilizes standard output parameters such as net present value (NPV), internal rate of return (IRR), return on investment (ROI), and other financial ratios (ESMAP, 2021). By combining data and expert assumptions, the financial model forecasts cash inflows (e.g., revenue from electricity sales, revenue from carbon credits) and outflows (e.g., capital expenditure, operating expenses, taxes) over a defined period. (ESMAP, 2021). The structure of financial model for the research shown in Figure 7.

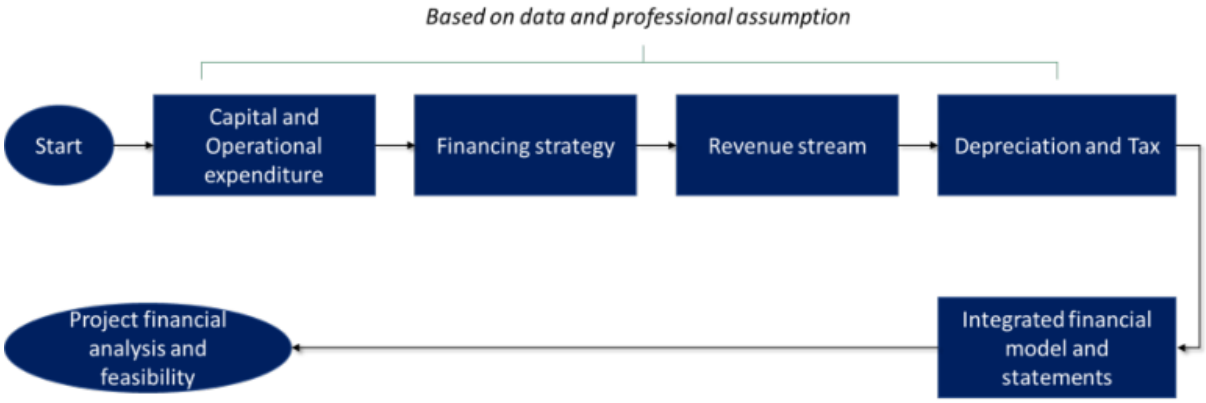


Figure 7: Structure of geothermal financial model.

2.5.1 Capital and operational expenditure

Capital Expenditure (CAPEX) for a geothermal project is defined as the expenditures that occur after obtaining the legal right to operate in a specific prospect area until the commercial date of the power plant. These expenses encompass various stages of the project, including surveys, infrastructure preparation, drilling, construction of the steam above ground system (SAGS), and the power plant. Additionally, subsequent major expenditures, such as make up well drilling, can be capitalized if it complies with asset recognition criteria, providing significant additional benefits to the project in the future (Fadhillah, Tjendarsa, Damayanti, Adityatama, & Purba, 2023). To accommodate the expenses related to exploration and evaluation activities, the capital recognition for geothermal projects may follow the accounting standard for conventional power generation with adaptations of PSAK 64. (PwC, 2018).

Operational Expenditure (OPEX) can be divided into two main components: the cost of electricity and operating expenses. Both types of costs occur after the commercial operation date (COD) of the geothermal power plant. The explanation of OPEX as below:

- The cost of electricity, also referred to as variable cost, encompasses various expenses associated with the operation and maintenance of the geothermal power plant. These costs typically include maintenance expenses, inspection costs, field office expenses, field transportation costs, camp-related expenses, and payment of royalty-production bonus (Radityo, 2009; Nur, Burton, Aida, & Ikhwali, 2023).
- Operating expense is any expense that must be paid by corporate/business unit that does not correlate directly to the operation (Nur, Burton, Aida, & Ikhwali, 2023). The changes in production volume would not change the operating expenses significantly. These expenses are also known as fixed costs. The general example of operating expenses is main office overhead, fee/permit, corporate branding, insurance, and fixed fee payment (Radityo, 2009).

2.5.2 Financing strategy

The financing strategy refers to business's approach to obtaining the necessary capital for its operations and expansion. The businesses utilize various methods such as shareholder capital, issuing stocks, or short and long-term debt financing to secure the required funds (Damodaran, 2011). ASEAN Center for Energy (2022) and Yescombe (2014) explained geothermal power plants during their pre-operation period, the financing strategy commonly involves a mix of financing sources. This includes contributions from shareholder equity and external financing options such as loans, government funds, or derisking facilities as shown in Table 2.

Table 2: Financing source for typical geothermal project.

Source of fund	Explanation	Project stage
Equity	Part of the capital sourced from the corporation's shareholders. This capital usually takes 30% of the project value with the ideal cost of equity ranges 13.5%-16.5% (GT Management, 2020). The shareholder equity is used to fund the project expenses during exploration phases since it faces the high risk that external financial institutions could not accept (Yescombe, 2014)	Preliminary survey; exploration; feasibility study, development-construction; operation
Government fund / derisking facility	Grants are part of the capital from the public sector (e.g. government and development banks). Grants serve as support funding for project developers in the early stage of the project (ACE, 2022). Indonesia's geothermal business has access to grant facilities from the government of Indonesia and the world bank to support the exploration activity before the developer could access the loans. Siahaan et al (2022) already summarize various government fund and derisking facility for Indonesia geothermal.	Preliminary survey; exploration; feasibility study,
Loan	Part of the capital sourced from the external financial institution with obligation for repayment after the start of the production period. Loans commonly support 70% of the project capital that could be accessed after the exploration phases, which has higher certainty related to the resource condition (GT Management, 2020).	Development-construction; operation

According to EBTKE (2021), Quinlivan (2015), Winofa (2020), and Lesmana (2020), the typical equity:debt ratio for geothermal projects is 30:70. Private geothermal power plants often have limited options for debt providers, primarily accessing loans from commercial banks or financial institutions. In contrast, soft loans, which prioritize social and environmental impacts over financial returns, are usually directed towards state-owned enterprises based on Climate Policy Initiative (2019).

During the operation period, the geothermal business still required high-cost reinvestment activity to maintain and expand the productivity of the field. The reinvestment activity includes the scheduled make-up well drilling and major plant overhaul, ideally financed from the operation activity reserved over the year in the cash reserve account (Nur, Burton, Aida, & Ikhwali, 2023; Yescombe, 2014). The reserve account would be sourced by cash flow from operation over the year to avoid sudden liquidity issues in the year of reinvestment occurred.

2.5.3 Revenue projection

Revenue is the total amount of cash obtained through operations related to the sales of goods (Anthony, 2011). The revenue is primarily affected by the sales volume and unit prices. Indonesia's geothermal business primarily sources revenue from electricity generation and/or steam sales. Furthermore, the geothermal business has several possible revenue streams, such as direct use, carbon trading, and other derivatives product.

2.5.4 Depreciation and tax

Depreciation is accounting technique used to allocate the cost of a long-term asset over the estimated useful life of the asset. The purpose of depreciation is to spread the asset's cost over the period, providing economic benefits rather than charging the entire cost to the year in which the asset was acquired. Corporate income tax for the geothermal sector that holds the license after Law. 21/2014 (known as WKP 'IPB') is referred to Law No 36/2008. The income tax would be 22% of positive taxable income.

2.6 Geothermal Project Economic Parameters

ADB (2014) highlights that the economic attractiveness of geothermal project is assessed based on parameters relevant to both equity and lenders. Furthermore, the government interest also needs to be considered since the government act as regulator that has right to permit the project. The attractiveness

for equity is measured by evaluating whether the project offers a fair reward to the investor. The lender perspective focuses on the project's ability to repay debt, while the government represent through government portion from tax and non tax payment. The feasibility of a project is typically evaluated using four key parameters, such as Net Present Value (NPV), Internal Rate of Return (IRR), Debt Service Coverage Ratio (DSCR), and government take. Table 3 shows the feasible criteria of each economic parameter.

- Net Present calculates the present value of all projected cash flows associated with the geothermal project, taking into account the time value of money. A positive NPV indicates that the project is expected to generate more cash inflows than outflows and is considered financially attractive. The project would be feasible if the NPV > Zero (Damodaran, 2014; Daryanto, 2021).
- Internal rate of return is defined as the discount rate that equates the net present value (NPV) of a project to zero. It provides a measure of the projected rate of return from the project, taking into account the discounted cash flows (Damodaran, 2014; Daryanto, 2021). According to the GT Management (2020), the financial feasibility of geothermal projects in Indonesia is determined based on the field and developer entity status. Exploration fields typically require a higher minimum acceptable IRR compared to brownfields due to higher project uncertainty and associated risks. For Independent Power Producers (IPPs), the equity IRR is used as a measure of financial feasibility. This is because funding for IPPs is typically sourced from a combination of equity and debt. On the other hand, state-owned enterprises (SOEs) use the project IRR as a measure of financial feasibility. This is because the capital for SOEs is often supported by equity from the government budget. The project would be feasible if the IRR > discount rate (Damodaran, 2014; Daryanto, 2021).
- Debt service coverage ratio (DSCR) is a financial metric that indicates the borrower's ability to meet its debt repayment obligations using the available annual free cash flow (Pacudan, 2015). Lenders use the DSCR as a parameter to evaluate the feasibility of providing financing for a project. A higher DSCR gives lenders confidence that the borrower will be able to repay both the interest and principal of the debt (Borgonovo & Gatti, 2013; Yescombe, 2014). ADB (2014) explain the financial institution categorize the geothermal project as feasible if DSCR is >1.8. Furthermore, an Indonesia financing institution set lower ratio (DSCR >= 1.2) as attractive condition of geothermal project (Fadhillah, Tjendarsa, Damayanti, Adityatama, & Purba, 2023).

Table 3: Key project economic parameters and feasibility criteria.

Perspective	Key consideration	Parameter	Feasible criteria
Equity	Reward and return to the equity that absorb the risk.	NPV Project and equity	NPV > 0 USD
		IRR Project and equity	IRR > Discount rate
Lender	Ability of the project to repay the debt service.	Debt Service Coverage Ratio	Min. DSCR > 1.2
Government	Government benefit from the project.	NPV Project	NPV > 0 USD
		IRR Project	IRR > Discount rate
		Government take	Government take > 0 USD

3. XYZ GEOTHERMAL PROJECT ASSUMPTION

The XYZ is hypothetical geothermal project with 55-Mw power plant project located in Java. The 55MW capacity is selected based on most common projected geothermal power plant in RUPTL 2021-2030. The Java area is projected to has highest additional installed geothermal power plant capacity. XYZ project has 20.000 Ha working area. The project has seven years for exploration, followed by commercial operation period of 30 years under royalty scheme. The produced electricity is 100% absorbed by PLN with take-or-pay scheme.

3.1 Capital and operating expenditure

The Capital Expenditure for XYZ geothermal project before COD is assumed on 5.1 million USD/MW with major contributor from power plant and drilling cost. The exploration of XYZ project assumed use

the standard hole drilling for exploration, appraisal, and development drilling. While the power plant technology uses single flash turbine. The total cost from preliminary survey until COD equals to 285.53 million USD. Furthermore, the project plans make up well drilling every 5 years with 8 MUSD/well. Figure 8 shows the CAPEX profile for overall project period.

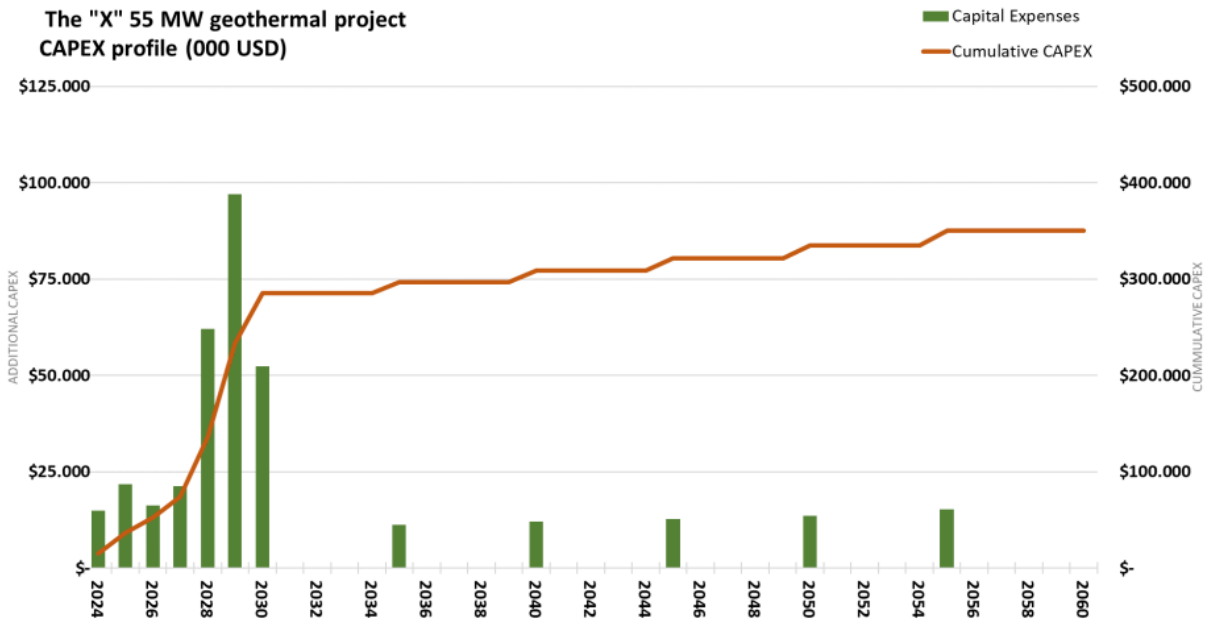


Figure 8: CAPEX profile for XYZ project.

The operation and maintenance cost for the XYZ geothermal project is estimated at 18 USD per megawatt-hour (MWh). Additionally, major plant overhauls are scheduled every 5 years, incurring a cost of 2 million USD per activity as per Quinlivan (2015). The operating expenses related general affairs are assumed to be 600 thousand USD annually, based on EBTKE (2021). To account for inflation, the expenses are escalated using the United States Producer Price Index (US PPI) index. The XYZ project also has responsibility to pay 0.5% production fee, 2.5% production bonus, and 4USD/Ha/Yr of fixed fee. Table 4 Summary of XYZ's operating expenditure

Table 4: Summary of XYZ's operating expenditure.

Parameter	XYZ Project	References
Operation and maintainance	18 USD/MWh	Quinlivan (2015)
Major overhaul cost	2 MUSD/ Activity	Quinlivan (2015)

Parameter	XYZ Project	References
Major overhaul period	5 year	Quinlivan (2015)
General admin and affair	600 thousand USD/Yr	EBTKE (2021)
Non tax government payment		
Royalty	2.5% of revenue	EBTKE (2021; 2022)
Production bonus	0.5% of revenue	EBTKE (2021; 2022)
Fixed fee	4 USD/Ha/Yr	EBTKE (2021; 2022)

3.2 Financing Strategy

The XYZ geothermal project adopts a mixed financing approach, combining equity and commercial loans. The equity portion accounts for 30% of the total construction costs, offering an expected return of 12%. While this return aligns relatively closely with the targeted equity return set by EBTKE at 11%, it falls below the ideal range of 13.5%-16% for geothermal greenfield projects, as indicated by GT Management (2020). the debt component constitutes 70% of the capital requirement, with drawdown initiated after 65% of the steam is confirmed under wellhead, which is expected to occur in the fifth year of exploration. The repayment structure involves 7% interest rate with three-year grace period. The

repayment period commences one quarter after the commercial operation date and follows the annuity method, spanning 15 years based on EBTKE (2021). The assumption also applied by EBTKE (2021), Quinlivan (2015), Winofa (2020), and Lesmana (2020).

With the given financing strategy assumptions, the XYZ project's weighted average cost of capital (WACC) is calculated to be 7.12%. The WACC serves as the discount factor for evaluating the project's financial feasibility and determining the present value of future cash flows. It represents the average cost of funding the project, taking into account both the cost of equity and the cost of debt. Table 5 shows the summary of XYZ project's financing strategy.

Table 5: Summary of XYZ's financing strategy.

Parameter	XYZ Project	References
Equity		
Equity ratio	30%	EBTKE (2021); Quinlivan (2015)
Cost of equity	11%	EBTKE (2021)
Debt		
Debt ratio	70%	EBTKE (2021); Quinlivan (2015)
Interest during construction	7%	EBTKE (2021)
Cost of debt	7%	EBTKE (2021); Quinlivan (2015)
Grace period	3 yrs	GT Management (2020)
Principal repayment period	15 yrs	EBTKE (2021)
WACC	7.12%	Calcutaed from Damodaran (2011)

3.3 Revenue Projections

The XYZ geothermal project has a single-stream revenue model, generating revenue from electricity sales to PLN. The power plant operates based on specific technical assumptions outlined in Table 6. For tariff determination, the project adopts the ceiling-staging scheme per Perpres 112/2022. Phase 1 has base price of 86.4 USD/MWh, while phase 2 has base price of 73.5 USD/MWh. Additionally, tariff escalation of 37.5% is of the base tariff using the US Producer Price Index (PPI) as per ADB (2014).

Table 6: Summary of XYZ's revenue assumptions.

Parameter	XYZ Project	References
Power plant capacity	55 Mw	Author discussion
Capacity factor	90%	EBTKE (2021); Quinlivan (2015); (Boston, Prieto, & Patzek, 2022)
Off-take absorption	100%	Author discussion
Tariff scheme	Ceiling with staging	Perpres 112/2022
Escalation portion	0.375	ADB(2014)
Stage 1 tariff		
Base tariff	86.4 USD/MWh	Perpres 112/2022
Location factor	1	Perpres 112/2022
End price	86.4 USD/MWh	Perpres 112/2022
Stage 2 tariff		
Base tariff	73.5 USD/MWh	Perpres 112/2022

3.4 Depreciation and tax

The XYZ geothermal project employs the straight-line depreciation method with an 8-year depreciation period and no salvage value as applied by Nur et al. (2023), and industrial practices (2005). Furthermore, the corporate income tax is 22%. XYZ geothermal project base plan use the existing tax holiday where the project is eligible for 7 years tax holiday.

Table 7: Summary of XYZ's depreciation and tax assumptions.

Parameter	XYZ Project	References
Depreciation		
Method	Straight line	Cases from GT management (2020)
Period	8 Yr	Nur et al (2023)
Salvage value	0 USD	Cases from GT management (2020)
Corporate tax		
Incentives	Not applied for incentives	
Tax rate	22%	

4. PROJECT ECONOMIC EVALUATION

4.1 Equity perspectives

Figure 9 illustrates the cash flow analysis of the XYZ project. During the initial seven years (2024-2030), both the project and equity cash flows exhibit negative values, attributed to the project's ongoing investment in the exploration and development phases. Notably, the most substantial cash outflow occurs between 2028 and 2030, coinciding with the commencement of the project's development phase. The cash inflow profile demonstrates two distinct drops during the project's timeline. The first drop transpires in 2041, triggered by the implementation of the second stages of tariff, resulting in an approximate 25% reduction in the free cash flow compared to the initial tariff period.

Over the project's duration, the cumulative cash flow amounts to 413.31 million USD, with the break-even point anticipated to be achieved within the 10th year of operation. Similarly, the cumulative cash flow for equity is projected at 277.44 million USD, with the break-even point estimated to be reached in the 15th year of operation.

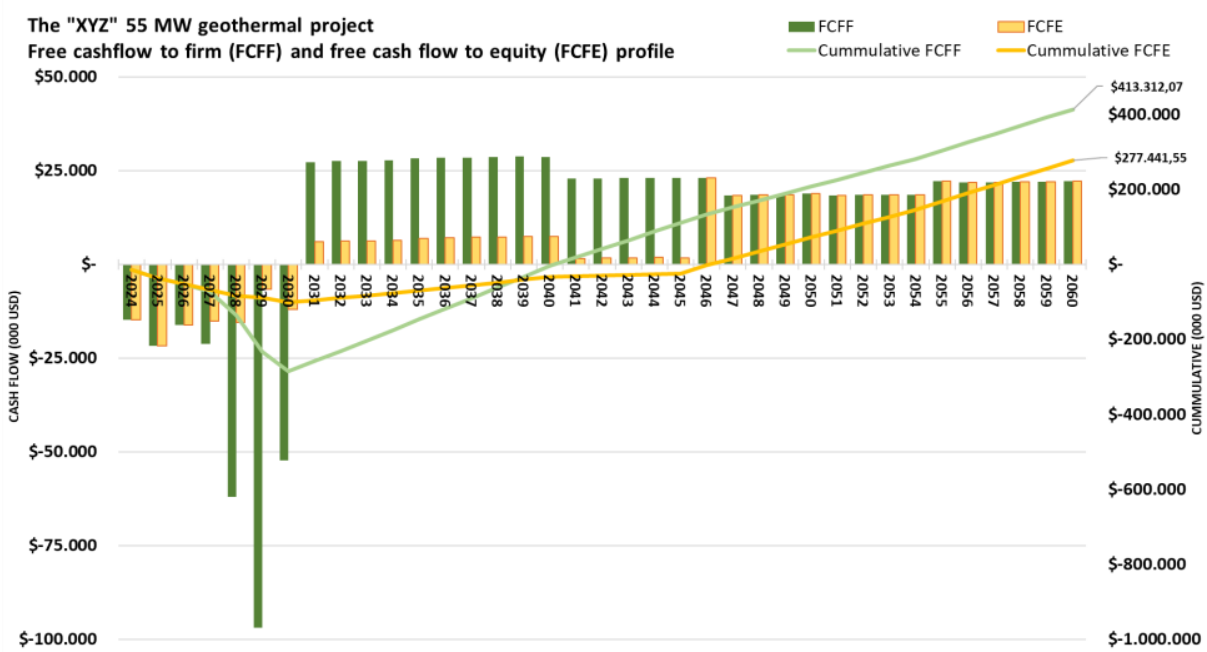


Figure 9: FCFF and FCFE profile of the XYZ geothermal project.

The cashflow is discounted to determine the project feasibility through NPV and IRR. The applied discount rate for project cashflow is equals to WACC (7.12%), while the equity cashflow use discount rate on cost of equity (11%). Although cumulative cashflow shows positive condition, the result of XYZ project economic calculations shows infeasible condition for equity. The NPV for project and equity cashflow shows negative condition, where NPV project equals -14.12 MUSD and NPV equity equals -41.22 MUSD. The IRR calculation for project and equity falls below the discount rate. The IRR project is 6.52%, while the IRR equity is 6.39%. The result of NPV and IRR indicates the project does not provide fair return to the equity. Table 8 The result of XYZ project economic from equity perspective

Table 8: The result of XYZ project economic from equity perspective.

Parameter	Requirement	Result	Remarks
Equity			
NPV Project @7.12%	>0 USD	-14.12 MUSD	Unfeasible
IRR Project	>WACC (7.12%)	6.52%,	Unfeasible
NPV Equity @11%	>0 USD	-41.22 MUSD	Unfeasible
IRR Equity	>Cost of equity (11%)	6.39%.	Unfeasible

The unfeasible condition of the XYZ project from an equity perspective highlights the need for additional actions to provide fair rewards to investors. Fadhillah (2023) explain several approaches to achieve fair reward for equity, such as:

- APEX Reduction through Strategic Partnerships: The project can explore strategic partnership approaches to reduce capital expenditures without compromising technical specifications and requirements. By consolidating efforts among geothermal developers and collaborating on procurement and sourcing for large cost items, expenses can be minimized. Strategic partnerships also offer the benefit of a faster learning curve, leading to a reduction in CAPEX.
- Tariff Negotiation: Particularly for stage 1 tariffs or location factors, engaging in tariff negotiation can significantly impact the project's return. The negotiation process involves discussions with the off-taker to potentially secure higher tariffs above the regulated rates, as allowed by Perpres 112/2022 article 5. Even if the targeted tariff exceeds the regulated rate, the project still has the opportunity to initiate negotiation.
- Project Acceleration: Shortening the construction period can lead to earlier revenue generation and potential cost reductions associated with construction delays, inflation, and market uncertainties. By accelerating the construction phase, the project's financial performance can improve, cash flow can be enhanced, and returns on investment can be realized more quickly.

4.2 Lender perspectives

Figure 10 illustrates the Cash Flow Available for Debt Service (CFADS) and Debt Service Coverage Ratio (DSCR) profile of the XYZ geothermal project under the base case scenario. The DSCR values range from a maximum of 1.41 to a minimum of 1.07. The CFADS and DSCR profile reveals two distinct periods: a high period spanning from 2031 to 2040, and a low period from 2041 to 2045. The shift from stage 1 to stage 2 tariff structure, characterized by lower tariffs, results in a significant drop in revenue starting from 2041. However, this decrease in revenue is not accompanied by a corresponding reduction in expenses, leading to a decline in both CFADS and DSCR during this period.

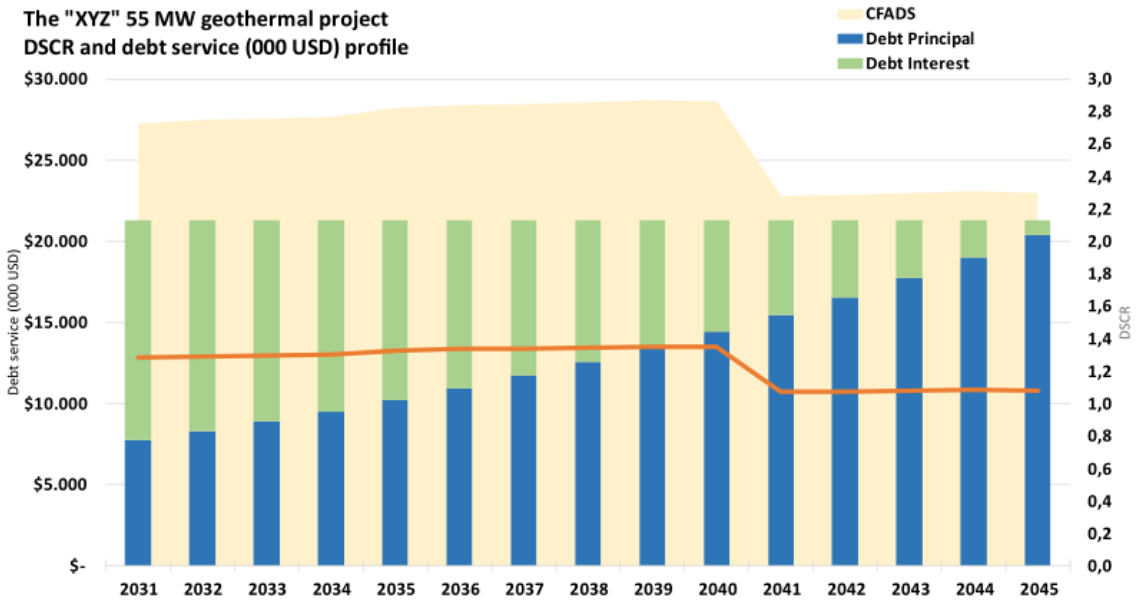


Figure 10: CFADS and DSCR profile for XYZ project.

The calculation of Debt Service Coverage Ratio (DSCR) reveals that the XYZ project fails to meet the lender's requirements regarding the minimum DSCR. The lender stipulates that the minimum DSCR should not fall below 1.2 throughout the project's duration. However, the XYZ project's minimum DSCR is recorded at 1.07, indicating a deficiency in meeting the lender's specified threshold. The low DSCR of 1.07 signals to the lender that the project may struggle to generate sufficient cash flow to service its debt obligations. As a result, the lender may view the project as higher risk and may be hesitant to extend the requested funding or could impose more stringent loan conditions to mitigate potential risks.

The primary reason for the low DSCR is attributed to the implementation of tariff stage 2, which significantly impacts the project's cash inflows, leading to inadequate coverage for debt service obligations. As a result, the project struggles to generate sufficient cash flow to comfortably service its debt obligations, raising concerns for the lender's risk assessment. Table 9 The result of XYZ project economic from lender perspective.

Table 9: The result of XYZ project economic from lender perspective.

Parameter	Requirement	Result	Remarks
Lender			
Minimum DSCR	>= 1,2	1,07	Unfeasible

Restructuring the debt repayment structure can be an effective approach to improve the Debt Service Coverage Ratio (DSCR). Fadhillah (2023) utilize the target DSCR/sculpting method to maintain the project's DSCR under varying cash flow conditions. By adjusting the debt service repayment to align with specific levels of cash flow, the project can maintain a desirable DSCR while ensuring that the tenor period remains acceptable to lenders. Moreover, USAID (United States Agency for International Development) also mentions that sculpting repayment structures are more favorable for renewable energy projects. This approach allows for greater flexibility in managing debt obligations, especially during periods of fluctuating cash flows, which is common in renewable energy ventures.

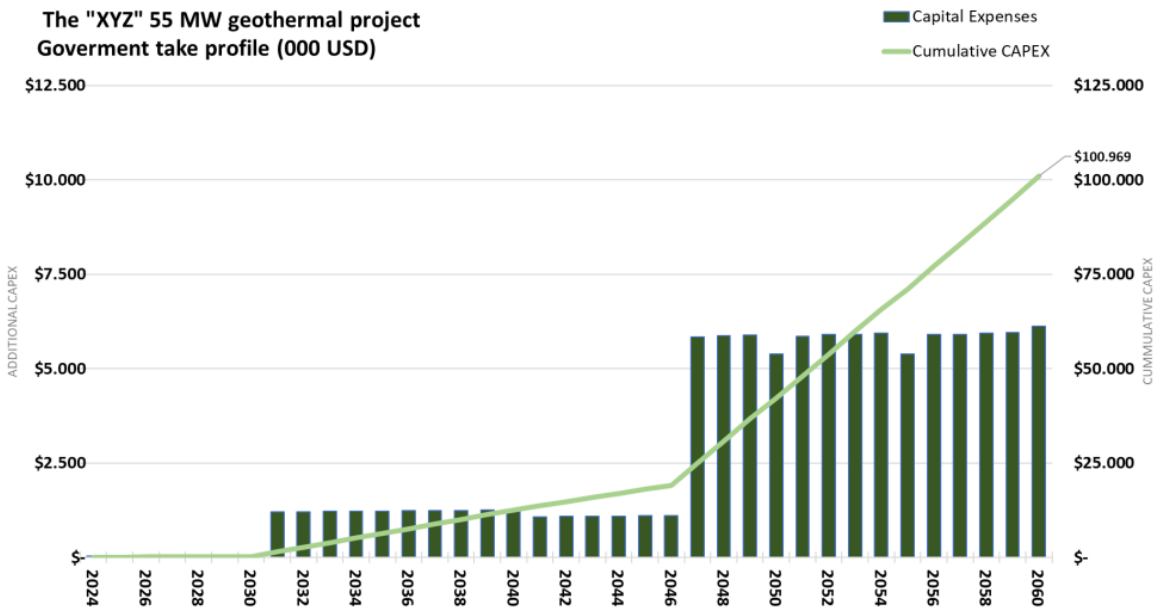


Figure 11: The profile of government takes from XYZ project.

4.3 Government perspectives

Figure 11 shows the profile of the government take from the project. The government take consisted of corporate tax payment and non tax (royalty, production bonus, and fixed fee) payment. During the exploration-development stage of project (2024-2030), government only obtained insignificant take from the project since the project does not generate revenue yet. While the early stage of the operation

(2031-2046), government obtain the take from the payment of non-tax component since the project do not pay the tax yet. It derived by condition that project has negative taxable income due to depreciation and interest payment. The notable government take records after 16 years of operation since the project already fulfill the debt repayment period. The cumulative government take along project equals to 100 MUSD. It indicates positive condition that fulfill the requirement criteria for government. The XYZ project could provide the feasible condition from government perspective.

5. CONCLUSION

The XYZ geothermal project shows unfeasible financial condition although already implement the ceiling with staging tariff scheme. The project does not provide fair reward to the equity that reflected through negative project-equity NPV and low project-equity IRR. Furthermore, the staging tariff scheme affects to the project cash flow profile that impacting to the ability of debt repayment. The tariff drops after 10 year of operation (stage 2 tariff) derive the drops of DSCR that triggered unfeasible condition for lender. The government perspective shows feasible condition. The path forward from this study is determine the required effort to provide the fair reward to equity and fulfillment of the lender requirement. This step is important to ensure the project sustainability.

REFERENCES

Abidin, M. Z., Rosdiana, H., & Salomo, R. V. (2020). Tax Incentive Policy for Geothermal Development: A Comparative Analysis in ASEAN. *Int. Journal of Renewable Energy Development*.

ACE. (2022). *Impact Analysis and Review on Governance of Renewable Energy Financing Schemes in ASEAN*. Jakarta: ASEAN Center of Energy.

ADB. (2014). *Unlocking Indonesia's geothermal potential*. Asian Development Bank.

ADB. (2018). *Developing Indonesia's Geothermal Power Potential*. Retrieved 12 22, 2022, from https://www.adb.org/news/features/developing-indonesia-s-geothermal-power-potential

Inherent Risks of Simultaneous Operations (SIMOPs) and Associated Mitigations in Patuha Geothermal Operations

Robertus Yulianto Kurniawan, Gilang Panatama Aziz,
Galih Satria, Ilen Kardani, and Sandi Ahmad Nurrachman

PT GEO DIPA ENERGI

julianto@geodipa.co.id, gilang@geodipa.co.id,
galih@geodipa.co.id, ilen.kardani@geodipa.co.id, nurrachman@geodipa.co.id

Keywords: Simultaneous operations; SIMOPs; risks and mitigations; safety; geothermal

ABSTRACT

Simultaneous Operations (SIMOPs) refers to the practice of conducting multiple operations concurrently within a specific area or facility. This approach is common in industries such as geothermal, oil and gas, construction, and manufacturing, where various activities must be carried out simultaneously to optimize resources and time. While SIMOPs can offer numerous benefits in terms of efficiency and productivity, it also introduces a range of potential risks that must be carefully managed to ensure the safety of all personnel, assets and the environment.

In the context of geothermal industry, SIMOPs typically involves activities like surveying, drilling, workover, production, operations, mobilizations, and maintenance, all occurring at the same time. The primary goal of SIMOPs is to optimize the use of resources, such as equipment, personnel, and time, while minimizing downtime and maximizing output. To achieve this, organizations must have a comprehensive understanding of the interdependencies between various operations and develop coordinated plans that account for these interactions.

This article will address the nature risks of the SIMOPs in Patuha Geothermal projects which will cover safety hazards, environmental risks, social issues, operational disruptions, and resources conflicts. Also, will discuss the best practices in managing SIMOPs from risk assessments, planning and coordination, communication flow charts, decision-making, people training and competency development, monitoring, and review. By leveraging the tools available in Health Safety and Environment (HSSE), QA/QC (Quality Assurance/Quality Control), and Project Management disciplines, organizations can create a robust framework to minimize the likelihood and consequences of these risks. This comprehensive approach ensures that all stakeholders are aware of potential challenges and are prepared to respond proactively, fostering a culture of safety and accountability throughout the project lifecycle.

1. INTRODUCTION

The Patuha Geothermal Area is located in West Java, Indonesia and has a potential of 400 MW. Patuha Geothermal Area has 10 production wells and 2 injection wells that are used to generate 1 PLTP unit with a capacity of 55 MW. To maximize the potential in the Patuha Geothermal Area, the development of PLTP unit 2 with a capacity of 55 MW is currently underway. To achieve this, it is necessary to drill 12 production wells, construct new pipelines and EPC PLTP.

Development activities must be carried out simultaneously with operational activities to optimize production targets. Simultaneous operations (SIMOPs) in the same area between development activities and operational activities are unavoidable. These activities can affect each other and increase the risk of the activities or create new risks that cause undesirable events or situations with negative impacts on safety, environment, property and other aspects.

Simultaneous operations (SIMOPs) that often occur during development activities are drilling activities carried out simultaneously with production well operations in the same wellpad area. Simultaneous operations (SIMOPs) conducted in the same wellpad can increase the risk of activities due to:

- Heavy vehicle and heavy equipment mobilization activities.
- Lifting activities.
- Potential H2S release due to drilling activities.
- Proximity of drilling activities to production wells.
- The presence of workers who do not understand the risks of simultaneous activities.

With the emergence of new risks outside of operational risks, PT Geo Dipa Energi (Persero) as the developer of Patuha Geothermal Area has developed SIMOPs Management. There are several best practices and lessons learned from SIMOPs Management implemented in the Patuha Geothermal Area that will be discussed in this paper.

2. SIMOPS MANAGAMENT

The first thing to do in managing SIMOPs is to limit and eliminate SIMOPs activities. SIMOPs activities should only be conducted on critical activities that have specific countermeasures in place. All potential hazards must be assessed and all possible events must be identified during SIMOPs activities. Controls to control risks must be specified in the SIMOPs document and prepared by authorized workers.

PT Geo Dipa Energi (Persero) has developed a standard operational procedure to manage SIMOPs. In managing SIMOPs in the Patuha Geothermal Area, communication between interested parties is the main concern. For every activity that will be carried out simultaneously, a SIMOPs plan must be prepared and developed by all parties involved. Workshop sessions can be conducted by a multi-disciplinary team consisting of management representatives, HSE specialists, engineers, operations representatives and maintenance representatives so that the SIMOPs plan developed is complete and comprehensive.

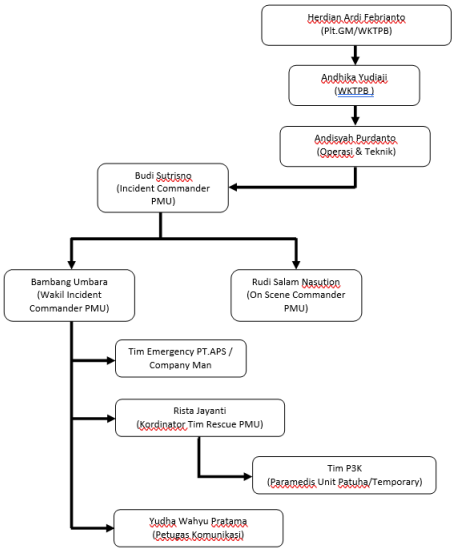
The SIMOPs plan should contain the duties and responsibilities of each party, scope of work, list of concurrent works, risk assessment of each concurrent work, emergency response plan, communication plan and permit to work system. Risk assessment is conducted based on an agreed matrix as per Figure 1. Mitigation strategies such as elimination of SIMOPs by scheduling and permitting processes, substitution of work processes with lower risk processes, separation of SIMOPs by distance and separation of SIMOPs by barricades, isolation or engineering are the main outputs of the developed SIMOPs plan.

MATRIKS RISIKO			LEVEL DAMPAK				
			1	2	3	4	5
			Sangat Kecil	Kecil	Sedang	Besar	Sangat Besar
LEVEL KEMUNGKINAN	5	Sangat Tinggi					
	4	Tinggi					
	3	Sedang					
	2	Kecil					
	1	Sangat Kecil					

Tingkat Risiko	
Low	1
Medium	2
High	3
Extreme High	4

Figure 1: Risk matrix.

In addition, the emergency response plan and communication plan must be agreed upon to prevent any miss communication. Emergency response plans and communication plans adjust to the conditions of SIMOPs. However, the standard of Emergency response plan and communication plan can refer to Figure 2. where in this case emergency events must always be known/reported to KTPB.



Emergency Response Plan :

Nomor Kontak Keadaan Emergency di Lokasi

No	Nama	Perusahaan	Posisi ER	No HP	Komunikasi Lain
1	Herdian Ardi Febrianto	GDE Patuha 1	Plt.GM/WKTPB	0812 2752 xxx	
2	Andhika Yudiaji	GDE Patuha 1	WKTPB	0812 5297 xxx	
3	Hari Darmawan	GDE Patuha 1	Superintendent Steam Field	0878 2244 xxx	
4	Dedy Setiawan	GDE Patuha 1	Superintendent maintenance	0813 3030 xxx	
5	Budi Sutrisno	GDE PMU 2	Incident Commander PMU	0822 1674 xxx	
6	Budi Setiawan	GDE PMU 2	On Scene Commander PMU	0896 812 xxx	
7	Bambang Umbara	GDE PMU 2	Wakil Incident Commander PMU	0812 2267 xxx	
8	Rudi Salam Nasution	GDE PMU 2	Wakil Incident Commander PMU	0812 2199 xxx	
9	Rista Jayanti	GDE PMU 2	Koordinator Tim Rescue PMU	0857 4332 xxx	
10	Yudha Wahyu Pratama	GDE PMU 2	Petugas Komunikasi	0812 3567 xxx	
11	Hermansyah	GDE Patuha 1	Paramedis Unit Patuha	0817 2811 xxx	
12	Diki	GDE Patuha 1	Paramedis Unit Patuha	0813 2355 xxx	
13	Indra	GDE Patuha 1	Paramedis Unit Patuha	0878 2103 xxx	
14	RSUD Soreang			(022) 5891355	
15	RS. Santosa Kopo			(022) 21001700	

Figure 2: Communication flow chart and emergency number.

Everyone involved in SIMOPs must exercise good judgment, promptly respond to any unusual situation, discontinue operations if a potentially hazardous situation arises, and recommend changes to reflect prevailing operational conditions (Singh, 2016). The structure within SIMOPs Management is led by a SIMOPs Leader who is assisted by a SIMOPs Coordinator and SIMOPs Controller as well as Company Representatives who are key personnel for each activity involved in SIMOPs.

The responsibilities of the SIMOPs Leader were as follows:

- Review the SIMOPs Plan and monitor the implementation of SIMOPs.
- In charge of coordinating SIMOPs Coordinators in one facility that conducts Simultaneous Operation activities. At least once a day coordinate with SIMOPs Coordinators.
- The SIMOPS Leader is responsible for the follow-up completion of all planned SIMOPs activities and reports to the Project Manager / General Manager for any deviations that occur and potentially jeopardize the overall SIMOPs activities.
- In the event that there is no agreement on HSSE aspects or the proposed SIMOPs schedule, the matter should be discussed with the Project Manager/General Manager; and
- The SIMOPs Leader is a designated personnel with a minimum position of Superintendent. The SIMOPs Leader may be concurrently employed by Company Representatives.

The responsibilities of the SIMOPs Coordinator were as follows:

- In charge of ensuring that the work under his/her responsibility has been implemented SIMOPs in accordance with the SIMOPs Plan that has been made.
- Checking the parts that have a high risk as a trigger for accidents using the SIMOPs checklist form.
- Always coordinate with the SIMOPs Leader and other SIMOPs Coordinators to ensure the implementation of SIMOPs runs in accordance with the SIMOPs Plan that has been made.
- Personnel on duty at the facility being worked on;
- Personnel with minimum Superintendent level on facilities owned by contractors.

The responsibilities of the SIMOPs Controller are to assist the SIMOPs Leader in documenting the SIMOPS Plan, SIMOPS Log and SIMOPS Plan Checklist.

The responsibilities of the Company Representative are as a liaison between the company and the contractors / implementers involved and provide input (advice) related to the implementation of Simultaneous Operations in an area.

The SIMOPs plan must be known by the General Manager/KTPB in the Patuha Geothermal Area and socialized to all workers involved. Monitoring of the SIMOPs plan is carried out by the SIMOPs Coordinator and SIMOPs Leader to ensure all activities and mitigation strategies are on track. In addition, monitoring of the SIMOPs plan also aims to update risks that were not previously identified.

In addition to being an administrative risk control tool, PTW is also a communication tool for SIMOPs leader, SIMOPs Coordinator and Company Representative to inform the situation and condition of various activities in the Wellpad V area/overhandled area. The PTW system was not only easy to use, but comprehensive in covering the mitigations needed to allow safe execution of multiple activities (Schmidt, 2009).

3. SIMOPS IN PATUHA AREA

3.1 Case 1 : Simops operation, drilling & well test

SIMOPs activities between operations, drilling and well testing were conducted at Wellpad V. Figure 3. Is a simplified work flow created by these SIMOPs activities and the shading shows the most critical interface of SIMOPs activities.

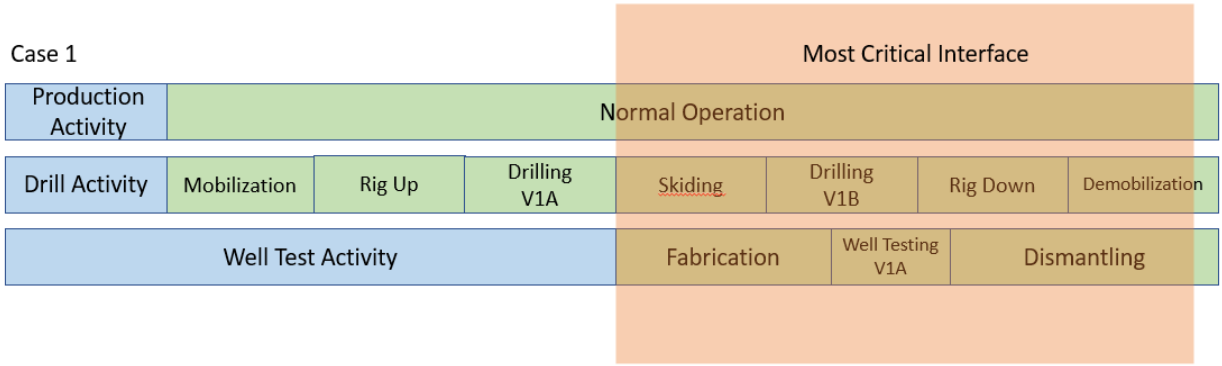


Figure 3: Most critical interface case 1.

Normal operation activities include well monitoring, steam quality sampling and preventive predictive maintenance. In the early stages of SIMOPs, only normal operations and drilling of the first well, V1A, took place. After the completion of drilling the first well, well test activities began. As more activities were added to SIMOPs, the risks of the work increased. Table 1. explains the risks and risks control that develop on the SIMOPs.

Table 1: SIMOPs risks and control case 1.

Simultaneous Operations	Example	Risks	Risk Level	Mitigation
Production operations	Monitoring parameters of the production process	H2S release, stumble, pressure, weather etc.	Medium	PTW, gas detector, safety sign, PPE etc.
	Pulling sample of the fluids	H2S release, stumble, hot surface, noise, spill, weather etc.	Medium	PTW, gas detector, safety sign, PPE etc.
Multiple maintenance operations	Hot work on part of the process	Fire, dropped object, welding fumes, weather etc.	High	PTW, gas detector, weld mask, respirator, safety sign, fire

Simultaneous Operations	Example	Risks	Risk Level	Mitigation
				extinguisher, PPE, etc.
Drilling operations	Rig moving, rig up and down, drilling, lifting, etc.	H2S release, hot surface, high voltage, dropped object, steam kick, working at height, noise, spill, fire, weather, social issue etc.	Extreme High	PTW, JMP, gas detector, weld mask, respirator, safety sign, fire extinguisher, BOP, PPE, full body harness, scaffolding, socialization, medic etc.
Well testing operations	Hot work on pipe fabrication, steam blowing, etc.	H2S release, hot surface, dropped object, steam kick, working at height, noise, spill, fire, weather, social issue etc.	Extreme High	PTW, gas detector, weld mask, respirator, safety sign, fire extinguisher, PPE, full body harness, scaffolding, socialization. medic etc.

Control plan efforts in the form of spacing and barrier installation are carried out to prevent interference between activities shown in Figure 4 and Figure 5.

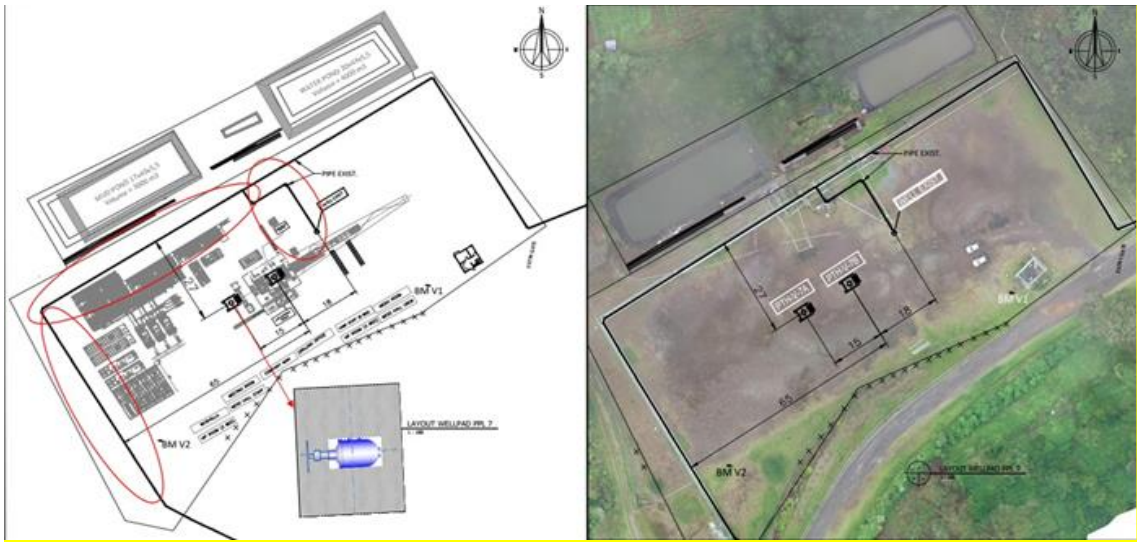


Figure 4: Rig layout.

After taking all precautions, SIMOPs between drilling and well testing remained impossible. Extreme weather conditions, such as strong winds, caused the steam released from the LECM move towards the rig, impairing worker visibility. Lifting activities could not be carried out and the driller could not see the activities on the rig floor. After communication by all parties, the well test activities were decided to be postponed until the V1B well drilling work was completed.

Figure 5: SIMOPs case 1 layout.

In the SIMOPs plan, it has been determined that there are no activities that can be carried out in SIMOPs, namely production equipment overhaul work at Wellpad V and well washing of existing wells. If such work is required to be carried out, SIMOPs must be temporarily suspended. However, the specified prohibition still cannot handle the increased risk due to interference between jobs. This is due to the absence of a guideline in determining activity restrictions. One of the tools that can be used as a guideline is the Matrix of Permitted Operations (MOPO).

MOPO is a matrix or a set of matrices that maps operational activity against foreseeable situation that could compromise safe operating limit when they arise. These situations are commonly identified from the thread and escalation factor of major accident hazard and an assessment of other operations and activities that could contribute to escalation of an accident. The foreseeable situation that could compromise safe operating limit usually grouped by:

- SIMOPs, where large work parties under different management carry out work which result hazards that may impact the other.
- External influence, e.g. extreme weather, lack of visibility and security issue.
- Inactive safeguard or protection system.

The objective of a MOPO is to maintain an acceptable level of risk for the operations. The matrix shall identify and differentiate between unpermitted condition and proceed with caution condition. Traffic lighting (e.g. red for unpermitted condition, yellow for proceed with caution, green for permitted condition) is a useful tool to highlight the different condition.

3.2 Case 2 : SIMOPs CTU, Construction & Fabrication

SIMOPs activities between tie-in, well intervention and well test preparation were conducted at Wellpad V. Figure 6. Is a simplified work flow created by these SIMOPs activities and the shading shows the most critical interface of SIMOPs activities.

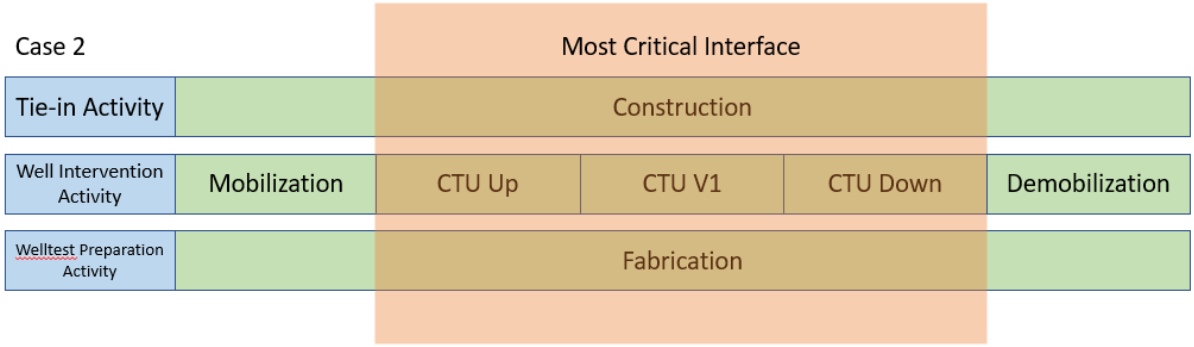


Figure 6: Most critical interface case 2.

This tie-in activity is a construction activity to build a production pipeline from the wellheads of V1A and V1B wells to the main SAGS to increase the steam supply for geothermal power plant generation. At the same time, the neighboring well, V1, is also scheduled for well maintenance using the coil tubing unit (CTU) method to clean the wellbore. As for the well test work due to land limitations and time efficiency, the fabrication work was carried out at Wellpad V because previously the V1A and V1B well tests had been carried out. Table 2. explains the risks and risks control that develop on the SIMOPs.

Table 2: SIMOPs risks and control case 2.

Simultaneous Operations	Example	Risks	Risk Level	Mitigation
Tie-in Activity	Civil construction, excavation, etc.	Fell, undermining of nearby structures causing their collapse into the excavation, damaged to underground services	High	PTW, safety sign, PPE, etc.
	Hot work on pipe fabrication, lifting etc.	Fire, dropped object, welding fumes, working at height, weather etc.	High	PTW, gas detector, weld mask, respirator, safety sign, fire extinguisher, PPE, etc.
Well Intervention Operations	CTU moving, CTU up and down, CTU, lifting, etc.	H2S release, hot surface, high voltage, dropped object, steam kick, noise, working at height, spill, fire, weather etc.	Extreme High	PTW, JMP, gas detector, weld mask, respirator, safety sign, fire extinguisher, BOP, PPE, full body harness, scaffolding, medic etc.
Well test Preparation	Hot work on pipe fabrication, lifting etc.	Fire, dropped object, welding fumes, weather etc.	High	PTW, gas detector, weld mask, respirator, safety sign, fire extinguisher, PPE, etc.

Control plan efforts in the form of spacing, barrier installation and structured division of work areas to prevent interference between activities are shown in Figure 7. By appropriately mitigating SIMOPs, tie-in, well intervention and well test preparation activities carried out at Wellpad V were carried out on time safely and securely, resulting in a time advantage that has an effect on increasing revenue because the V1 well which has been carried out wellbore cleaning and tie-in activities can be completed quickly so that the V1A and V1B wells can be utilized in a timely manner to maximize output and minimize downtime.

Figure 7: SIMOPs case 2 layout.

4. RESULT

In case 1 shows that the plan didn't go well because several things such a nature factor, a hardly wind that blow the steam towards the rig it's too dangerous and it should stop the activity and in case 2 shows that the SIMOPS run well. SIMOPs need appropriate control management systems for effective use of resources to minimize risk. An inherent risk assessment for all the activity and the mitigation plans should be identifying on every scope of work. By optimize resources, identifying the risk and use SIMOPs best practices can achieve the goals minimizing downtime and maximizing output. For improvement on the case MOPO application it's a mandatory especially for the operations with extreme high risk level to identifying the SIMOPs risk with comprehensively, not just defined the boundary operations.

Mastering SIMOPs requires continuous improvement, learning from past experiences, and implementing effective strategy. By regularly reviewing and analyzing operations, sharing lessons learned, and implementing best practices, organizations can enhance safety, reduce risks, and ensure successful SIMOPs. It is crucial to prioritize safety while optimizing efficiency to achieve operational excellence in complex and dynamic environments. One thing about success of SIMOPs is the comprehensive and clear communication between the SIMOPs organization (SIMOPs Leader, Coordinator, Controller, Company Representative) and all workers involved.

REFERENCES

Baybutt, Paul.: Simultaneous Operation (SIMOP) Review: An Important Hazard Analysis Tool, AIChE Process Safety Progress, 36, 1 (2017).

Fan, Hongjun et al.: Safety Philosophy and Risk Analysis Methodology for LNG Bunkering Simultaneous Operation (SIMOPs): A Literature Review, Safety Science, 136 (2021).

Internal SIMOPs Document

Nur, Suardi et al.: Evidence on Optimal Risk Allocation Models for Indonesian Geothermal Project Under PPP Contracts, Utilities Policy, 81 (2023).

Schmidt, Kevin.: SIMOPS During Construction, Commissioning, Startup, and Operation of the World's Largest LNG Project, International Petroleum Technology Conference 13705 (2009).

Singh, Barinder.: SIMOPs – Simultaneous Operations in Oil and Gas Installations and Work Sites, International Journal of Innovative Science, Engineering & Technology, 3, 3 (2016).

Spada, Matteo et al.: Comparative Accident Risk Assessment with Focus on Deep Geothermal energy System in the Organization for Economic Co-operation and Development (OEDC) Countries, Geothermics, 95 (2021).

Lesson Learned from Eco-friendly Oyster Mushroom Cultivation Pangalengan

Ismail Hidayat, Firman Hidayat, Rahmat Hidayat, and Taufik Hidayat

Star Energy Geothermal (Wayang Windu), Limited

ismail.hidayat@starenergy.co.id

Keywords: Oyster mushroom cultivation, Sustainable program, Geothermal

ABSTRACT

Geothermal development can't be separated from any social aspects, community development is an important aspect needs to be managed properly. Penta-helix an approach by prioritizing all parties involved such as government, education, non-governmental organizations, media, society, companies that need to synchronize all their needs by prioritizing programs.

In order to run the program smoothly it's required social mapping study, the result as reference to prioritization program as well creation of long-term improvement to-be sustainable program, the successful programs become examples of the development of similar programs to increase their impact.

Budidaya Jamur Tiram Ramah Lingkungan – BURAMLI, the oyster mushroom cultivation program carried out by **Villa Mushroom Agrifarm** in Pangalengan which was developed starting in 2014 has developed become independent business as well a foster father for prospective developers of similar mushroom cultivation in other places. Sustainable mushroom cultivation so that it is independent and can pass on its knowledge to become an example for candidates implementing the same program in order to reduce the impact of potential failures, especially in the early phases of development, which of course have quite a lot of obstacles.

1. INTRODUCTION

Corporate Social Responsibility (CSR) programs are common practice in the geothermal industry. CSR programs are usually carried out to address social problems in the community, increase the economic and environmental potential in an area and also to meet the company's operational requirements. However, actually CSR is not only to meet requirements or regulations but also to demonstrate the quality of performance of its business strategy. One of the CSR programs for the purpose of community empowerment that is superior to Star Energy Geothermal (Wayang Windu), Limited (SEGWWL) is the Environmentally Friendly Mushroom Cultivation Program (BU RAMLI) managed by Villa Mushroom Agrifarm (VMA) as the community group that is the beneficiary of the program CSR. The location of VMA activities in mushroom cultivation is located in Situ Cileunca, Dangdang Village, RT.01/RW.01, Pulosari Village, Pangalengan District, Bandung Regency, West Java Province.

2. BACKGROUND AND LITERATURE REVIEW

Star Energy Geothermal (Wayang Windu), Limited (SEGWWL) is a geothermal power plant company operating in Indonesia since 1994 and part of the Star Energy Geothermal (SEG) Group, with a total installed capacity of 875 MW. SEGWWL operates under a Joint Operation Contract with PT Pertamina Geothermal Energy in Margamukti Village, Pangalengan District, Bandung Regency, West Java. SEGWWL is registered as a permanent establishment in Indonesia and conducts its business under the laws of the British Virgin Islands. SEGWWL manages two geothermal power plant units (PLTP), namely Unit-1 with a capacity of 113.5 MW and Unit-2 with a capacity of 117 MW (Sustainability Report of Star Energy Geothermal (Wayang Windu), Limited year 2022).

SEG, as the largest producer of geothermal energy in Indonesia, strives to encourage community self-sufficiency, preserve the environment, improve operational security and work safety. This is aligned with efforts to produce reliable renewable electrical energy in Indonesia. Based on the results of a social mapping study around the SEGWWL operational area, 3 groups of vulnerable people were found, namely farm workers, tea plantation workers and youth. Some of the main social problems are the

limited ability of the community to improve their standard of living, the lack of employment opportunities and conflicts over land use which have the potential to cause landslides and floods.

Efforts made by SEGWWL in solving these social problems, in the form of implementing an inclusive CSR program involving multi-stakeholders or known as the Pentahelix Strategy. The Pentahelix strategy is a concept of involving elements of government, academia, media, community or society, and business entities or actors working together to coordinate and commit to developing the local potential of villages and rural areas. The local potential of villages and rural areas that still prioritizes local wisdom and local resources.

The Pentahelix strategy aims to accelerate the process of community independence, both in the economic sector (such as ownership of production assets, entrepreneurial knowledge and the ability to build networks), the environmental sector (the formation of an energy-efficient and environmentally friendly mentality, knowledge of managing organic and inorganic waste, and a culture of planting and caring for trees) and the education sector (increasing the level of education, eradicating illiteracy and a culture of community literacy), where these three things are contained in the three pillars approach of SEG. Multi-stakeholder involvement is carried out in every CSR program activity which consists of training (soft skills and technical skills), technical assistance, institutional capacity strengthening, easy access to markets and finance as well as providing technical support such as infrastructure, production facilities and technology. The aim of this strategy is to improve people's livelihoods by increasing their skills and knowledge about their business, changing their entrepreneurial mindset, increasing the level of community education, maintaining natural sustainability and maintaining community acceptance of the continuity of companies and businesses by involving multi-stakeholders.

One of the CSR programs from SEGWWL which operates in the economic sector based on local village potential and is considered capable of solving major social problems in Pangalengan District is Environmentally Friendly Mushroom Cultivation (BU RAMLI). The common mushroom commodity cultivated in the BU RAMLI program is oyster mushroom, where this mushroom is a type of edible mushroom that is included in the type of mushroom that is often consumed and is included in a functional food source. Apart from that, the cultivation process is quite easy and the weather conditions in Pangalengan are humid and cool like the original habitat of oyster mushrooms, which are the main reasons why the people of Pangalengan choose to cultivate this mushroom. Oyster mushrooms are cultivated by inserting oyster mushroom seeds into a planting medium called baglog. This baglog is in the form of a tube made of a clear plastic bag filled with sawdust with some other mixture, then placed in a semi-permanent building (commonly called a mushroom kumbung) that is shaded (minimum direct sunlight), inside of which there are vertical shelves which are usually made of wood. of bamboo for a place to put baglog mushrooms. When the oyster mushrooms start to grow from inside the baglog, the oyster mushrooms are identical with their white, wide shape, growing in clusters like an umbrella, and their shape resembling an oyster shell. The part of the oyster mushroom that is harvested for sale by the community is the upper part of the mushroom in the shape of an oyster shell, where the majority of the harvest is usually sold fresh or raw, either slightly wet or dried. The economic value of the oyster mushroom lies in its nutritional content, where the protein contained in the oyster mushroom averages 3.5% to 4% of the wet weight of the mushroom. The content is two times higher than cabbage and asparagus. In dry conditions, the protein content of oyster mushrooms reaches 19% to 35%. This value is higher when compared to rice, wheat and cow's milk (http://lipi.go.id/lipimedia/jamur-pangan-alternatif-unggul/20310).

The BU RAMLI program, in addition to having a target of economic independence for program beneficiaries, also encourages efforts to preserve the environment through a responsible production process, which is in line with goal 12 of Indonesia's Sustainable Development Goals (TPB) which is aligned with the Sustainable Development Goals (SDGs) namely Responsible Consumption and Production. This conservation effort is proven in the process of mushroom cultivation which utilizes waste mushroom growing media (baglog sawdust) as fuel for the mushroom baglog heating furnace (autoclave) while the remaining baglog which cannot be used as fuel, is used as a mixture of fertilizer for agriculture (zero waste). The mushroom cultivation process as a whole is an effort to create food

security at the local level by utilizing limited land so that it does not raise issues of land conversion that usually occurs in the agricultural sector in the Pangalengan District.

Figure 1: Oyster Mushrooms that come out of the baglog.

Efforts to manage waste and use limited land to obtain economic value from oyster mushroom cultivation will certainly not be successful without the involvement of multi-stakeholders, especially the community as beneficiary subjects of the CSR program. The active role of the community in managing and developing mushroom cultivation is the main capital for the success of sustainable environmentally friendly oyster mushroom cultivation. One of the figures in the BU RAMLI program who has become the 'engine' of the mushroom cultivating community is Taufik Hidayat. Taufik Hidayat is a young man from the area who graduated from the SEG Scholarship program – Bandung State Polytechnic (Polban), who had worked for a multinational company in Jakarta but chose to resign to become an entrepreneur in his hometown, Pulosari Village. The persistence of Taufik Hidayat in developing oyster mushroom cultivation is also strengthened by his social spirit in inviting the surrounding community to participate in oyster mushroom cultivation so as to create new entrepreneurs and encourage new jobs.

3. CSR PROGRAM DESCRIPTION

This environmentally friendly mushroom cultivation program was carried out on the basis of findings on the potential for mushroom cultivation in Pulosari Village in the 2015 social mapping and also as a follow-up to efforts to solve the unemployment problem that existed at that time. In 2018, SEGWWL initiated the program by conducting a Focus Group Discussion (FGD) with the Pulosari Village community and related stakeholders. The FGD decided to establish a mushroom cultivation program in the Pulosari Village area and at that time the Villa Mushroom Agrifarm (VMA) group was selected to become SEGWWL's target group in the economic empowerment program.

Before joining the Environmentally Friendly Mushroom Cultivation Program (BU RAMLI), the VMA group had various internal problems within the group, especially in the ability to cultivate mushrooms, as summarized in the following Table 1.

Table 1: Program Achievements of VMA Group.

Program Achievements	2014 (Nov)	2015	2016	2017
Cultivation success rate	0%	10%	20%	45%
Number of replication groups	0	0	0	0
Number of people trained in mushroom cultivation per year	0	0	0	0
Amount of oyster mushroom production	0 Ton	2 Ton	3 Ton	12 Ton
The amount of waste that is reused	0	0	0	0
The amount of greenhouse gas reduction resulting from the cultivation process*	0	0	0	0
Gross revenue per year (in million)	Rp 0	Rp -45,000	Rp -25,000	Rp 100,000

* Based on the report on the results of verification of Environmentally Friendly Innovations in the BU RAMLI (Environmentally Friendly Mushroom Cultivation) program by the Sepuluh Nopember Institute of Technology (ITS)

The VMA group started cultivating oyster mushrooms in November 2014 and at that time all members did not have the ability or knowledge at all regarding oyster mushroom cultivation. This resulted in their mushroom cultivation success rate of only 10% in 2015, crop failures during that year caused the VMA Group to lose around IDR 45,000,000. In fact, this problem continued until 2016, even though they succeeded in obtaining a harvest of 3 tons, in terms of gross income they still lost money because they had to pay the rent for the mushroom house and the repair of the mushroom house which was damaged by strong winds. At the end of 2016, the head of the VMA group (Taufik Hidayat) tried to find business capital by participating in the Mandiri Young Entrepreneur program organized by Bank Mandiri and managed to win 2nd place at the national level and business capital of IDR 100,000,000. The capital is then used to pay off debts, re-design mushroom kumbung so that humidity is maintained at 80% and the rest is to buy mushroom baglogs. This effort was able to increase the success rate by 45% in 2017, but because they still don't understand how to manage business cash flow, the money from this harvest is not properly allocated and recorded.

Until 2018, the VMA group became a SEGWWL CSR target group, at that time the group received benefits that had never been obtained before, namely routine assistance by the Community Development Officer (CDO) as a SEGWWL representative in fostering community groups. During the VMA being fostered by SEGWWL from 2018 to the present (2023), there have been many significant positive changes in the VMA institution and in the mushroom cultivation replication group fostered by the VMA. These positive changes are the result of routine assistance, training and capacity building for the VMA group, network expansion and especially the provision of venture capital. The positive changes in question are:

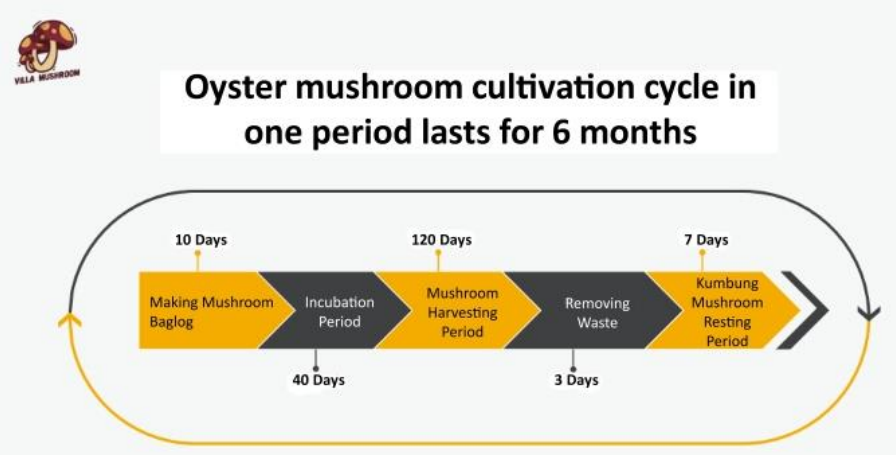


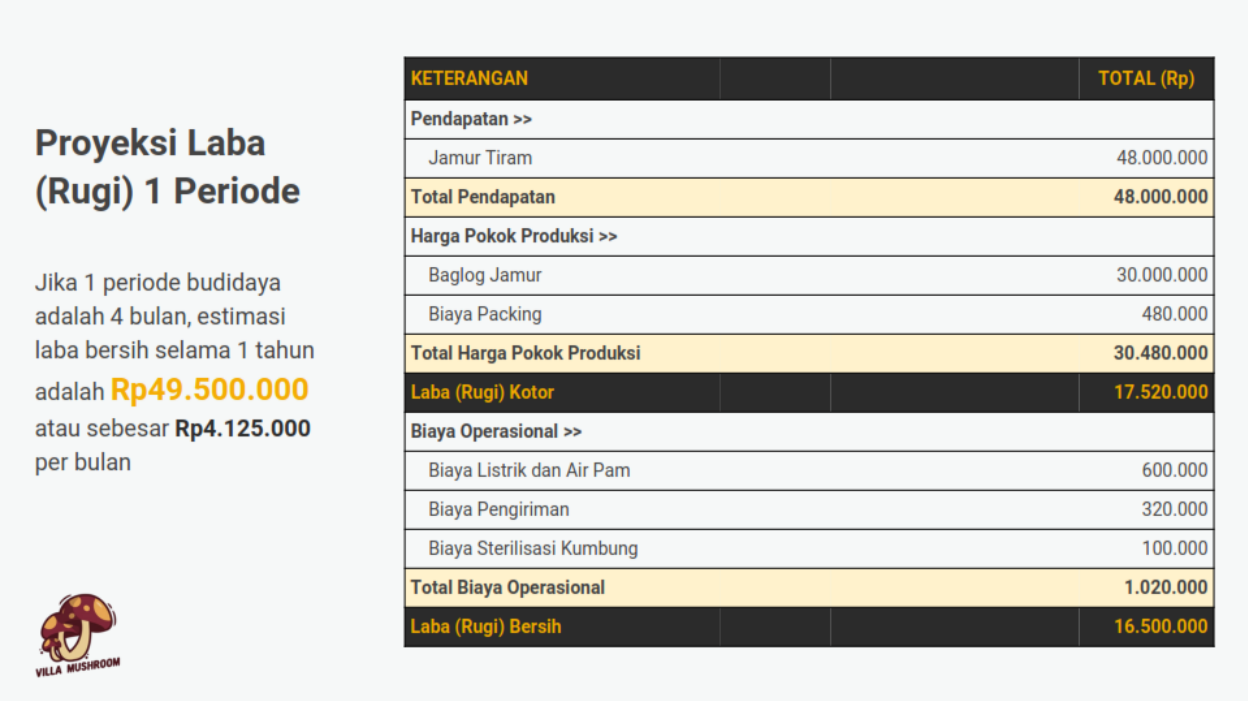
Figure 2: Understanding of the oyster mushroom cultivation cycle.

Figure 3: Development of mushroom products.

Figure 4: Processing of mushroom products.

Figure 5: Mushroom cultivation educational activities.

Before becoming the SEGWWL CSR target group, the VMA group did not have the ability to cultivate at all, but Figure 2 shows that they already understand the oyster mushroom cultivation cycle. Even in Figure 3, the VMA group was able to make their own oyster mushroom seeds and make mushroom baglogs, where previously they had to buy baglogs from outside the Pangalengan area. In addition, not all of the VMA group's crops are sold raw, but are processed into mushroom satay, mushroom dumplings, mushroom fat and crispy mushrooms (Figure 4). Even though the VMA group has become a growing business group, they are still trying to share their knowledge and experience in oyster mushroom cultivation to the wider community through educational activities on mushroom cultivation (Figure 5.) which are conducted both offline and online. They are even able to make profit/loss projections (Figure 6.) in mushroom cultivation as an illustration to their potential investors.



KETERANGAN	TOTAL (Rp)
Pendapatan >>	
Jamur Tiram	48.000.000
Total Pendapatan	48.000.000
Harga Pokok Produksi >>	
Baglog Jamur	30.000.000
Biaya Packing	480.000
Total Harga Pokok Produksi	30.480.000
Laba (Rugi) Kotor	17.520.000
Biaya Operasional >>	
Biaya Listrik dan Air Pam	600.000
Biaya Pengiriman	320.000
Biaya Sterilisasi Kumbung	100.000
Total Biaya Operasional	1.020.000
Laba (Rugi) Bersih	16.500.000

Figure 6: Projection of Profit/Loss of Mushroom Cultivation in 1 year.

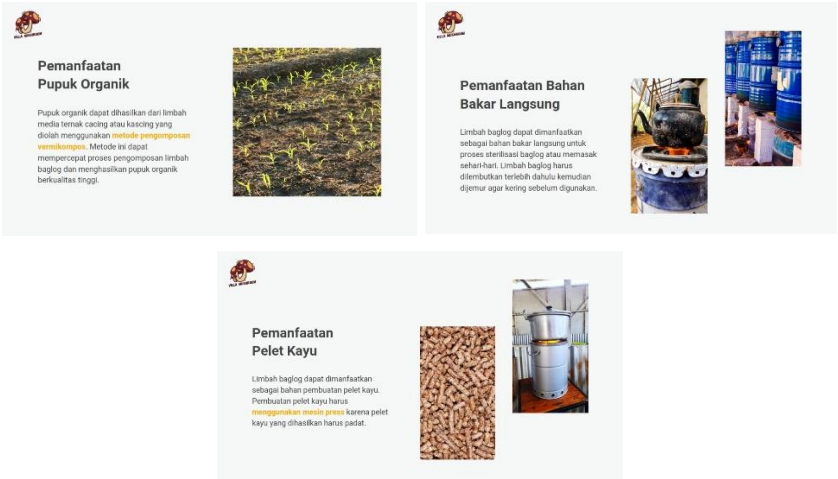


Figure 7: Re-use of generated waste.

4. RESULT AND DISCUSSION

The results obtained from the RAMLI BU Program for 5 years (2018-2022) are as follows:

Table 2: Results of RAMBLI BU Program (2018-2022).

Program Achievements	2018	2019	2020	2021	2022
Cultivation success rate	70%	75%	80%	90%	90%
Number of replication groups	0	0	7	10	12
Number of people trained in mushroom cultivation per year	0	0	120	200	310
Amount of oyster mushroom production	63 Ton	77 Ton	81 Ton	100,8 Ton	42 Ton

Program Achievements	2018	2019	2020	2021	2022
The amount of waste that is reused	0	0	0	128 Ton	84 Ton
The amount of greenhouse gas reduction resulting from the cultivation process*	948 kg CO^2eq	0	362.4 kg CO^2eq	1,898 kg CO^2eq	1,243 kg CO^2eq
Gross revenue per year (in million)	Rp 945,000	Rp 1,116,000	Rp 1,134,000	Rp 1,584,000	Rp 960,000

* Based on the report on the results of verification of Environmentally Friendly Innovations in the BU RAMLI (Environmentally Friendly Mushroom Cultivation) program by the Sepuluh Nopember Institute of Technology (ITS)

Figure 8: Awards earned by the VMA group.

The lessons learned from the result are:

1. The VMA group was able to increase the success of mushroom cultivation due to the training they received while being a SEGWWL CSR target group and the VMA's ability to evaluate each activity on a trial and error basis.
2. Public interest in studying oyster mushroom cultivation is increasing every year.
3. The success of mushroom cultivation management in terms of economic improvement and waste management was awarded by stakeholders (Figure 7 and 8).
4. Reducing the amount of production needs to be done when market demand decreases.

Based on the monitoring and evaluation results of the BU RAMLI Program for 2022, the following recommendations can be considered:

1. Increase the number of replication groups to increase the production capacity of oyster mushrooms.
2. Technological engineering needs to be done to increase efficiency in each cultivation process.

5. CONCLUSION

Based on the results of the program's achievements for 5 years (2018-2022) it can be concluded that:

1. From an economic perspective, the VMA group already has the ability to expand marketing, owns complete production assets, is able to think strategically, and continuously disseminates their knowledge to the public.
2. In terms of the environmental aspect, the VMA group has been able to process waste from mushroom cultivation, and even use it as a form of saving production costs.
3. The involvement of several stakeholders is able to play a role in increasing the development of the VMA group as well as covering the lack of roles of other stakeholders in the BU RAMLI Program.
4. The journey of the RAMLI BU Program from 2018-2022 shows that the VMA Group is considered to be independent and capable of carrying out mushroom cultivation activities without the help of SEGWWL.

The lessons learned from this case are as follows:

1. The provision of assistance should be carried out after the beneficiaries have received capacity building training in terms of cultivation.
2. Replication groups that receive free training and capital are more often unable to survive in the first year of cultivation due to a lack of sense of belonging to the sustainability of their own mushroom cultivation.
3. In a CSR program, there must be a key figure who acts as an encouragement and motivation for other group members.
4. Good planning includes social mapping as a basis for planning and FGDs with the community and stakeholders at the CSR target locations have a positive initial impact.

ACKNOWLEDGEMENT

Thank you to Taufik Hidayat for your help in discussing and providing supporting data for writing this paper. For further information related the Villa Mushroom Agrifarm (VMA) group, please visit https://villamushroom.com/

Managing Social Risk and Impact Through Stakeholder Engagement and Social Empowerment Programs and its Impact Evaluation to the Society

Erwin Patrisa Floris and Muhammad Roza

SUPREME ENERGY

erwin-patrisa@supreme-energy.com, m-roza@supreme-energy.com

Keywords: Social Risk and Impact, Stakeholder Engagement, Impact Evaluation, Social Return on Investment

ABSTRACT

Almost in every project development, either conducted by the public authority or private sector may facing the environmental and social risk. The social license to operate or some people call it social acceptance shall be obtain beforehand. The project social expert shall address and mapping the risk involved in either development or operation of the geothermal power plant. For this purpose, the project shall have adequate social documentation in terms of policy, procedures and guidelines. The implementation of those, the project social team delivers the social program that have an ultimate goal is to gain social acceptance. The program may vary from Stakeholder Management Program up to Sustainable Development Program. The risk mitigation may come up in the early stage of the project planning. In Solok Selatan, where the Muara Laboh Geothermal Power Plant (MLGPP) operated by Supreme Energy Muara Laboh, the project challenge is to ensure the community that the project would delivers the advantages, such as: the opportunities of employments and involvement of local supplier, not mention also the direct and indirect impacts related to economic improvement. To adhere these advantages, the project delivers the social programs. Those programs divide into four big pillars, Education and Health, Economic Empowerment, Infrastructure Support and Community Relations. Solok Selatan Regency were among the three latest regency just formed in 2004 in West Sumatra Province. As with most new districts, the socio-economic and infrastructural problems are numerous

During the mitigation and followed by the stakeholder engagement, there were some issues raises. Transparency in terms of recruitment of local workers and local suppliers' involvement, socialization / site visits to other fields for the community, provision of training and support on village or sub-district infrastructure. Another issue according to respect to the local wisdom and it was utilizing by the project as an approach. The project utilized local wisdom symbols as communication tools and method. The traditional market or Pasar in bahasa or Balai or Pakan in Minang language plays a significant role in Solok Selatan region especially in Pekonina Village, the closest village to the MLGPP. Same as the other region West Sumatra, including Solok Selatan Region, become a trader is ingrained in the body of the Minang tribe. With these two factors, the project teams initiate to develop the traditional village market as one of the output of the Stakeholder Engagement and Social Empowerment Programs.

1. INTRODUCTION

Social acceptance is essential for the successful development and operation of geothermal power plants. The achievement of social acceptance enhances trust between local communities and geothermal developers/operators while scaling down potential conflicts, time delays, and reactions that could lead to increased costs. It also empowers a company's acceptance. In this context, the present work aims to present the different levels of social acceptance, relevant stakeholders, and the factors affecting it; the importance of public engagement; potential socioeconomic impacts deriving from the implementation of the power plant, and methods for their measurement; cases of controversy, in respect to acceptance of geothermal power plants; best practices from the side of developers and operators, focusing on the minimization of undesirable effects, the provision of benefits, and the enhancement of engagement procedures; and actions from the side of public authorities, based on the implementation of suitable legislative frameworks, educational activities, and participation in the development of required social infrastructure.

The objectives of the research utilizing Social Return on Investment is to seeks to reduce inequality and environmental degradation and improve wellbeing by incorporating social, environmental and economic costs and benefits.

2. STAKEHOLDER ENGAGEMENT PLAN AND SOCIAL EMPOWERMENT PROGRAM (SEP^2)

During the mitigation, transparency in terms of recruitment of local workers and local suppliers' involvement, socialization / site visits to other fields for the community, provision of training and support on village or sub-district infrastructure issues raised. PT. SEML responding to these issues by developing Stakeholder Engagement Plan that consist of Stakeholder Identification, Stakeholder Analysis, Stakeholder Engagement Program including its Grievance Mechanism. The Stakeholder Engagement Plan also identifies, understands and considers the concerns, interests and relationships of stakeholders; implement consultation activities that address specific needs of different stakeholders as documented in the stakeholder analysis. In terms of recruitment and local workers and local suppliers' verification to ensure those workers and suppliers are genuinely local, PT. SEML forms an independent community committee with the head of villages and head of sub-district, including police and military sub-district head as the member and patrons. PT. SEML also deploy the Community Relations Plan as the implementation of their Stakeholder Engagement Plan.

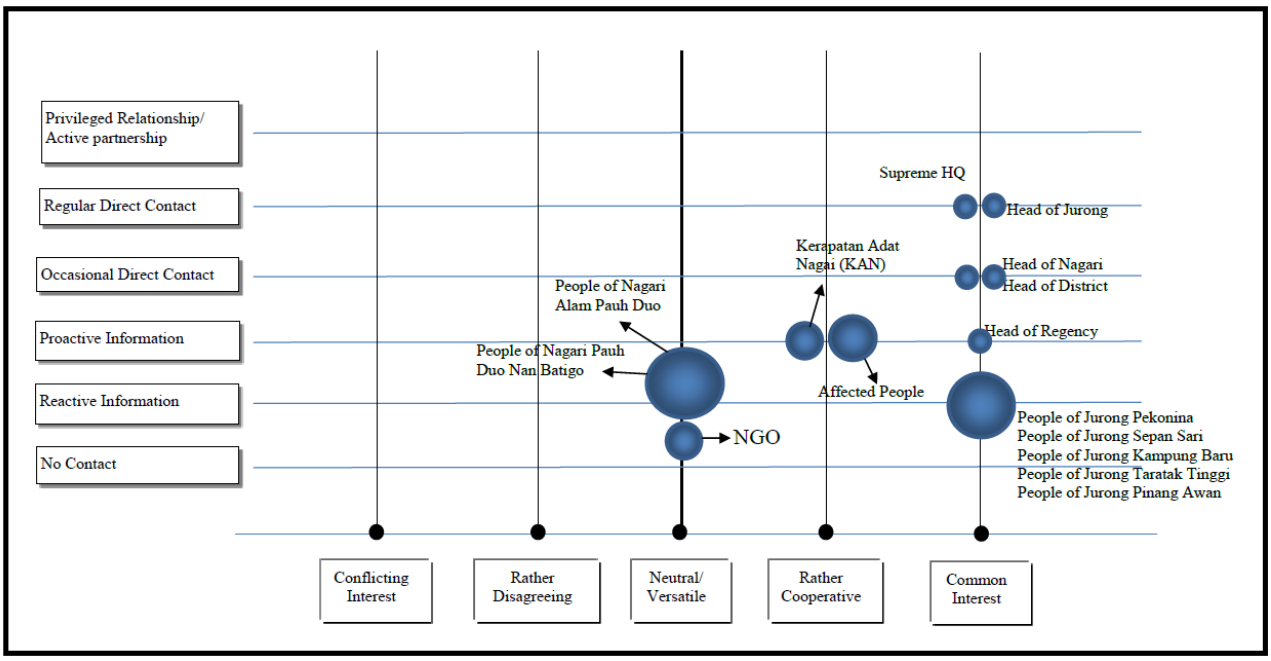


Figure 1: Stakeholder Identification and Analysis in Stakeholder Engagement Plan.

From Figure 1 that based from Cartesian diagram that the describe the roles and interests of internal and external stakeholders across a two-by-two grid shows the closest community have bigger interest and positive interest with development of Muara Laboh Geothermal Power Plant.

Besides that, to response to the community needs assessment and align with the Company values, PT. SEML also launch their Social Empowerment Program as part of Corporate Social Responsibility (CSR). CSR is a concept which we integrate the interests of society into our development plans, by accepting responsibility for the impact of our activities on stakeholders and on the environment, in an effort to improve the quality of life for our employees and their families as well as the local community and society at large. Supreme Energy will develop active and sustainable Corporate Social Responsibility programs based on social justice and mutual respect. By implementing this concept, we want to become a company that demonstrates a commitment to its stakeholders through socially responsible business practices and transparent operations. PT. SEML's CSR focused on four pillars,

which are: Education & Health, Infrastructure Support, Economic Empowerment and Community Relations.

We established three focused and complementary policies to support the program:

- Creating conducive ambiance and building relation with all parties in the local community where we operate in order to contribute to its development, to identify and solve any potential problems through a comprehensive Community Relations Policy.
- Providing resources to address community needs in order to widen the opportunities and access to the development of the community and its members through Community Social Services and Infrastructure Policy.
- Enhancing community capacity/income and self-sustaining capabilities through Community Empowerment Policy. This program aims to optimize and promote the use of resources by supporting technically and financially viable income, and generating activities leading to improved quality of life of the community. It is a social process that helps people gain control over their own lives. In simple words, making the neighborhood stronger by 'helping people to help themselves'.

Some of the programs have launched include: capacity building for the 'Project Affected People' skills in superior fields such as organic farming, poultry and fish farming, coffee cultivation and managing grocery stalls. Not only given training on business management, the program participants were also trained for business development that is monitored regularly. Supreme Energy also provides an integrated agricultural training area as a practical class.

Figure 2: CSR on Education & Health Pillars – Scholarship (a) and Blood Donor(b); CSR on Infrastructure Pillars - Road Improvement (c) and Welcome Gate of Regency (d); CSR on Economic Empowerment Pillars – Cooperative Group Coaching (e) and Coffee Marketing Support (f);); CSR on Community Relations Pillars – Customary Program Support (e) and Government Program Support (f).

2.1 Development of Village Traditional Market

To respect to the local wisdom and it was utilizing by the project as an approach, the project utilized it as communication tools and method. The traditional market or *Pasar* in bahasa or *Balai* or *Pakan* in *Minang* language plays a significant role in Solok Selatan region especially in Pekonina Village, the closest village to the MLGPP. Same as the other region West Sumatra, including Solok Selatan Region, become a trader is ingrained in the body of the *Minang* tribe. PT. SEML is located in the Pauh Duo Nan Batigo Village and Pekonina Village at Pauh Duo Sub-District. Pekonina formerly was just the sub-village in Alam Pauh Duo Village at Pauh Duo Sub-District.

During exploration phase in 2012, the SEML team realize that there was a potential economic growth initiator around Kampung Baru Sub-Village near the Pekonina Sub-Village. Since the nearest village market was above 10 km away, the trader starts to open their stalls beside the village access road

between Pekonina and Kampung Baru. This village access road also utilizes by PT. SEML as their entering point to the project sites. From the safety point of view, this situation potentially leads to near miss or accident case caused by the community and company activities.

After several discussions with the head of village, head of sub-villages and community leader, it was concluding to support the development of new traditional village market around Kampung Baru. In late 2012, the community informs that the land for the village market was ready and PT. SEML requires to support to develop the market. Starting from 2013 to 2014, the development of the market was conducted.

Figure 3: Time-lapse of the Development of Traditional Village Market and on utilization.

Following the utilizations of the new Kampung Baru Traditional Village Market on 2014, the number of traders was significantly increase from only 25 traders become more than 70 traders. The new traditional village market gives a significant impact to the society.

2.2 Evaluating the Social Investment Through Social Return on Investment (SROI)

The SROI framework was first developed by the Roberts Enterprise Development Fund (REDF) in 1996, after which there has been a gradual revision of the original methodology. Organizations are required to demonstrate their social impact in terms of social and economic value. Social return on investment (SROI) is a tool that measures socio-economic impacts on stakeholders to assist in identifying the most impactful intervention, program, or policy (Gosselin, et al., 2020). SROI is a framework for measuring and accounting for this much broader concept of value; it seeks to reduce inequality and environmental degradation and improve wellbeing by incorporating social, environmental and economic costs and benefits. SROI measures change in ways that are relevant to the people or organizations that experience or contribute to it. It tells the story of how change is being created by measuring social, environmental and economic outcomes and uses monetary values to represent them. This enables a ratio of benefits to costs to be calculated. For example, a ratio of 3:1 indicates that an investment of IDR 1 delivers IDR 3 of social value. The urgency of Social Return on Investment (SROI) in business is that CSR is no longer seen as a cost center but CSR is currently a cost of investment. The benefits using SROI is helping organizations understand the social value of activities through rigorous and robust assessments. The process opens discussions with stakeholders so that the project's success can be measured. Social Return on Investment involves the social impact of the assessment carried out

There are 8 SROI Principles:

1. Involve stakeholders.
2. Understand what changes.
3. Value the things that matter.
4. Only include what is material.
5. Do not over claim.
6. Be transparent.
7. Verify the result.
8. Be Responsive

In this case, we found that the development of the traditional village market makes a huge impact to the society. The outcomes impact could be quantification using the SROI method. We calculate the SROI by dividing the total social and environmental value created by the investment by the financial cost of the investment.

$$\textbf{SROI Ratio} = \frac{\textbf{Present Value}}{\textbf{Value Input}}$$

Those data were collected from the market organizer using total statistical data of market visitors, interview with local traders and also audience with Camat / Head of Sub-District.

3. CONCLUSION

The SROI calculation obtained shows a ratio of 28.45: 1, meaning that every Rp. 1 investment generates a social impact of Rp. 28.45, this shows that the implemented program has had a **positive social impact on the stakeholders involved**. This is in line with the statement that: The multiplier effect for the electricity industry is around 2.07 (reference to the LPEM UI study at MNL, 2006). This means that every Rp. 1 increase in electricity demand will result in an increase in economic output of Rp. 2.07. Meanwhile, from an investment point of view, the income multiplier ratio in the electricity industry is 2.9: 1. Each additional local salary of IDR 1 will result in an increase in economic output of IDR 2.9.

SROI helps manage and communicate the social value a project creates in the form of a measurable number that can be understood by all relevant stakeholders. The SROI measurement also helps to increase the social value or impact the project creates. In SEML case, it was shows that the development of the traditional market gives an added **social value** for the operation of geothermal power plants around the village.

Based on this calculation and also the demand of the expansion of the market, in line with the mission to providing resources to address community needs in order to widen the opportunities and access to the development of the community and its members through Infrastructure Policy and looking back the positive impact of the development of Traditional Village Market at Kampung Baru, SEML in 2022 starts to accommodate the community needs proposal for the Expansion of Traditional Village Market Program. This program also to accommodate the additional trader who are not accommodate with the old building since the amount of the traders become twice (almost 150 traders).

SROI can help you identify and quantify the positive and negative effects of your activities, as well as the trade-offs and risks involved. By using a common currency of value, such as dollars, euros or even rupiahs, SROI can also help you compare and communicate your impact across different contexts and sectors.

SROI can be a useful and powerful tool for social impact measurement and communication, if used appropriately and responsibly. To maximize the effectiveness of SROI, it’s essential to define your purpose and scope, engage your stakeholders, follow guidelines and standards, and use the tool as a learning tool. When defining your purpose and scope, consider why you want to use SROI, who your intended audience is, and what the boundaries and limitations of your analysis are. Engaging stakeholders is also important; identify who is affected by or interested in your work and find ways to involve them in the process and results. Additionally, following guidelines and standards will ensure the quality and consistency of your SROI. Lastly, use SROI as a learning tool to improve your work, derive insights and recommendations from the analysis, and monitor and evaluate progress.

SROI helps SEML to identify the impact of the delivered CSR Program and good tools to evaluate significant impact to the community around.

Table 1: SROI Worksheet Calculation.

No.	Stakeholders	Role	Outcome (What changed)							
1	Beneficiary Community in Nagari Alam Pauh Duo (lately, now Pekonina Village)	Beneficiaries of the Kampung Baru Traditional Market Development Program	Form: fund	**Reducing Transportation Costs to the Pakan Salasa Market** The community previously shopped at the Pakan Salasa Market, which is 13 km from Jorong Kampung Baru	Calculate the number of families experiencing savings	The number of people who experienced savings was 800 people	Total statistical data of market visitors	Multiply the number of households that experience savings multiplied by the difference in transportation costs. Before the 2014 program: Rp. 160,000/month/pers. After the 2015 program: Rp. 40,000/month/pers, so the difference is Rp. 120,000/month/person	Interviews with beneficiaries	The amount of savings/difference multiplied by the number of families = 500 people x Rp. 40,000 = 20,000,000.
			Shape: Person	**Increase in the number of traders** Before the construction of traditional markets, the number of traders was only a few, after having a permanent building, the number of traders increased.	Calculation of the number of traders before and after the implementation of the program:	Before the program: 25 local traders, after the program as many as 70 local traders, the difference in the addition of local traders is 45 people	Interview with local traders	Multiplying the number of traders by their weekly profit of Rp. 1. 500,000/week x 1 month x 45 traders x 12 months	Program data for the number of traders before and after the construction of traditional markets	The number of traders multiplied by the number of profits a month = 45 local traders x IDR 1,500,000 x 4 weeks x 12 months = 5,040,000,000
2	PT. Supreme Energy Muara Laboh	Program Initiator	Calculation of the corporate	**Improved corporate image** Improving the	Calculation of the corporate image index before & after	Positive coverage with local coverage	Audience with *Camat* / Head of	Calculating the news value of the program	Standard news values	Positive News: 4 pieces (4 Media) Regional: 1 x Rp. 2 million = 2

			image index	company's image as a company that cares about community issues related to clean water and healthy sanitation	the program. calculated from the cost of the image enhancement program from implementation of PR/Public Relations of the Company		Sub-District			million Local: 3 x Rp. 500 thousand = 1.5 million Negative News: 0 ea

Table 2: SROI Final Calculation in IDR.

	2014	2015	2016	2017	2018	2019	Total
Total outcome *)	3,087,047,657	2,993,753,762	2,867,580,232	2,746,724,360	2,746,724,360	2,630,962,030	17,072,792,400
Total Investment	600,000,000	-	-	-	-	-	600,000,000
SROI Ratio	5.15	-	-	-	-	-	28.45

*) in IDR

Figure 4: The Expansion of Traditional Village Market (additional building).

REFERENCES

Cataldi, R.: Social Acceptance of Geothermal Projects: Problems and Costs

Colpan, Can Ozgur., Ezan, Mehmet Akif, and Kizilkan, Onder., Thermodynamic Analysis and Optimization of Geothermal Power Plants, 2021, Pages 65-79

Erik, PTSE Bantu Rp500 Juta Bangun Pasar Pekonina, Jumat, 2 November 2012, Antara Sumbar, https://sumbar.antaranews.com/berita/3978/ptse-bantu-rp500-juta-bangun-pasar-pekonina

Imansyah, SEML Alokasikan Rp800 Juta Bangun Pasar dan Jalan, Jumat, 13 September 2013, Antara Sumbar, https://sumbar.antaranews.com/berita/60156/seml-alokasikan-rp800-juta-bangun-pasar-dan-jalan

Kvam, Reidar., Meaningful stakeholder consultation: IDB series on environmental and social risk and opportunity (2017) /(IDB Monograph ; 545)

LinkedIn Social Team, What are the advantages and disadvantages of using the Social Return on Investment (SROI) method?

Meijaard, E., Dennis, R.A., Saputra, B.K., Draugelis, G.J., Qadir, M.C.A., and Garnier, S. 2019. Rapid Environmental and Social Assessment of Geothermal Power Development in Conservation Forest Areas of Indonesia. PROFOR, Washington, DC

Purnomo, Social Return On Investment Training Material, November 2022

Social Value International, The SROI Network, A guide to Social Return on Investment, January 2012.

Social-Change.Co.UK, An introduction to Social Return on Investment.

Supreme Energy Muara Laboh, Stakeholder Engagement Plan, 2014.

Addressing Geothermal Exploration Resource Risk in Indonesia: Introducing GREM as a Pioneer De-Risking Facility

Desak Nyoman Inten Apriani[1], Rizka Chandra Amorini[1], Andreas Suseno[1], and Dorman Purba[1,2]

[1]PT Sarana Multi Infrastruktur (Persero), Sahid Sudirman Center, Jakarta, Indonesia
[2]PT ENERKA Bhumi Pratama, Cibis Nine Park, Jakarta, Indonesia

desak@ptsmi.co.id

Keywords: geothermal, resource, exploration, risk, mitigation, GREM, finance, funding, drilling, geoscience, derisking, due diligence, feasibility, fair market value, forgiveness, Indonesia

ABSTRACT

Geothermal exploration in Indonesia presents significant potential for clean and sustainable energy development. However, exploration resource risks and associated uncertainties have often hindered the progress of geothermal projects. This paper focuses on mitigating these risks by introducing the Geothermal Risk Mitigation Facility (GREM) as the first de-risking facility in Indonesia.

Through literature review, this study examines the challenges faced by geothermal exploration projects in Indonesia and explores the limitations of existing risk mitigation strategies. It then introduces the concept and implementation of GREM, highlighting its objectives, funding structure, key features, and collaboration with stakeholders in the geothermal sector.

As an introduction, this paper provides a brief review of several geothermal derisking schemes that are already available in various other countries. The paper then emphasizes the benefits and impacts of GREM on geothermal exploration projects. By leveraging GREM's services, such as risk assessment, technical assistance, and financial guarantees, exploration risks can be effectively mitigated. This, in turn, enhances the attractiveness of geothermal investments, improves project bankability, and facilitates access to financing.

While acknowledging the challenges in implementing and operating GREM, this study also identifies opportunities for future improvements and expansion of GREM's services. The role of GREM in advancing geothermal exploration in Indonesia is underscored, emphasizing its potential to accelerate project timelines and contribute to the country's renewable energy goals.

In conclusion, GREM emerges as a pioneering de-risking facility in Indonesia, effectively addressing geothermal exploration risks. The findings of this study offer valuable insights for policymakers, investors, and industry stakeholders, highlighting the importance of GREM in unlocking the vast geothermal potential of Indonesia. Furthermore, the research presents opportunities for further exploration and collaboration to enhance the effectiveness of de-risking facilities and propel sustainable geothermal development.

1. INTRODUCTION

1.1 Importance of Geothermal Development for Indonesia

The utilization of geothermal as green energy is become critical component in Indonesia’s efforts to achieve 23% renewable energy by 2025 and additional 21% of renewable power generation by 2030 (DEN, 2022a). Indonesia is the nation that has enormous geothermal potential (approx. 23 GWe) and is one of the top two geothermal producers (approx. 2,356 MW) globally (Darma, Imani, Shidqi, Riyanto, & Daud, 2021; ADB, 2018). Unfortunately, the potential is still under-utilized since current utilization is only 8% of the total potential (Fadhillah, et al., 2022). Indonesia is targeting geothermal utilization to reach 5,799 MW in 2030, which equals 259% addition to the current capacity (PLN, 2021). Figure 1 shows the existing and targeted Indonesia geothermal development.

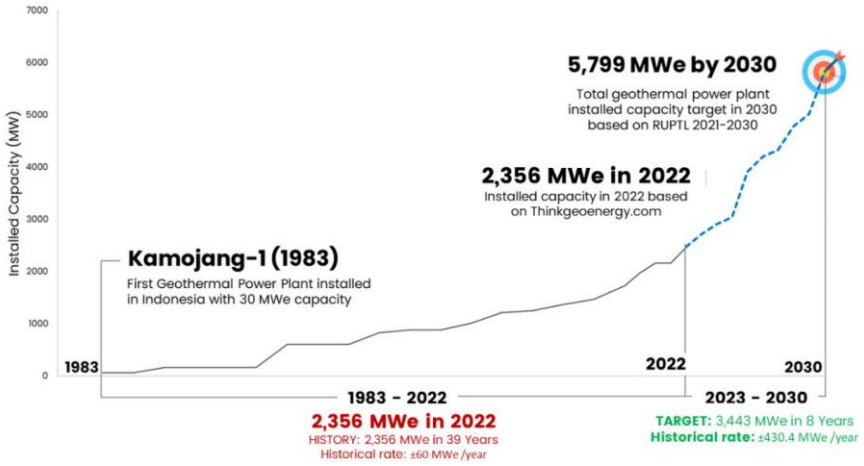


Figure 1: The historical and projected Indonesia geothermal development (modified from Purba et al., 2022; PLN, 2021; EBTKE, 2022; ThinkGeoenergy, 2023).

Currently, Indonesia's geothermal industry operates 16 power plants under either the management of state-owned enterprises (SOE) or Independent Power Producers (IPP). Additionally, there are 63 areas designated as "geothermal working areas" in the exploration-development phases and 15 areas classified as "preliminary survey-exploration areas" in the pre-exploration phases (MEMR, 2022). Despite these efforts, the present condition of geothermal development poses significant challenges to achieving the government's targets by 2030. To accelerate geothermal development, it is imperative to focus on promoting exploration activities while also addressing associated exploration risks to enhance investment attractiveness.

1.2 Risk of Geothermal Project

The geothermal sector faces substantial initial financial investment that is accompanied by high risk due to uncertainties related to resources, social-environmental factors, finances, and technical challenges (IRENA, 2022). Research by Geothermex (2010) and Castlerock (2010) emphasizing that the main barrier to geothermal development in Indonesia lies in the significant risk involved during extensive investments, particularly in the preliminary survey and test drilling stages. These stages encounter limited data and rely on interpretations by geoscientists, leading to uncertainties about critical resource conditions, such as reservoir temperature, fluid characteristics, and permeability, which directly affect to the development strategy and financial performance. The cost-risk curve and funding source of each phase shown in Figure 4 modified from IGA (2014) and Purwanto (2019), while Table 1 summarize the identified risk of general geothermal project based on ESMAP (2021).

1.3 Research objectives

This research has the objective to provide a review related various de-risking facility for geothermal exploration in global. Furthermore, the paper also introduces the Geothermal Resource Risk Mitigation Program (GREM) as de-risking facility in Indonesia through literature review. The research question addressed as below:

1. What are the predominant risks faced by geothermal projects during the exploration stage in Indonesia?
2. What global mechanisms exist for the mitigation of risks during the exploration phase of such projects?
3. How does the Geothermal Resources Risk Mitigation program (GREM) operate?

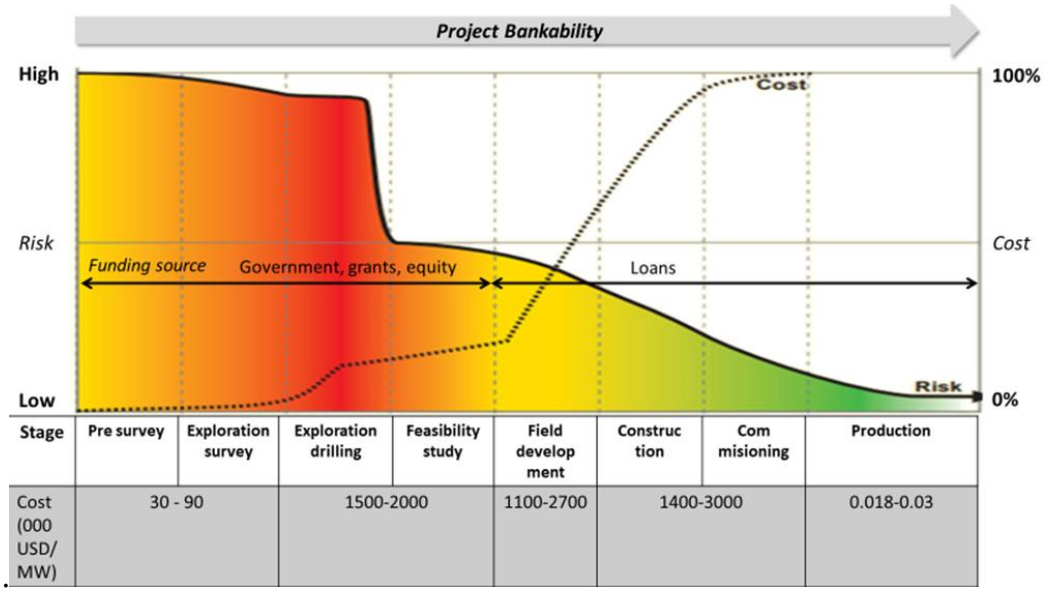


Figure 2: Geothermal projects' risk, cost, and funding source modified from IGA (2014) and Purwanto (2019).

Table 1: Typical risk in geothermal project (modified from ESMAP, 2022).

Type of risk	Remarks
Market	Potential discrepancy between the expected revenue of the project and the actual realization, not necessarily due to lower production, but rather the possibility that the developer may not receive the payments for the production as initially anticipated.
Geothermal resource	The risk that the production drilling campaign may fail to achieve the required capacity or do so with cost overruns. This pertains to the possibility of encountering challenges during the drilling process that could impede reaching the intended capacity or result in unforeseen expenses. Risk of resource depletion due to exploitation, making it unsustainable for the planned duration. In this scenario, the geothermal resource may not perform as initially estimated, leading to difficulties in maintaining production at the power plant in accordance with the intended capacity.
Location and site	Risks related to natural hazards such as earthquakes, floods, and volcanoes, which could impact the project's operations and infrastructure. Additionally, security risks in the area may pose challenges and uncertainties that need to be considered.
Technical	Risks related to technical issues that may arise during drilling, plant construction, or plant operation. The challenges may lead to adverse impacts, including escalated costs, delays in project timelines, or revenue losses due to reduced energy generation.
Social and environment	Social environment risks in geothermal projects include community opposition, land rights and displacement issues, environmental impacts, concerns about cultural heritage, health and safety risks, and challenges in equitable benefit sharing.
Project execution	Risks include delays, management issues, inadequate budgeting, and procurement challenges. Proactive strategies and effective planning are crucial to address these risks and achieve project objectives.
Financial	One of the primary risks is cost increases, which can occur due to factors such as inflation, fluctuations in material prices, or unforeseen expenses during construction and operation. These cost overruns can strain the project's budget and affect its economic feasibility. Furthermore, changes in financing conditions, including fluctuations in interest rates or currency exchange rates, can expose the project to financial volatility. Higher interest rates can increase borrowing costs, while currency changes may affect debt repayment obligations and project revenue.

Type of risk	Remarks
Legal and regulatory	Uncertainties due to changes in government policies, regulations, or permitting processes. Delays in obtaining necessary approvals or unexpected changes in regulatory requirements can lead to project disruptions, increased costs, and uncertainty in project timelines.
Political	Geothermal projects can be influenced by political instability, changes in government, or shifts in energy policies. Political instability can lead to delays in decision-making and project execution, affecting the project's financial performance and overall viability.

2. GEOTHERMAL EXPLORATION CHALLENGES

The main goal of an exploration program is to identify and characterize geothermal resources that can be economically developed using appropriate plan of development based on the findings of the exploration activities (Siahaan, Septiani, Purba, & Paripurna, 2023). During the exploration stages, geothermal developers and investors often encounter dilemmas when making investment decisions during the exploration stage due to invest significant upfront capital while relying on limited and uncertain information about the geothermal resource potential.

Cost wise, the drilling activities and construction of supporting infrastructure, such as access roads and well pads, represent the most significant cost components of an exploration project. The main challenges of geothermal exploration in Indonesia are summarized as follows (IGA, 2014; Poernomo A. S., 2015; Darma, 2016; Umam, Adityatama, & Purba, 2018; Siahaan, Purba, Septiani, & Paripurna, 2023):

1. Difficulty in locating the "hottest area": Geothermal resources could not directly be manifested at the surface, necessitating detailed geological, geochemical, and geophysical (3G) surveys and test well drilling. The lack of clear surface indications or thermal manifestations can make it challenging to identify the most promising areas for exploration, leading to an increased risk of drilling dry wells.
2. High exploration costs: The expenses for 3G surveys, developing a reliable conceptual model, and drilling test wells can be substantial. There is always a risk that geothermal projects may not yield viable resources, making it challenging for developers to secure funding for exploration activities due to the high upfront capital and uncertainties involved.
3. Complex geology: Geothermal resources in Indonesia are mainly located in a volcanic area with complex geological environments, making it difficult to understand the subsurface conditions and identify the most promising areas for exploration.
4. Lack of direct and reliable data: In some cases, there may be a need for more data on the geology and geochemistry of an area, making it challenging to identify potential resources and plan the exploration activities.
5. Environmental impacts: Exploration activities can have various environmental impacts, such as air and surface water pollution, soil degradation, hazardous noise, release of hazardous gases, landslides, deforestation, and the potential for groundwater contamination. Mitigating these impacts can be costly and time-consuming.
6. Social and community impacts: Exploration activities can also have social and community impacts, such as displacement of local communities and land-use conflicts. Developers need to address these impacts and engage with local communities to ensure their support and minimize the risk of project delays or cancellations.
7. Uncertain regulations: Geothermal exploration is subject to various national, regional, and local regulations. The uncertainty can make it difficult for developers to navigate the regulatory environment and can increase the risk of project delays or cancellations.

2.1 Resource Risk

To provide an example illustrating the high drilling risks in the exploration stage, Sanyal et al. (2011) presented statistical data from the Kamojang field in Indonesia, which showed a drilling success rate of

20-50% for the initial six wells in the exploration phase. The paper demonstrated how the success rate fluctuated significantly as additional wells were drilled. However, the fluctuations gradually decreased during the development phase and eventually stabilized in the operational phase at a level exceeding 70%. The number highlights the inherent challenges and uncertainties associated with geothermal exploration drilling, emphasizing the need for effective risk mitigation strategies to enhance the overall success rate of geothermal projects.

Similar to Sanyal et al. (2011), a study conducted by IFC (2013) provides additional insights into the success rates of geothermal exploration drilling. The study revealed an average success rate of 50 percent across a dataset comprising 2,613 wells. Interestingly, the success rate increased over subsequent drilling activities, with an average success rate of 59 percent for the first five wells and further rising to 71 percent for the first 30 wells. This upward trend in success rates persisted beyond the 50th well. The dataset used for this analysis consisted of publicly available information and confidential data shared by individual geothermal developers with GeothermEx, Inc. over four decades.

These studies' findings provide evidence indicating that the drilling success rate during the exploration stage exhibits considerable variability, ranging from 20 to 59 percent. These results underscore the inherent uncertainty and unpredictability associated with geothermal exploration drilling.

The exploration stage of geothermal development is characterized by the primary risk associated with the uncertainty of identifying economically viable geothermal resources. Recognizing this challenge, institutions within the global geothermal industry have undertaken efforts to develop schemes aimed at mitigating risks for geothermal developers during the exploration phase. Subsequent chapters will delve into an in-depth examination of the various schemes presently employed in the geothermal industry.

2.2 Typical Exploration Cost

The cost of geothermal exploration in Indonesia can vary significantly, as it is contingent upon project-specific factors and the chosen exploration drilling strategy. An estimate of exploration costs is presented in Table 2, providing an overview of the anticipated expenses associated with conducting geothermal exploration drilling.

Table 2 illustrates the sequential stages involved in the execution of an exploration project, encompassing a range of activities that are conducted progressively, beginning with low-cost data collection attempts. Following the initial data collection, developers can proceed with activities that entail more significant investments if the results exhibit positive indications of geothermal potential. Notably, Table 2 provides a distinct representation of the climax of all exploration activities, which is the drilling of deep wells. This activity incurs the highest costs within the exploration stage.

The tabulated information underscores the systematic progression of exploration efforts, whereby preliminary activities with relatively lower expenses pave the way for more resource-intensive undertakings. The delineation of cost variations among the stages underscores the significance of prudent financial planning and decision-making in geothermal exploration initiatives. By comprehending the cost implications associated with each stage, developers can effectively allocate resources and assess the financial feasibility of progressing further in the exploration process.

It is important to note that the costs outlined in Table 1 are subject to variations based on multiple factors, including the depth and complexity of drilling, geological conditions, logistical considerations, and local context. Therefore, the figures provided should be regarded as approximate and indicative rather than absolute values.

Table 2: Cost estimate of geothermal exploration drilling (modified from IGA, 2014; GeothermEx, 2010; Purwanto et al., 2018; Purba et al., 2019; Purba et al., 2020; Adityatama, 2020; Purba et al., 2021).

Activity	Geology survey	Geochemistry survey	Geophysical survey	Initial conceptual integration and well targeting	Exploration drilling
Activity Description	Geological mapping on an area of 400 km^2. The work package including pre-field-work study, rock sampling and identification, structural mapping, and reporting.	Work package including a pre-field-work study, liquid and gas sampling from 30 locations, laboratory analysis and reporting.	Work package including pre-field-work study, 100 MT stations and 150 Gravity stations, interpretations, and reporting.	Integrate all report from 3G surveys to create several scenarios of conceptual models, including peer review.	Using 3 (three) standard/big hole type or 5 (five) slimhole type or combination of 2 (two) slimholes and 1 (one) full-size well. The cost estimate includes infrastructure construction cost to support the drilling operation. The duration estimate includes procurement process, preparation, equipment mobilization, drilling, well testing and demobilization.
Estimated Duration	4-8 months	4-8 months	4-8 months	3-6 months	18 - 36 months
Cost Estimate (USD)	300,000 – 700,000	200,000 – 400,000	1,000,000 – 2,000,000	100,000 – 200,000	15,000,000 – 50,000,000
Considerations	Accuracy might be affected by terrain, weather, and field personnel experiences.	Accuracy might be affected by sampling method (minimize contamination) and laboratory competences.	Accuracy might be affected by noise during data acquisition and data processing method, including personnel interpretation.	Accuracy might be affected by 3G data accuracy and personnel experiences and interpretation.	Allow the exploration team to acquire downhole data directly from the reservoir, which is valuable for more accurate resource assessment but requires higher cost and time than the 3G survey.

3. GEOTHERMAL EXPLORATION DE-RISKING PRACTICE

Geothermal exploration de-risking scheme is a strategic approach designed to mitigate the financial risks inherent in geothermal exploration projects. The primary objective of this scheme is to create efficient exploration program that enhances the ratio of success exploration (Siahaan, Septiani, Purba, & Paripurna, 2023). ESMAP (2016) and Nur (2023) strengthen the significance of exploration de-risking program as a critical path to accelerate and enhance the development and utilization of geothermal resources.

3.1 Geothermal Exploration Schemes and Terminologies in Indonesia

During the exploration stage of geothermal development in Indonesia, the government introduced several schemes and terminologies to facilitate the process. These schemes aim to reduce the risks associated with exploration and foster a conducive environment for investment. The following are some of the critical schemes and terminologies implemented by the government (Table 3):

Table 3: Geothermal exploration schemes and terminologies in Indonesia.

***Wilayah Terbuka* (Geothermal Open Area)**	An area suspected of having geothermal potential outside the coordinate boundaries of a Geothermal Working Area
Assignment Area	A Geothermal Open Area with certain coordinate boundaries offered to an Other Party for PSP or PSPE
WKP (Geothermal Working Area)	An area with defined coordinate boundaries used for the exploitation of Geothermal for Indirect Use (power)
***Penugasan Survei Pendahuluan*/PSP (Preliminary Survey Assignment)**	The assignment given by the Ministry of Energy and Mineral Resources to carry out the Preliminary Survey activity
***Penugasan Survei Pendahuluan dan Eksplorasi/PSPE* (Preliminary Survey and Exploration Assignment)**	The assignment given by the Ministry of Energy and Mineral Resources to carry out the activities of the Preliminary Survey and Exploration
***Izin Panas Bumi/IPB* (Geothermal License)**	Permit to conduct exploration and/or exploitation of Geothermal for Indirect Utilization in certain working areas
Government Drilling	Scheme for government to conduct the early stage of geothermal development (preliminary survey and exploration drilling)

3.2 Government Led Exploration

Government agencies and entities play a critical role in mitigating the risks associated with geothermal projects, especially during the exploration phase. This can be done through a variety of mechanisms, such as providing financial support, technical assistance, and regulatory oversight. In some cases, governments may even act as the sole developer of a geothermal project, assuming all the risks involved. Even when development financing is made available, the typically associated sovereign guarantees mean that the government ultimately bears the risk of project failure. The government led exploration program needs the entity that has strong in-house expertise, access to appropriate technology, and sufficient financial resources (ESMAP, 2016).

ESMAP (2016) emphasizes the government led exploration program already executes in 12 countries with 31 projects that equals to 3.613 MW capacity. Siahaan (2023) provides the example of government led exploration program as below:

1. Indonesia-Geothermal Energy Upstream Development Program (GEUDP)
   The Geothermal Energy Upstream Development Program (GEUDP) is joint initiative between the Government of Indonesia and the World Bank with the primary goal of promoting the development of greenfield geothermal areas that have not yet been tendered, particularly in remote regions of Indonesia. The program aims to support and facilitate exploration and drilling activities in order to assess the geothermal potential in untapped areas and promote the development of clean and sustainable geothermal energy resources. Currently, the program includes four pipeline projects: Waesano, Jailolo, Nage, and Bittuang. However, most of these projects are still in the early stages of exploration activities (Siahaan, Septiani, & Purba, 2023).

   Under the Geothermal Energy Upstream Development Program (GEUDP), the Indonesian government assumes full responsibility for the risk of exploration drilling if the geothermal resource is not proven or deemed economically viable. In cases where the geothermal resource is found to be feasible for electricity generation, the relevant Working Areas (WKP) will be tendered, along with the geothermal data package acquired during the exploration drilling process. The winner of tender

has obligation to repay the exploration cost with certain margin (Siahaan, Purba, Septiani, & Paripurna, 2023).

2. Indonesia-Government Drilling Geological Agency
   Government drilling is a geothermal exploration campaign under the Ministry of Energy and Mineral Resources (MEMR) that is funded by the state budget. The government faced all of exploration risk and responsible to exploration cost. The activities carried out by the Geological Agency include preliminary surveys, land acquisition, obtaining necessary permits, infrastructure construction work, drilling, well testing, and updating the pre-Feasibility Study (pre-FS) document (Siahaan, Septiani, Purba, & Paripurna, 2023).

   The current geothermal exploration program includes three pipeline projects: Nage, Bittuang, and Cisolok Cisukarame. Notably, the Nage and Bittuang projects are also part of the GEUDP sub-projects. This strategic approach aims to expedite project progress by implementing a hybrid financing scheme. Initially, the Geological Agency carries out early exploration activities, such as drilling two slimhole wells, utilizing funds from the state budget (APBN). If the drilling results from the Geological Agency do not conclusively demonstrate the presence of an economically viable geothermal resource, the subsequent activities will be funded under the GEUDP program (Siahaan, Septiani, Purba, & Paripurna, 2023).

3. Turkiye-Government led exploration.
   Turkish introduces the government exploration program that modify the Geothermal Development Cooperation model in Kenya. The government through the General Directorate of Mineral Research and Exploration absorbs the exploration risk, while the developer will continue the project in development phase. The scheme is performed by undertaking the exploration drilling activity that is funded by provided budget. The success area will be listed for open competitive bid where government collect certain bid fee. The fee utilized to reinvested to finance additional exploration drilling and the exploration of new prospect area. Independent Power Producers (IPPs) continue the projects with a certain degree of risk reduction, allowing IPP to secure financing for completing field development and constructing power plants. The government also reduce the long-term project risk by providing the Power Purchase Agreement (Siahaan, Septiani, Purba, & Paripurna, 2023; Ram & Letvin, 2014)

4. New Zealand-Government led exploration.
   Government of New Zealand perform significant portion of geothermal development through led the exploration stage. The government agency directly engages in exploration or delegates it to private companies through contractual agreements. The area with confirmed resources will be developed by the government or listed for private developer bid competition. This scheme absorbs the exploration risk to government and provide more attractive conditions for private developers (Siahaan, Septiani, Purba, & Paripurna, 2023).

3.3 Grants / Loan and Cost Sharing

Grants and loans, along with cost-sharing arrangements, play crucial roles in supporting geothermal projects. Grants are non-repayable funds provided by governments, organizations, or agencies to support geothermal development and mitigate financial risks. It is often utilized to fund exploration, feasibility studies, and early-stage development. While loans funds borrowed by geothermal developers from financial institutions or governments to cover project expenses. Unlike grants, loans need to be repaid with interest over a specified period, adding to the project's overall costs (Fadhillah, 2023).

Cost-sharing arrangements involve sharing project expenses between various stakeholders, such as government entities, private investors, and development agencies. These arrangements spread the financial burden and incentivize collaboration, promoting sustainable geothermal development (ESMAP, 2016). The cost shared exploration could be conducted in effective through:

1. Government Commitment to Geothermal Expansion: When the government aims to rapidly increase geothermal generation capacity through private-sector involvement and implements supportive policies to achieve this goal.
2. Mobilizing Private Expertise and Investment: In cases where the government lacks geothermal expertise and seeks to attract private investment and know-how to unlock the nation's geothermal potential.
3. Developer Experience and Selection Process: The success of cost-shared drilling relies on experienced developers, selected transparently based on clear criteria, including their ability to contribute to the risk capital for exploration drilling.
4. Commitment to Full Development: The recipients of cost-share funds should be committed to developing the project through all post-exploration stages until it becomes operational, rather than selling development rights to other investors after benefiting from cost-shared drilling. This ensures the continuity and completion of the geothermal project.

Siahaan (2023) provides the example of grants/loan and cost sharing of derisking facility, as bellow:

1. United States- Industry-Coupled Case Studies Program

   The Department of Energy (DOE) introduced the Industry-Coupled Case Studies Program with two primary objectives. Firstly, the program aimed to facilitate geothermal exploration by implementing a cost-share mechanism to offset some of the high initial costs and risks associated with exploration drilling. At that time, there was limited knowledge about the locations of geothermal resources in the United States, and the cost-share mechanism served to encourage investment in exploration activities and stimulate research in unexplored field (Moore, Ross, & Wright, 2010). The provided financial support covers portion of the exploration and reservoir confirmation costs for participating projects, ranging from 20% to 50% (Bloomquist, 2005). The second objective was to acquire more data on geothermal resources and projects to enhance knowledge and facilitate future geothermal power development. DOE mandated industry participants to provide the well and drilling data collected during the exploration process. Throughout the program's duration, industry partners evaluated 14 sites, leading to the development of eight geothermal power plants. As of 2010, seven of these plants were operational, boasting a combined capacity of 137 MW, with the possibility of additional plants being established subsequently (Moore, Ross, & Wright, 2010).

   Despite its initial successes, the program eventually lost congressional support and is no longer in operation (Speer, Economy, Lowder, Schwabe, & Regenthal, 2014). Nonetheless, the valuable data gathered during the program's tenure has contributed significantly to the understanding and advancement of geothermal power development, leaving a lasting impact on the geothermal industry in the United States.

2. United States- User Coupled Confirmation Drilling Program

   The UCDP (User-Coupled Drilling Program) is collaborative initiative between the US Department of Energy (USDOE) and industrial organizations aimed at fostering industry participation in the early stages of geothermal development, primarily focusing on direct use projects but also encompassing some electrical generation projects. The program's fundamental objective is to share expenses related to the confirmation of hydrothermal resources, covering activities like site selection, drill hole placement, drilling operations, flow testing, reservoir engineering, and well testing. The program facilitates the development of infrastructure for exploration, reservoir confirmation, and utilization engineering. This includes fostering the growth of expert consultants, contractors, and equipment manufacturers in the geothermal sector, further reducing the risks involved in reservoir confirmation processes (Lund & Gordon Bloomquist, 2012).

3. Indonesia-State owned enterprise drilling

   The SOE Drilling program has similarities with the GREM Public Window Facility since the program is entirely funded by the PISP fund and has a capped amount of USD 30 million. It consists of the combination of blended loan and de-risking facility to support geothermal exploration projects. The application process and eligibility criteria for the SOE Drilling program are comparable to the GREM Public Window, and both adhere to the provisions outlined in Ministry of Finance Regulation No.80/PMK.08/2022. However, the key distinction is that developers under the SOE Drilling program are not mandated to follow the World Bank's Environmental Social Safeguards (ESS) and Procurement Standards, which could potentially offer more flexibility in their project implementation.

4. Turkiye-Risk sharing mechanisms.

   The risk sharing mechanism in Turkey initiated by world bank with local bank to cover the cost of well that failed to achieve success criteria. The bank coverage set on 40%-60% of total well cost depends on geographical location. The higher level of coverage is provided for projects situated in Aydin, Denizli, and Manisa regions. This deliberate emphasis on extended coverage aims to stimulate investments in geothermal exploration within less explored regions across the country. By offering this coverage, the mechanism significantly diminishes the risk for project sponsors, facilitating ability to raise necessary funds for exploration drilling (Siahaan, Septiani, Purba, & Paripurna, 2023; TKYB-Türkiye Kalkınma ve Yatırım Bankası and World Bank, 2021).

3.3 Loan Guarantees

The loan guarantees provide as form of financial assurance for lender that if the project faces unforeseen difficulties or default condition, the guaranteed portion of the loan will be covered by government or certain financial institutions. This not only mitigates the perceived risks for lenders but also serves as an incentive for lenders to offer more favorable lending terms to project developers. Several practice of loan guarantees for geothermal project as below:

1. United States-Geothermal Loan Guarantee Program
   The Geothermal Loan Guarantee Program (GLGP), instituted in 1975, was a pioneering and widely recognized geothermal loan initiative within both US state and federal. The Act stipulated that loan guarantees could be extended to cover 75% of the project expenses, with the Federal government pledging its guarantee for the entire 100% of borrowed amount. The amendment in 1980 expanded the scope of the program to permit loans to be granted for up to 90% of the cumulative project cost for entity related to electricity, housing, or other relevant sectors.

   The GLGP achieved positive results in advancing geothermal endeavors across various sites and effectively facilitating the implementation of both direct utilization and electrical generation projects. However, the program faced two significant shortcomings. Firstly, the stringent loan approval requirements often acted as a constraining factor, limiting program access to those entities that ideally could have qualified for conventional loans even without the guarantee. Secondly, utilities exhibited reluctance to engage with the loan guarantee program due to the potential implications on their credit ratings in the event of default, despite the assurance of federal government backing (Siahaan, Septiani, Purba, & Paripurna, 2023).

2. United States- Loans for Geothermal Reservoir Confirmation Program
   The Loans for Geothermal Reservoir Confirmation Program, established through congressional authorization in 1980, operated as a direct loan initiative. This program was designed with the purpose of extending financial support to geothermal heat and power projects engaged in surface exploration and drilling activities. The financial assistance provided by this program was capped at a maximum of $3 million per project, with the loan amount restricted to 50% of the overall project expenses for power-related initiatives. Although enshrined within the Energy Security Act of 1980 and officially sanctioned by the Secretary of Energy, the program encountered a significant impediment in its progress – the absence of financial appropriations from Congress

(Bloomquist, 2005; Speer, Economy, Lowder, Schwabe, & Regenthal, 2014; Siahaan, Septiani, Purba, & Paripurna, 2023).

Table 4 illustrates a comparison of various exploration financing facilities across different countries worldwide. A more detailed comparison for each of these facilities will be presented on a separate table at the end of this paper.

Table 4: Comparison of Various Exploration Financing Support in Various Countries.

Country	Government led exploration	Grants / loan and cost sharing	Loan guarantee
Turkiye	Government led exploration	Risk sharing mechanism	-
New Zealand	Government led exploration	-	-
East Africa	-	1. East Africa Rift Geothermal Development Program 2. Africa Geothermal Risk Mitigation Program	-
United States	US DOE through national laboratories.	1. User Coupled Confirmation Drilling Program (UCDP) 2. American Recovery and Reinvestment Act (ARRA)	1. Geothermal Loan Guarantee Program (GLGP) 2. Loans for Geothermal Reservoir Confirmation Program
Indonesia	1. Geothermal Energy Upstream Development Project (GEUDP) 2. Government Drilling through Geological Agency	1. Geothermal Resource Risk Mitigation Project (GREM) 2. State Owned Enterprise (SOE) Drilling	-

4. INDONESIA GEOTHERMAL RESOURCE RISK MITIGATION PROGRAM (GREM)

Geothermal Resource Risk Mitigation (GREM) is a de-risking facility for geothermal exploration project that developed by Sarana Multi Infrastruktur (SMI) and World Bank. The main objective of the facility is to accelerate the Indonesia geothermal development investment by financing facility for upstream resource development, especially the exploration and delineation drilling as critical path of resource confirmation. Facility provides geothermal developers that already obtain working area and perform preliminary survey with debt package for exploration-delineation drilling.

It is become critical since the common debt and financing facility is hesitated to fund the exploration drilling due to high uncertainty and risk, while the GREM support funds the exploration drilling to confirm the presence of sufficient productive steam resource for power generation. If the resource is sufficient, the developer can continue the project through commercial project finance for exploitation drilling and power plant development. It makes GREM also increase the level of confidence from other financing institutions for them to finance the next development stage of the pertinent Working Area (Siahaan, Purba, Septiani, & Paripurna, 2023; Siahaan, Septiani, Purba, & Paripurna, 2023; SMI, 2021).

4.1 Main Features of GREM

The main features of GREM can be summarized into six points, as depicted in Figure 3. A comprehensive explanation of GREM is documented in a publication (Developer Manual) available on the PT Sarana Multi Infrastruktur (Persero) website, which encompasses various key details concerning the GREM facility.

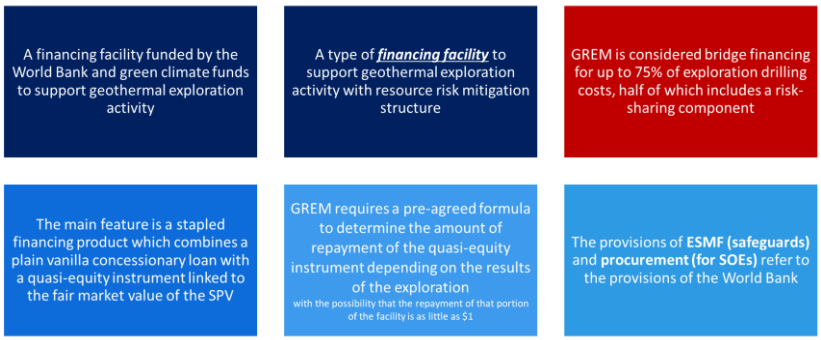


Figure 3: Key features of GREM,

Siahaan et al (2023) emphasizes that the unique feature of GREM is the availability of a de-risking facility in the event of an exploration failure. It means the developer does not fully bear the risks and costs of exploration. SMI (2021) explains the developer equipped with "forgiveness" for each project. The forgiveness allow developer only to a partial repayment (up to 50%) of total facility in the event of exploration and/or political risk as below:

1. Exploration risk involves the possibility that one or the entire drilling activities specified in the work plan, as well as the exploration cost budget, have been completed, and an independent party confirms from its assessment on the geothermal data and information generated from these stages that the exploitation and/or utilization stage in that area is not feasible to be carried out.
2. Political risk occurs in an area when the government, based on the applicable laws and regulations, takes actions that halt the implementation of activities specified in the work plan and exploration cost budget.

The total commitment of GREM funding amounts to USD 651.25 million, sourced from various multilateral funds, including the International Bank for Reconstruction and Development (IBRD), Green Climate Fund (GCF), Clean Technology Fund (CTF), Global Infrastructure Facility (GIF), and PISP funds. The overview of the institutional arrangement and flow of funds of the GREM facility is shown in Figure 4.

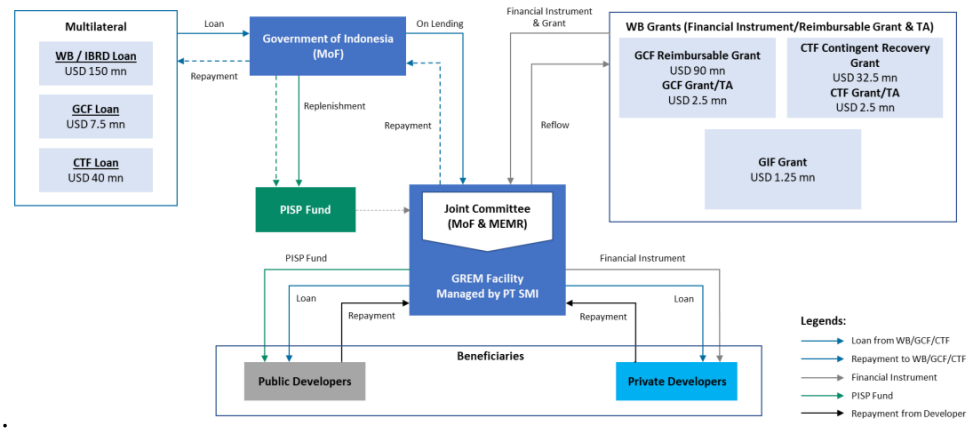


Figure 4: The Institutional Setting and Flow of funds of GREM Facility.

The amount of GREM would vary on each borrower but could not exceed 75% of total drilling program cost or 30 million USD. Total drilling program cost refers to the amount of project expenditure during exploration period that used for land acquisition, site preparation and construction of drilling infrastructure, drilling activity, well testing, and update of pre-feasibility study report (SMI, 2021). The total drilling program cost would be reviewed by the lender to ensure the fairness of the cost.

4.2 Public Window and Private Window

Furthermore, GREM is designed to provide the facility through public and private developers based on the borrower entity status (SMI, 2021; Siahaan, Purba, Septiani, & Paripurna, 2023; Siahaan, Septiani, Purba, & Paripurna, 2023). Table 5 summarize the eligible criteria of each facility with explanation as below:

1. The GREM public window is available for geothermal/energy state-owned enterprises or geothermal companies with controlling shareholders owned by geothermal/energy SOEs. The facility provides up to 75% of the total drilling cost, with a maximum cap of 30 million USD. The funding is sourced from a blended fund of PISP and IBRD/GCF/CTF. The forgiveness calculation will be based on the projected project value (PPV) financial model, subject to the decision of the Joint Committee.
2. The GREM private window is available for private developers who have obtained exploration rights and have conducted preliminary surveys but need exploration drilling to confirm the resource feasibility. This window offers loans and de-risking facilities by purchasing financial instruments (FI) issued by the developers, with a maximum total limit of USD 30 million. The facility comprises two categories: Facility A, which provides a blended loan from IBRD, and Facility B, which offers FI de-risking from GCF/CTF reimbursable grants.

Table 5: Comparison of GREM facility for Public and Private Developers.

	GREM Public Window	**GREM Private Window**
Entity status	State Owned Enterprises	Private entity
Facility amount	75% of total drilling cost (max. 30 MUSD)	
Eligibility / requirement	1. Geothermal/Energy SOE 2. Geothermal company with controlling shareholder owned by geothermal/energy SOE. 3. Already obtain the geothermal data through preliminary survey. 4. Already has legal control with no dispute of land right for exploration activity.	1. Already obtain the geothermal data through preliminary survey. 2. Already has legal control with no dispute of land right for exploration activity. 3. Strong financial condition through 2 years audited financial statement. 4. Controlling shareholder has experience in indirect geothermal exploitation, and/or willing to provide guarantee to obligation payment.

4.3 Eligible Activities

4.3.1 Public Window

Figure 5 outlines eligible geothermal development stages and associated activities under the GREM Facility's public sector window.

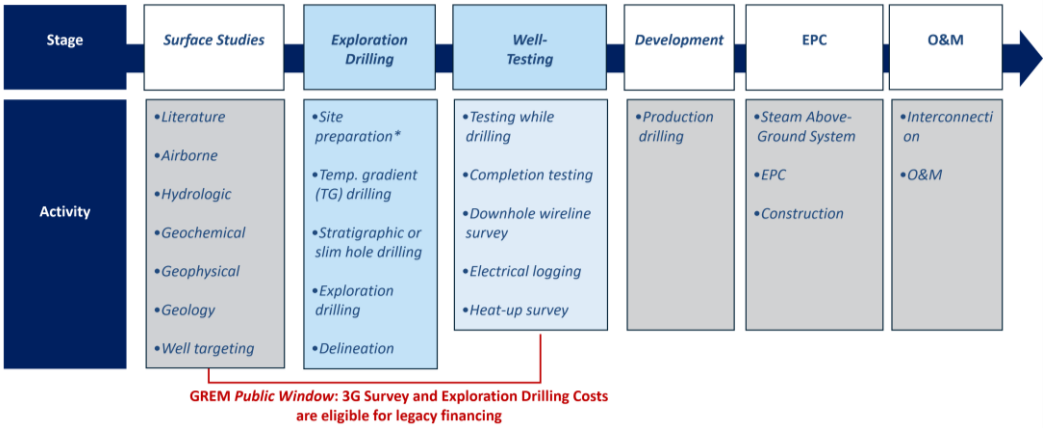


Figure 5: Eligible activities to be funded with GREM under the public sector window facility.

Infrastructure assets within the drilling program's working area and consultancy services tied to eligible drilling activities are fundable under GREM's Public Sector Window. Costs will be verified by independent consultants.

Public developers can seek financing for 3G/preliminary surveys and exploration drilling costs incurred with their equity before the GREM facility agreement. This is termed "legacy financing" (within USD 30 million limit). Legacy financing caps at 25% of Total Drilling Program Costs, not covering costs before May 15, 2020. Developers provide Preliminary Identification of Eligible Costs (PIEC) and financing application, adhering to procurement regulations and safeguards.

Legacy financing is also valid for GREM's delineation or extended exploration. Developers can seek legacy financing for exploration and drilling costs paid with their funds before GREM's agreement. Eligibility criteria match PIEC's 12-month payment date, procurement regulations, and safeguards. Cap is 25% of Delineation/Extended Drilling Program, excluding costs before May 15, 2020. Public developers must follow Section 10's defined procurement regulations.

4.3.2 Private Window

Figure 6 outlines eligible geothermal development stages and associated activities under GREM's private sector window.

Infrastructure assets within the drilling program's working area and consultancy services tied to eligible drilling activities are fundable under GREM's Private Sector Window. Costs will be verified by independent consultants, including equity contribution (minimum 25% of Total Drilling Program Costs).

Private developers can apply for legacy financing (within USD 30 million limit) for eligible exploration drilling costs incurred before the GREM facility agreement. Legacy financing also requires a minimum of 25% Equity In-Kind Contribution. Cap is 25% of Total Drilling Program Costs, excluding costs before May 15, 2020. Developers provide Preliminary Identification Cost (PIEC) and financing application, adhering to payment date limits (12 months before PIEC submission), and World Bank's safeguards.

Legacy financing is also available for GREM's delineation or extended exploration, with a fulfilled 25% equity contribution. Eligibility criteria match PIEC's 12-month payment date and World Bank's safeguards. Cap is 25% of Delineation/Extended Drilling Program, excluding costs before May 15, 2020.

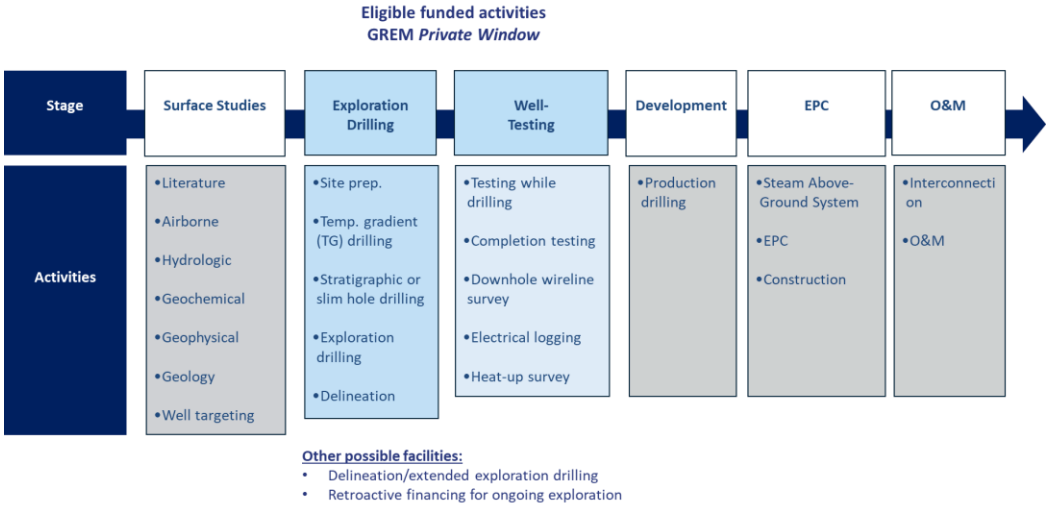


Figure 6: Eligible activities to be funded with GREM under the private sector window facility.

4.4 Application Process and Feasibility Analysis

Developer applications for GREM facility must be submitted in paper form. Review follows the sequence of submissions and initiates an appraisal process, as shown in Figure 7. Costs for application preparation and negotiation are the responsibility of the developers.

Before formal full application documents are submitted by developers, PT SMI offers a pre-screening option for Sub-Projects. This pre-screening evaluates project maturity and offers guidance for application document preparation, ensuring comprehensive information and documentation for thorough assessment and potential project financing. PT SMI may also assist in compiling necessary documentation during pre-screening. This step is voluntary and doesn't impact the overall appraisal and approval process. Feedback from PT SMI during this stage is non-binding and carries no liability.

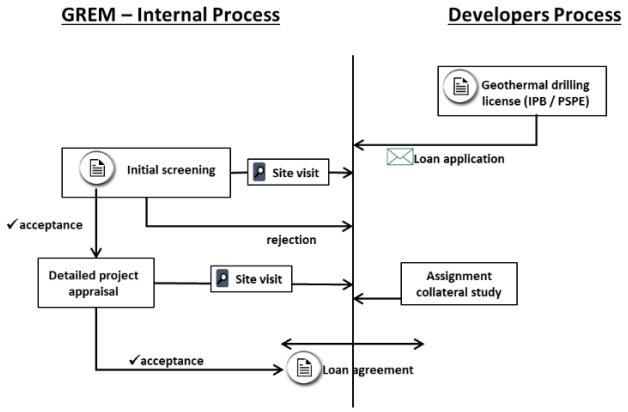


Figure 7: Overview on the Application Process.

The assessment process follows a two-step approach. The initial step involves a preliminary review of technical documents, geothermal license validity, and the adequacy of environmental and social documents. After a positive initial screening, including the first site visit, a thorough evaluation of all provided information takes place. This assessment entails an additional site visit to verify technical, environmental, and social aspects. Moreover, the developer (and sponsor) might be requested to attend meetings at PT SMI, where they can present their sub-project and address any queries.

Furthermore, the developer must engage an independent third party for collateral study. The selection of this third party should be made from a list of contractors provided by PT SMI. The outcomes of this study are to be directly communicated to PT SMI by the third party. The costs associated with this study

are the responsibility of the developer. PT SMI's feasibility analysis encompasses various factors, including those detailed in Figure 8.

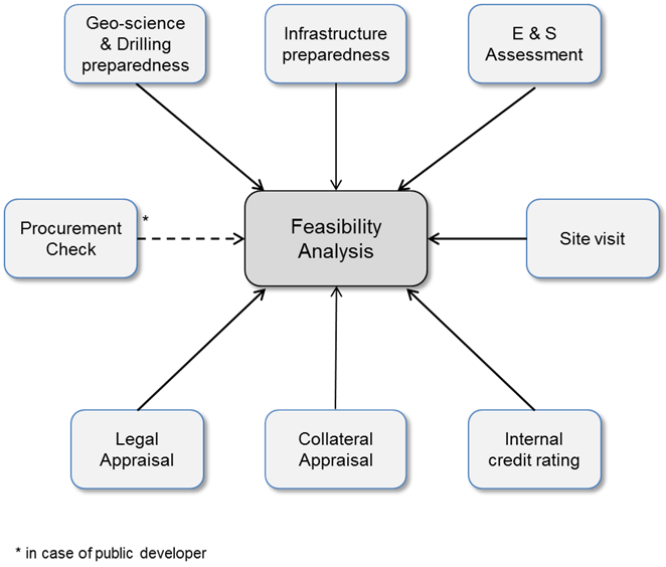


Figure 8: The Components of Feasibility Analysis.

4.5 Derisking Mechanism

Based on MoF Regulation No. 80/2022 Article 34, financing extended by PT SMI to public developers could include a risk-sharing mechanism, which allows forgiveness up to 50% of total facility for each project in the event of exploration and/or political risk. GREM offers a risk-sharing mechanism where in the event of unsuccessful explorations, the developers may be entitled for partial repayment of the facility (up to 50 percent of the total facility limit extended to the geothermal developers). As such, the GREM facility provides the early-stage support needed to mobilize downstream financing by commercial and other financiers at scale. However, there is no forgiveness provided for loans that finance delineation activities.

The forgiveness calculation is based on the Projected Project Value (PPV) model for public developer or Developer Fair Market Value (DFMV) model for private developer. PPV or DFMV model (the "Model") is a spreadsheet model that calculates the amount of forgiveness in the exploration financing for developer (if any) primarily based on net present value of the project. The Model includes all relevant assumptions (including technical and economic assumptions), which need to be filled in by the developer as part of the application process.

PT SMI will evaluate the Model alongside other aspects of the GREM application. Once the Model is approved as part of the application process, the Model (and its variables and assumptions) (the "Approved Model") will be fixed and not subjected to any future adjustment, except in respect of the following parameters (Adjustable Parameters).

Table 6: Adjustable Parameters of PPV Model and DFMV Model.

PPV Model	DFMV Model
1. Enthalpy	1. Enthalpy
2. MW production from the project	2. MW production from the project
3. Total budget	3. Total budget
4. MW production from exploration wells	4. MW production from exploration wells
5. GREM outstanding loan	5. Outstanding Financial Instrument facility
6. Exploration period	6. Exploration period
7. Expected PPA tariff or formula	7. Expected PPA tariff or formula
	8. Discount rate (Indonesia government 5-year bond rate)

The Approved Model will be put into a mutually agreeable escrow arrangement and will be updated by sub-borrower if it is required by PT SMI (the lender), such as when confirmation of exploration result is available.

4.6 Comparison of GREM with Other Similar Facilities Worldwide

Table 7 provides a comparison of various exploration financing support in Indonesia and other countries particularly facility supports that are intended to the public and private geothermal developers as explained above. Due limited information on the geothermal de-risking facility, the comparison will not include United States and New Zealand geothermal exploration de-risking scheme.

Table 72: Comparison of Various Exploration Financing Support in Various Countries (Siahaan et al, 2023).

Parameter	GREM Public Window (Indonesia)	GREM Private Window (Indonesia)	RSM (Turkey)	GRMF (East Africa)
Source of Funding	A combination of Multilateral Funds (channeled through the IBRD) and Geothermal Fund from the Indonesian Government	Multilateral Funds (channeled through the IBRD)	Clean Technology Fund (CTF)	German Federal Ministry for Economic Cooperation and the European Union (EU) - Africa Infrastructure Trust Fund through KfW Entwicklungsbank (KfW)
Eligible Beneficiary	Public geothermal developers (SOE/ majority owned by SOE developers)	Private geothermal developers	Private geothermal developers	Public developers, private developers, and Public Private Partnership (PPP)
Type of Facility Support	Loan with de-risking feature	Loan combined with subscription of Financial Instrument(s) issued by the private developers	Reimbursable Grant	Grant
Facility Limit	75% of the approved Total Drilling Program Costs with cap at maximum USD 30 million per project	75% of the approved Total Drilling Program Costs with cap at maximum USD 30 million per project	Maximum USD 4 million per project	- Infrastructure grants: up to 20% of the costs for infrastructure required for surface studies and drilling programs. - Surface study grants: up to 80% of eligible costs for surface study (excluding infrastructure costs). - Drilling grants: up to 40% of cost of exploration drilling and testing programs for reservoir confirmation wells (excluding infrastructure costs). - Continuation Premium: up to 30% of the approved costs of continuation activities or up to 30% of the developer's share of the eligible costs incurred. during the

Parameter	GREM Public Window (Indonesia)	GREM Private Window (Indonesia)	RSM (Turkey)	GRMF (East Africa)
				initial drilling, whatever is lower.
Eligible Expenditures	- Surface Studies (only for legacy financing) - Exploration drilling - Well-Testing	- Exploration drilling - Well-Testing	Exploration drilling (infrastructure costs shall not be included). Depending on the project location, exploration study costs may be eligible	- Surface studies - Exploration drilling and well testing
Facility Disbursement Scheme	- The disbursement schedule is discussed and agreed between PT SMI and the beneficiary during loan negotiation. - Every disbursement request will require the beneficiary to qualify that they are within an acceptable bound of the pro-forma budgets. - All disbursements must result in debt-to-equity ratio being maintained of not more than 75:25	- The disbursement schedule is discussed and agreed between PT SMI and the beneficiary during loan negotiation. - Every disbursement request will require the beneficiary to qualify that they are within an acceptable bound of the pro-forma budgets. - All disbursements must result in debt-to-equity ratio being maintained of not more than 75:25	Reimbursement of actual Acceptable Well Cost (AWC) incurred by the license holder.	Disbursement of grant funding based on project milestones and achievement of specified targets.
Repayment Obligation of the Beneficiary	Principal and interest with potential principal forgiveness if the exploration is unsuccessful	Principal and interest with potential principal forgiveness if the exploration is unsuccessful	5 (five) percent of success fee of the Acceptable Well Cost (AWC) if the exploration is successful	Grant funding, no repayment obligation

5. DISCUSSION AND PATH FORWARD

Indonesia has a robust geothermal target, aiming to expedite exploration projects in various geothermal prospect areas and Geothermal Working Areas (WKP). Swift progress in exploration is essential to identify viable geothermal resources for subsequent development. The potential capacity of the 73 exploration-stage geothermal areas is substantial at 3,520 MW. Even with a conservative assumption of 50-70% economic viability, Indonesia has a strong chance of achieving its 5,486 MW national target by 2030.

However, the exploration phase presents challenge due to high investment risks, primarily from drilling costs and limited data. This complexity hinders timely decision-making, delaying projects and complicating goal attainment. The high level of risk in the exploration phase can serve as both challenges and barriers for potential investors or geothermal developers in making investment decisions for geothermal development projects in Indonesia. Despite progressive pre-drilling activities, the drilling success rate remains low, impacting investor interest. Alternative schemes to share risks are needed to create a conducive environment for geothermal exploration.

One approach to stimulate geothermal exploration drilling is by utilizing public funds through cost-sharing mechanisms, mobilizing international funding such as climate-related funds, and employing suitable strategies for risk allocation and mitigation. This can serve as an incentive for developers to

mobilize larger investment funds. Particularly for cost sharing, this mechanism has been employed in several countries due to limitations in public funding and the intention to reduce the potential risk of failure for investors/developers in geothermal development.

This study compares global de-risking schemes, like Turkey's Risk Sharing Mechanism, East Africa's Geothermal Risk Mitigation Facility (GRMF), and Indonesia's Geothermal Resource Risk Mitigation Facility (GREM), to reduce financial uncertainties and stimulate investment. The study has compares GREM, Turkey's RSM, and East Africa's GRMF. It examines funding sources, beneficiaries, support types, limits, eligible expenses, and disbursement schemes to reveal strengths and limitations, aiming to foster geothermal development.

GREM is a form of support for the development of the geothermal sector in Indonesia, in the form of exploration financing facility with a key feature of risk sharing to mitigate resource risks at the exploration stage. GREM is developed by the World Bank and the Government through PT SMI as a financial intermediary institution and the fund manager and implementer of the program. In general, the geothermal exploration financing facility under the GREM scheme offers financing for geothermal exploration (particularly drilling) with de-risking features that enable partial forgiveness of the facility based on exploration outcomes. Additionally, GREM provides other support, including technical assistance and capacity building to stakeholders, including government agencies, businesses, and PT SMI specifically in terms of geothermal development.

Specifically, this paper has covered various facets of the GREM facility, commencing with its core features, eligibility criteria, the application process, and the de-risking mechanism. This comprehensive examination of these aspects aims to aid developers in Indonesia in comprehending the means of leveraging this facility to effectively manage risks in the exploration stage, particularly concerning resource feasibility.

Additionally, resource risk is just one challenge to be faced in geothermal development. Therefore, it must be strongly acknowledged that while the GREM scheme has the potential to mitigate resource risks in the exploration and/or delineation stages, GREM is not a silver bullet that can resolve all challenges and obstacles in geothermal development in Indonesia. Effective coordination among all stakeholders and government support are required to address other risks in geothermal energy development, including regulatory certainty that supports investments such as tariffs, incentives, and subsidies, if necessary.

The authors anticipate that this paper will initiate discussions on the most appropriate de-risking strategies to attain Indonesia's geothermal potential in a sustainable manner and attain its 2030 goal. Various aspects not addressed in detail within this paper, such as technical reviews and environmental and social safeguards, will be explored in separate papers to achieve a level of detail that proves beneficial for readers.

REFERENCES

ADB. (2018). *Developing Indonesia's Geothermal Power Potential*. Retrieved 12 22, 2022, from https://www.adb.org/news/features/developing-indonesia-s-geothermal-power-potential

Bisset, N., Soraya, N., Kurniawan, F., Sungkono, K., & Ang, K. (2021). *PLN's New 2021-2030 Business Plan: High Hopes and Greener Project*. Jakarta: BackerMcKenzie.

Bloomquist, R. G. (2005). The Evolution of U.S. Policy Designed to Encourage Geothermal Development Provision of Access and Encouraging Project Development. *World Geothermal Congress*.

Castlerock. (2010*). Phase 1 report: Review and Analysis of Prevailing Geothermal*.

Darma, S. (2016). Indonesia: Vast geothermal potential, modest but growing exploitation. *Geothermal Power Generation:Developments and Innovation*.

Darma, S., Imani, Y. L., Shidqi, M. N., Riyanto, T. D., & Daud, M. Y. (2021). Country Update: The Fast Growth of Geothermal Energy Development in Indonesia. Reykjavik: WCG.

DEN. (2022a). *Indonesia Energy Outlook 2022-2032*. Jakarta: Ministry of Energy and Mineral Resources.

EBTKE. (2022). *Pengembangan Panas Bumi di Indonesia*. Jakarta: Ministry of Energy and Mineral Resources.

ESMAP. (2016). *Comparative Analysis of Approaches to Geothermal Resource Risk Mitigation*. World Bank.

ESMAP. (2021). *Preparing Feasibility Studies For Financing of Geothermal Project*. Washington DC: World Bank.

Fadhillah, F. R. (2023). *Economic Evaluation of Bravo Geothermal Prospect*. Jakarta: ITB School of Business and Management-Thesis.

Fadhillah, F. R., Asyari, M. R., Bagaskara, A., Vanda, D. V., Adityatama, D. W., & Purba, D. (2022). Challenges in Getting Public Acceptance on Geothermal Project in Indonesia. *Indonesia International Geothermal Conference*. Jakarta: IGA.

Geothermex. (2010). An Assessment of Geothermal Resource Risk in Indonesia. California: Geothermex.

IGA. (2014). *Best Practice Guide for Geothermal Exploration*. Jakarta: World Bank.

IRENA. (2022). *Indonesia Energy Transition Outlook*. Abu Dhabi: International Renewable Energy Agency.

Lund, J. W., & Gordon Bloomquist, R. (2012). DEVELOPMENT OF GEOTHERMAL POLICY IN THE UNITED STATES WHAT WORKS AND WHAT DOESN'T WORK. Thirty-Seventh Workshop on Geothermal Reservoir Engineering.

MEMR. (2022). *Presentasi: Pengembangan Panas Bumi di Indonesia*. Jakarta: KESDM.

Moore, J., Ross, H., & Wright, P. (2010). Exploration 1976–2006: A History of Geothermal Energy Research and Development in the United States. US DOE.

Nur, S., Burton, B., Aida, N., & Ikhwali, M. F. (2023). Determining Optimal Incentives for Geothermal Project Procured within PPP Framework under Tariff Constraint. *Elsevier*.

PLN. (2021). *Rencana Usaha Penyediaan Tenaga Listrik*. Jakarta: Perusahaan Listrik Negara.

Poernomo, A. S. (2015). An overview of Indonesia Geothermal Development – Current Status and Its Challenges. *Proceedings of World Geothermal Congress*. Melbourne.

PT SMI. (2022a). Indonesia Geothermal Resource Risk Mitigation Project Developer Manual. https://ptsmi.co.id/strategic-cooperation/grem

PT SMI. (2022b). De-risking of Geothermal Exploration from Lender's Perspective.

Purba, D.P., Adityatama, D.W., Nugraha, R. P., Ayuningtyas, R. R., Chandra, V. R., Al-Hassan, M. A., Ramadhan, R. F., Rizqy, M. M. (2021). Resource Assessment Methods Selection for Geothermal Exploration Project in Indonesia: What Are the Considerations? Proceedings, 46th Workshop on Geothermal Reservoir Engineering, Stanford University, Stanford, California, United States.

Purba, D.P., Adityatama, D.W., Agustino, V., Fininda, F., Alamsyah, D., and Muhammad, F. (2020). Geothermal Drilling Cost Optimization in Indonesia: A Discussion of Various Factors, Proceedings, 45th Workshop on Geothermal Reservoir Engineering, Stanford University, Stanford, California, United States.

Purba, D.P., Adityatama, D.W., Umam, M.F., and Muhammad, F. (2019). Key Considerations in Developing Strategy for Geothermal Exploration Drilling Project in Indonesia, Proceedings, 44th

Workshop on Geothermal Reservoir Engineering, Stanford University, Stanford, California, United States.

Purwanto, E. H. (2019). Assessment of Exploration Strategies, Result, and Cost of Geothermal Fields In Indonesia. United Nation University.

Ram, H., & Letvin, A. I. (2014). Using Financial and Policy Tools to Address Exploration/Drilling Risk. GRC.

Siahaan, M. F., Purba, D., Septiani, G. A., & Paripurna, A. (2023). Preparing Technical and Commercial Documents for Geothermal Exploration Project Financing in Indonesia. *Stanford Geothermal Workshop*.

Siahaan, M. F., Septiani, G. A., Purba, D., & Paripurna, A. (2023). Geothermal Exploration Project De-risking: Discussion on Various Scheme. *Stanford Geothermal Workshop*.

SMI. (2021). *Indonesia Geothermal Resource Risk Mitigation Program*. Jakarta: Sarana Multi Infrastruktur.

Speer, B., Economy, R., Lowder, T., Schwabe, P., & Regenthal, S. (2014). Geothermal Exploration Policy Mechanisms: Lessons for United States from International Applications.

ThinkGeoenergy. (2023). *ThinkGeoEnergy's Top 10 Geothermal Countries 2022 – Power Generation Capacity (MW)*. Retrieved from https://www.thinkgeoenergy.com/thinkgeoenergys-top-10-geothermal-countries-2022-power-generation-capacity-mw/

TKYB-Türkiye Kalkınma ve Yatırım Bankası and World Bank. (2021). *RSM Geothermal Resource Validation - Beneficiary Manual 2.0*.

Umam, M., Adityatama, D., & Purba, D. (2018). Tantangan Pengembangan Energi Panas Bumi Dalam Perannya terhadap Ketahanan terhadap Ketahanan Energi di Indonesia. *Swara Patra*.

Pentahelix Model in Forest Conservation Program on Patuha Geothermal Area

Laurentia Mutiara Sani Widyawati, Muhammad Gantang Nugraha,
Annisa Nadhilah, Agung Maulana, and Ilen Kardani

PT GEO DIPA ENERGI

laurentia@geodipa.co.id, gantang@geodipa.co.id, nadhilahannisa@gmail.com,
agung@geodipa.co.id, ilen.kardani@geodipa.co.id

Keywords: Pentahelix, forest conservation, geothermal projects, community development

ABSTRACT

Indonesia has 14,5% on-grid electricity capacity and 40% world geothermal potential which is scattered over the country. Geothermal projects and power plants are mostly surrounded by forest or conservation area which leads to special permit needs and programs to ensure the sustainability of the forest which indirectly affect the sustainability of the geothermal operation. PT Geo Dipa Energi (Persero) geothermal power plant is in Mt. Patuha, Sugihmukti Village, West Java, geographically more than 40% of the village area is covered with forestry.

The purpose of this study is to analyze the role of parties in the Pentahelix model on the Forest conservation program in the Patuha geothermal area. There also not many papers conducted the study of the Pentahelix model in forest conservation aspect. This study is conducted by interview and document review in the period of 2021-2023.

Forestry conservation program involves multi-stakeholders with each interest and power. To maintain the forest and geothermal sustainability, the company has to conserve as many forests as possible in the surrounding area. One of the collaboration concepts involving multi-stakeholders is the Pentahelix model. Through the role of university students and institutions, PT Geo Dipa Energi as the business entity in collaboration with the experienced NGO (Burung Indonesia) facilitates and encourage the local government of Sugihmukti Village to issue the regulation on Environmental Management as well as developing the new local institution (Pasukan Jaga Leuweung/PJL) in forest/environment conservation. Meanwhile, the activities in protecting the environment are published by the local and each stakeholder's communication or dissemination media which enables more parties to support the community. Pentahelix model optimized the role of the Academician, Business entity, Government, Community, and Media (ABCGM) to enhance the social transformation which creates values for the society and environment.

With the issuance of Local Regulation (Peraturan Desa) in Environmental Management, the local government committed to spare the annual village funds for conservation-related activities. Local institution (PJL) created by the local government has the right to disallow illegal hunting and farming activities in the forest. Besides the physical facilities given by the company and NGO, PJL also gets the training and technical knowledge to conduct bird watching and monitoring, forest patrols, and nursery management to support their conservation activities.

Through the Pentahelix model in forest management programs, from 2021 to 2023 there is the 5% increase on birds and mammals species richness as well as 74% increase of birds and mammals individual abundance, also 60% decrease in the findings of threats to the environment.

1. INTRODUCTION

PT Geo Dipa Energi (Persero) Unit Patuha is one the Geothermal Power Plant located in West Java, Indonesia. The company is now running 60 MW electricity connected to Java-Madura-Bali electricity grid through Perusahaan Listrik Negara as national electricity company. Geothermal projects and power plants are mostly surrounded by forest or conservation area which leads to special permit needs and programs to ensure the sustainability of the forest which indirectly affect the sustainability of the geothermal operation. PT Geo Dipa Energi (Persero) has 34.900 ha operational area (Wilayah Kuasa

Pengusahaan Panasbumi) which 57% of it is overlaid with forestry area: conservation forest, protected forest, and production forest, as seen in the Figure 1 below.

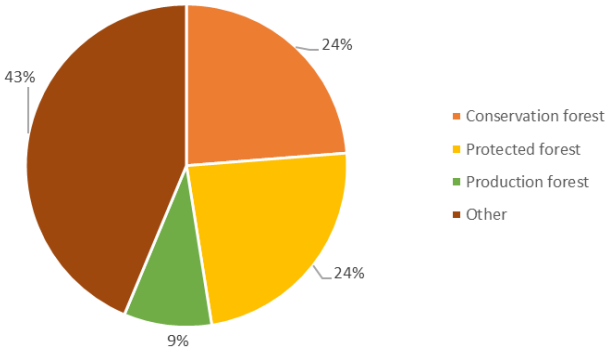


Figure 1: Patuha operational area based on Keputusan Menteri ESDM no. 2192/2014.

The ecosystems of our world depend on forests, which have several positive ecological, economic, and social effects. However, their long-term viability is seriously threatened by growing deforestation, climate change, and unsustainable activities. As well as geothermal companies whose have to have their forest in good condition in order to achieve sustainable production. Protected forest and production forest is managed by Perum Perhutani (as state-owned company on forest management) while conservation forest is managed by BBKSDA. In the implementation of forest management by Perum Perhutani, the surrounding community is engaged. Considering the number of stakeholders involved, the company uses Pentahelix model of collaboration as a tool to develop forest conservation programs.

Pentahelix model is used to build a collaborative environment built on information and creativity that integrates five different sectors. The Pentahelix Program is a cutting-edge and comprehensive framework for managing forests that considers the interdependence of five main stakeholders: governmental organizations, non-governmental organization, businesses worlds, academician, and mass media (Kismartini,2020). The Pentahelix seeks to address the complex issues related to forest conservation, restoration, and sustainable use by combining the aggregate knowledge, resources, and viewpoints of these various actors. In response, multidisciplinary and holistic forest management strategies have developed to ensure the conservation and sustainable use of these priceless resources.

This paper aims to explore each of the party in Pentahelix program including PT Geo Dipa Energi (Persero) as business entity, Universitas Gadjah Mada and Universitas Padjadjaran as academicians, Burung Indonesia and Pasukan Jaga Leuweung as non-governmental organization, Sugihmukti Village Government as governmental organization, and journalist or social media as mass media. It acknowledges the necessity of teamwork, knowledge exchange, and innovation to handle the intricate issues facing our forests. The Pentahelix Program works to protect and restore forest ecosystems while advancing the welfare of both nature and communities through the adoption of sustainable practices.

2. METHODS

This paper uses qualitative data collection method by interviewing the key person and document study in the period of 2021-2023. This method is suitable to use because the authors are trying to find a picture of how actors are involved in the pentahelix model (Yunas, 2023). Interview conducted to Burung Indonesia Project Manager and Community Development Officer PT Geo Dipa Energi. Document study is carried out on the Social Mapping Report (UGM, 2021), Burung Indonesia Terminal Collaboration Project Report period of 2021-2023, and Study of Community Perceptions and Intentions towards the Environment (Burung Indonesia, 2020).

Started with the Community Perceptions and Intentions towards the Environment study in 2020, which resulted in the baseline and strategic guidance to develop the intervention programs in the community. One of the results is that the villagers in Sugihmukti Village have the high intention to eradicate illegal hunting, the concern to sustainability of natural resources, and the intention to promote the pro-

environmental activities. While the Social Mapping Study in the Sugihmukti Villages by Universitas Gadjah Mada (2021) has identify the actors in forest management with each degree of power and importance, to be the baseline for the company to determine which stakeholders will be engaged in the pentahelix program.

To begin with, SWOT analysis is conducted to create the strategy matrix. As stated by Gurel (2017), SWOT Analysis is a strategic planning framework used in evaluation of an organization, a plan, a project or a business activity. SWOT Analysis is therefore a significant tool for situation analysis that helps the managers to identify organizational and environmental factors.

3. RESULTS AND DISCUSSION

3.1 SWOT Analysis & Strategy Matrix

SWOT analysis consist of the analysis of internal and external factors of the company regarding the program of forest conservation which can be used as the guidance to effectively identify which of its resources and capabilities are likely to be sources of competitive advantage and which are less likely to be sources of such advantages (Gurel, 2017). The actors in the SWOT analysis are referred to the Social Mapping Study and the Community Perception Study. Based on SWOT Analysis, the company can determine the appropriate strategy for implementing the forest conservation program, as explained in the Table 1 below.

Table 1: Strategy Matrix for the Forest Conservation Program.

	Strength • The company has the annual budget for CSR and environment sustainability • The company already have an agreement with conservation-based NGO	**Weakness** • Lack of knowledge and human resource of the company regarding the forestry management and conservation • The forest area surrounds the company operational area is not belongs to the company but managed by Perhutani and BBKSDA
Opportunity • Village Government in Ring-1 of the company (Sugihmukti Village) has strong intention in environment sustainability • The existence of local forest community • The village government hasn't had the internal policy on forest protection or environmental conservation • There are several universities which already engaged with the village and the NGO (forestry & social development major)	• Company engages the non-governmental organization to facilitate Villages conservation Policy (Local Policy) • Encourage the local forest community to be the part of the local policy	• Knowledge sharing/ training to increase the community capacity in forest conservation from the experts in university • Company engages Perhutani and BBKSDA in the forest conservation program
Threat Due to the wide area of forest in the village, there is not enough monitoring in the forest, so the illegal hunters and farmers are uncontrolled	Company set the budget to supports village on forest monitoring program	• Create the publication of program development in the village • Engage Perhutani and BBKSDA in the forest conservation program

Based on the Table 1, there are several strategies for the company to develop the forest conservation program, though the most important activities are to strengthen the Partnership Agreement either with other business entity, government institution, or the NGO. Also define the details for long- and short-term program planning with the consent form the stakeholders.

3.2 Pentahelix Actor Analysis

In Pentahelix, multiple actors play a role in forest management. These various actors have roles and functions in forest sustainability. Each of the roles and responsibilities of the 5 actors involved in the Pentahelix model is explained in this section, which is Governmental organization, non-governmental organization as well as community, private sector or business entity, academics, and the media.

3.2.1 Governmental Organization

Government plays a central role in establishing policies, regulations, and enforcement mechanisms to protect forests. Through the Pentahelix Program, these agencies collaborate with other stakeholders to develop robust forest management plans, establish protected areas, and enforce sustainable practices. By fostering interagency coordination and incorporating input from other sectors, government agencies can ensure the effective implementation of conservation strategies. Sugihmukti Government support for forest conservation by establishing Peraturan Desa no. 3 years of 2022 about Environment Management and Conservation. As a local policy, it can control the villagers and stakeholders to protect the environment (including forestry, domestic waste, water, etc.) as well as the punishment for breaking the law. In consequence of the enforcement of local policy, there is a special budget for environmental conservation in the Village Funds.

Balai Besar Konservasi Sumber Daya Alam (BBKSDA) as the government institution on natural resource conservation is also an actor stated in the SWOT matrix because BBKSDA owned and managed nearly 30% of the forest area in Sugihmukti Village. Though, those forest is stated as Conservation Forest which needs special permit from the central government to conduct the activities inside. BBKSDA role is to confirm that the conservation area is not encroached by the illegal farmers and hunters.

3.2.2 Non-governmental Organization

Non-governmental organizations around forest areas along with the local communities have invaluable knowledge and are directly impacted by forest conservation programs. The Pentahelix Program recognizes the importance of engaging and empowering local communities in decision-making processes. This involvement ensures that conservation measures are aligned with local needs, aspirations, and socio-economic realities. By integrating traditional knowledge and community-based management approaches, the program can enhance the long-term success of forest conservation initiatives. One of the conservation-based NGO, Burung Indonesia (as a part of Birdlife International in Indonesia), is involved in the pentahelix program because it already has the Partnership Agreement with the company since 2020. NGO play a crucial role in advocating for forest conservation and driving community engagement. Burung Indonesia helps accelerate and provide technical facilitation for the local government to announce the official local community focuses on forest protection, called Pasukan Jaga Leuweung (PJL). PJL was established in 2022 as the implementation of the local policy, which has an important role in protecting the forest from illegal hunters. Along with Burung Indonesia, this local community has been trained and given assistance to do the forest patrol, birdwatching and monitoring, as well as managing the nursery for reforestation. As regulated in local policy, PJL has its own operational budget and has the authority to enforce the illegal hunters and farmers out of their forest.

Burung Indonesia makes a significant contribution to forest conservation efforts by advocating for policy change, empowering local communities, giving assistance for the company in implementing local projects, conducting research and promoting cooperation. Their active involvement and pragmatic approach to the local community have made them central players in collective efforts to protect and sustainably manage forest ecosystems.

3.2.3 Private Sector Entities (Business)

PT Geo Dipa Energi, a geothermal energy company, has a high interest in protecting the surrounding forests as the steam for power generation is derived from water flowing into forest areas to the reservoir. Although the impact of meteoric water infiltration is indirect as shown in Figure 2, the forest is vulnerable to steam sustainability. Beside PT Geo Dipa Energi (Persero), there are other private sector entities around the Sugihmukti Village, which is the forestry management company (Perum Perhutani), tea plantation company (PT Perkebunan Nusantara), and geothermal tourism company, that have significant influence over forest landscapes. Referring to Table 1, the strategic business to engage in the pentahelix program is Perum Perhutani, because it managed almost 70% of the forest in the village. Collaboration with the Perum Perhutani enables the development of responsible supply chains, supports investment in reforestation and restoration projects, and promotes sustainable land-use practices that align economic growth with ecological integrity.

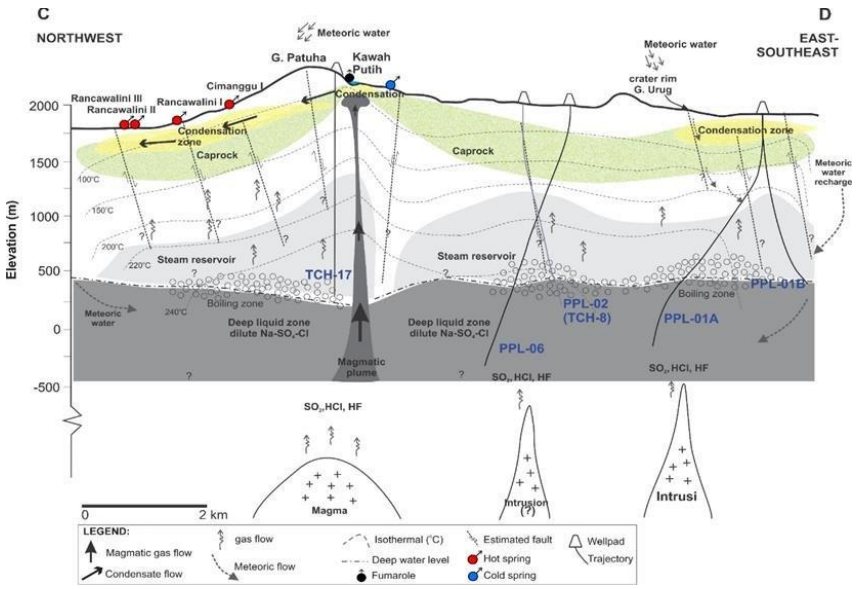


Figure 2: Patuha Geothermal Modelling Conceptual (Ashat, 2019).

One of PT Geo Dipa Energi mission is to maintain the sustainability of the company's business by optimizing the assets to give benefit for the society. The sustainability programs manifested in the GDE Peduli, GDE Maju, GDE Pintar, and GDE Hijau. In accordance with the company's mission in sustainability, the company invested in human capital and financial capital dedicated in environment and community development programs. Annually, the company spares its budget for the environment and community development programs around 4% of its operational budgetary.

Perum Perhutani as a forest manager take the role in involving and encouraging the local community on their activity in managing the forest in Sugihmukti Village, such as by forming the local institution called Kelompok Tani Hutan (KTH). KTH is given the opportunity to manage dedicated areas in the forest. In the pentahelix program, Perum Perhutani has an important role in giving the permission to another stakeholder to run the participatory forest patrol. The business entity acts as an enabler in the pentahelix model.

3.2.4 Academics

Academic institutions bring scientific expertise, research capabilities, and innovation to the forefront of forest conservation. By collaborating within the Pentahelix Program, academia contributes valuable insights, conducts research on ecosystem dynamics, and helps develop sustainable management strategies. This involvement fosters knowledge exchange, capacity building, and the integration of cutting-edge research into practical conservation initiatives. Universitas Gadjah Mada (UGM) and Universitas Padjadjaran (UNPAD) are institutions that contribute significantly to the advancement of forest conservation. Their research, education, and collaborative efforts with the local community as well as the NGO provide the foundation for evidence-based decision-making, capacity development,

and the implementation of sustainable practices necessary to ensure the long-term preservation of forest ecosystems. UGM conducts the study of social mapping as well as stakeholder mapping which is an important baseline document to conduct this program. Also, UNPAD and other academics institution especially major in social and conservation or agriculture has been the mentor and assist the local community and government in implementing the programs.

3.2.5 Media

The media play an important role in promoting forest conservation by raising awareness, influencing public opinion, holding stakeholders accountable and promoting cooperation. By leveraging their reach and influence, news outlets and journalists can contribute to broader efforts to protect and sustainably manage forest ecosystems. The collaborative program used to publish by multiple media owned by each stakeholder. It fastens and broadens the programs leverage and influence on different circles.

Figure 3 shows the relationship among the actors in the pentahelix program in forest conservation on Patuha Geothermal Area.

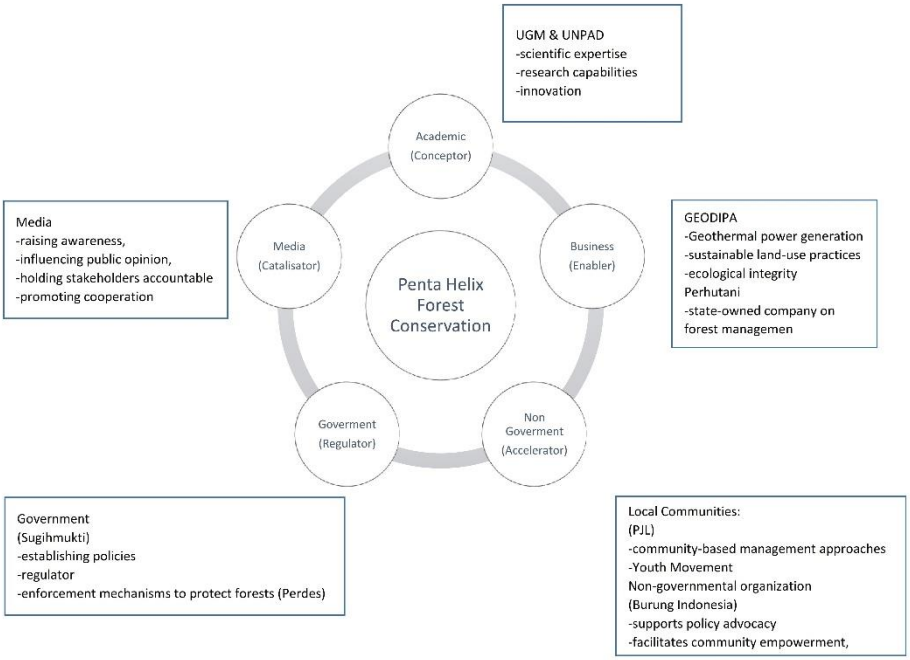


Figure 3: Pentahelix model on Patuha Geothermal Area.

3.3 Pentahelix Success in Forest Conservation Program

PT Geo Dipa Energi and Burung Indonesia (BI) share the same interest to protect forests. The company needs forests to be protected in order to sustain the business by assuring rainwater infiltration to the reservoir so the steam supply continuously available, while BI needs to protect forests as habitats for birds and other animals to assure the environment services are always available for the community. The same passion leads to the partnership agreement to protect the forest by community empowerment. The partnership agreement uses a co-founding model which shares various resources such as knowledge and costs.

Starting with the study of community perception towards the environment in Sugihmukti Village, compliment with Social Mapping study ahead, known that the Village Head (Kepala Desa) has a strong intention in protecting and creating a sustainable environment for his villagers. Thus, among various partnership programs, one of them is to facilitate the local government to establish the Local Policy in environment protection. Village head as the regulator takes the role as the local policy initiator. The local government does not have enough knowledge and technical skills to analyze the condition of the forest they want to protect. Therefore, the NGO (BI) along with their volunteers from the academic,

UGM, UNPAD, also other students from other university, take the role in assisting local government on local policy development. The Local Policy aims to control stakeholders to protect the forest area and give punishment for breaking the law. In the process of preparing local policy, all the actors' opinions were asked by organizing several Focus Group Discussion. In the end, all actors supported the Local Policy as the legal basis for forest conservation and their activity in the Sugihmukti Village, Local Policy established is Perdes no. 3 year of 2022 about Environment Management and Conservation.

With the excessive illegal hunters and farmers in the Sugihmukti Village, the Village Head feels the urge to create the special taskforce to manage them refer to their Local Policy. Recognizing the existence of local communities' activities in forest conservation, the Village Head established the legitimate local community called Pasukan Jaga Leuweung (PJL), it responsible as local law enforcers. As part of Local Policy implementation, PJL has its own budget for its operational activities sourced from Village Funds. PJL who do not have sufficient knowledge are still assisted by the NGO and its volunteers from the academician, with the PT Geo Dipa Energi (Persero) funding to support half of its empowerment, such as capacity building in seedling nursery technique, forest monitoring, and birdwatching technique. The company also builds and facilitates the nursery for PJL activities in forest conservation and revegetation, which also enables them to create economic value from their activities in nursing the forest seedling.

The collaborative programs which show the satisfactory result is the combination of routine forest patrol by PJL and participative forest patrol which involves all stakeholders who actively occupy the forest, such as ranger from Perum Perhutani, ranger from BBKSDA, PJL, BI along with their volunteer students, local government representative, as well as the security personnel and employee of PT Geo Dipa Energi. Monthly PJL patrols combined with half-yearly participative patrol resulted in the increase of bird species encounter and decrease in forest threats. In addition, in line with the growth of Industry 4.0, the forest patrol is done using online platform in Kobo Collect which available in web-based and android based. It helps the ranger and participant of the patrols to track their encounters with the flora/fauna and other environmental potential (waterfalls, spring, etc.) also the environmental threats (hunter hut, bird trap, illegal logging, etc.). The rangers are entitled to demolish the hunter's facility they found in the forest as well as reprimand the illegal farmers and chase them away from their forest. Table 2 below shows the result of programs with the comparation before (2021) and after (2023) program implementation.

Table 2: Comparison of the richness and abundance of indicator animals before and after program (Burung Indonesia Terminal Report, 2023).

	2021	2023
Richness of species	**72**	**77**
Bird	65	71
Mammals	7	6
Abundance of individual	**311**	**540**
Bird	290	508
Mammals	21	32

Table 2 shows there is increasing bird and mammals species richness along with the individual abundance after the 3 years program implementation. This participatory monitoring is also a tool to identify signs of success in forest conservation by finding more and more endemic birds and decreasing forest threats (before program 53 threats after program 21 threats) and decreasing animal hunting activities resulted in the increase on richness of species and abundance of individual as seen in the Table 2. In pentahelix implementation, the actors gathered to share resources in forest conservation, one of the activities is participatory monitoring. This activity aims to protect the forest so that the needs of the actors can be met and even have a positive impact on the surrounding village area. Due to the publication of this participatory monitoring results, and also PJL activities, one former hunter joined the PJL to

protect the forest. It is hoped that publication will further encourage more people to participate in forest conservation.

4. CONCLUSION

To conclude, all elements provide a very decisive role in the sustainable management of conservation forest in the Patuha Geothermal Area. Cooperation in the form of pentahelix is very effective in achieving common goals and providing benefits to all stakeholders. Pentahelix collaboration has resulted in developing regulation, establishing and empowering the local community, encouraging and inspiring others, also implementing the program itself. Quantitatively, participatory forest patrol program resulted in the change of species encounters in the forest, which shows the 5% increase on birds and mammals species richness as well as 74% increase of birds and mammals individual abundance, and 60% decrease in the findings of threats to the environment. It is hoped that this Pentahelix collaboration can prosper the community, keep forests sustainable, and maintain the recharge of geothermal areas.

REFERENCES

Ashat, Ali & Pratama, Heru & Itoi, Ryuichi. Updating conceptual model of Ciwidey-Patuha geothermal using dynamic numerical model, IOP Conference Series: Earth and Environmental Science (2019).

Gurel, Emet and Merba Tat. SWOT Analysis: A Theoretical Review, The Journal of International Social Research, 10, 51 (2017).

---.: Laporan Pengelolaan Bentang Alam Pegunungan Patuha Kerjasama PT Geo Dipa Energi (Persero) Unit Patuha dan Burung Indonesia Periode Januari-Juni 2023, Burung Indonesia (2023).

Kismartini and Hartuti. Pentahelix Model for Sustainable Coastal Area Management in Bangka Island, Advances in Social Science, Education and Humanities Research, 510, Atlantic Press (2020).

Social Development Study Center: Social Mapping Report, UGM (2021).

Supomo, Siti Zumrotin et al.:Study of Community Perceptions and Intentions towards the Environment Report, Burung Indonesia (2020).

Yunas, Novy Setia and Anik Susanti. The Pentahelix Mode in the Development of Agro-Culture-Based Edutourism in the Taman Nasional Bromo Tengger Semeru Buffer Village Area (A Study in Tosari Village, Pasuruan Regency and Sapikerep Viilage, Probolinggo Regency), Sodality: Jurnal Sosiologi Pedesaan, 11(01), 76-85 (2023).

Roles of Geothermal Industries to Accelerate Talent Development and Build a Robust Well-Connected Ecosystem

Rita Purwita I, Genny M Yudawinata,
Hadhy M Fauzy, Robby Oka Y, and Ilen Kardani

PT GEO DIPA ENERGI

rita_p@geodipa.co.id, genny@geodipa.co.id,
hadhy@geodipa.co.id, robby@geodipa.co.id, ilen.kardani@geodipa.co.id

Keywords: Talent Development, Geothermal Training, Internship, Competency Enhancement, Penta Helix

ABSTRACT

The geothermal industry plays a crucial role in accelerating talent development to meet the rapid demands on renewable energies. The expansion of the geothermal sector has created an urgent need for professionals who possess the skills and knowledge required to develop and manage geothermal resources efficiently. This need has highlighted the significance of training and competency development systems to accelerate and foster the capabilities of the talent pool.

In Indonesia, developing geothermal energy is a challenge due to the lack of skilled labor or experts to manage geothermal projects. Therefore, it is essential to invest in the competency development of talent to meet the growing demand for geothermal energy and ensure that there is a steady supply of skilled professionals in the industry. By doing so, we can create a sustainable and efficient geothermal industry that supports the transition towards renewable energies.

Apart from providing access to facilities, geothermal industries can also offer various programs that support students and professionals in gaining practical experience. Scholarships, internships, seminars, workshops, field trips, mentoring, and on-the-job training are some of the initiatives provided by industries. These programs help individuals gain hands-on experience, develop skills, and build networks within the industry. Knowledge sharing and benchmarking among practitioners can help to build competent workforce that can meet the demands of the industry. With their support and resources, individuals can gain the necessary skills and knowledge required to excel in the field and contribute to its growth.

The importance of collaborations between geothermal industries, universities, practitioner, and research institutions has grown significantly. These strategic partnerships are essential in fostering a continuous flow of innovative ideas and advancements in geothermal technology. By actively investing in research projects and promoting data sharing among professionals, the geothermal industry can ensure that cutting-edge solutions are developed and implemented. Furthermore, these collaborations benefit the overall training and education system by aligning academic curricula with industry requirements. Additionally, these partnerships create a strong network between industries, universities, and research institutions, promoting knowledge exchange and driving progress in the field of geothermal technology.

This article will elaborate the importance of collaborations in the geothermal industry and its impact to create a robust and well-connected ecosystem. How do we bridge the gap between theory and practice, ensuring that industry advancements are grounded in scientific research and validated by real-world experiences. Ultimately, fostering strategic partnerships across the geothermal landscape will drive growth and contribute to a more sustainable energy future.

1. INTRODUCTION

In recent years, there has been a growing interest in geothermal energy as a way to reduce our reliance on fossil fuels and combat climate change. Geothermal energy, as a clean and renewable source of power, has gained significant attention in recent years due to its potential for sustainable energy

production. However, the development of geothermal resources requires a skilled workforce. Geothermal industries can play a key role in accelerating talent development and building a robust well-connected ecosystem that will support the growth of the geothermal industry. This article delves into the vital role of collaboration in the geothermal industry, highlighting PT Geo Dipa Energi's program in the Patuha Geothermal Area as a model for talent development.

2. THE ROLE OF GEOTHERMAL INDUSTRIES IN ACCELERATING TALENT DEVELOPMENT

Geothermal industries can accelerate talent development in a number of ways. First, geothermal companies can provide training and education programs for their employees. These programs can cover a wide range of topics, including geology, engineering, and operations. Second, geothermal companies can partner with universities and other educational institutions to develop training programs. These partnerships can help to ensure that the geothermal workforce has the skills and knowledge that are needed to develop and operate geothermal projects. Third, geothermal companies can support research and development in the field of geothermal energy. This research can help to improve the efficiency of geothermal power plants and to develop new geothermal technologies.

2.1 PT Geo Dipa Energi's Talent Development Program in Patuha Geothermal Area

Talent development has emerged as a pivotal factor in fostering a sustainable and thriving workforce. For an organization like PT Geo Dipa Energi, committed to shaping the future of renewable energy, harnessing the full potential of its human capital is a must. Moreover, with a well defined talent development programs, PT Geo Dipa Energi (Persero) unit patuha could make great contribution to geothermal industries as well.

2.1.1 Talent Acquisition and Recruitment Strategies

Talent acquisition and recruitment strategies are an important part of any organization's success. By carefully defining and implementing a talent acquisition strategy, organizations can increase their chances of attracting and hiring the best talent for their open positions. A well-defined talent acquisition strategy can help organizations to achieve their long-term goals by ensuring that they have the right people in the right roles.

PT Geo Dipa Energi (Persero) employs various strategies to attract and recruit talented individuals. These strategies include partnering with educational institutions, participating in job fairs, and offering competitive compensation packages. Right now PT Geo Dipa Energi (Persero) has partnering with Institute Teknologi Bandung (ITB), Politeknik Bandung (Polban), and other universities as our source of talent by participating their job fairs. Since PT Geo Dipa Energi (Persero) targeting to attract Gen Z and millennial candidates, the company also using digital platform to publish job vacancy and search best candidates such as Kalibrr, LinkedIn Premium, Instagram.

To ensure recruitment process in company able to attract best candidates, the recruitment process consists several step, including : creating recruitment plan, internal or external job posting, interviews, FGD, and last job offering and hiring.

2.1.2 Training and Development Programs

PT Geo Dipa Energi recognizes the importance of continuous professional development for its workforce. The company encourages its employees to participate in certification programs and training courses offered by reputable institutions. These programs cover a wide range of topics, from geothermal reservoir management to advanced drilling techniques and geothermal power plant optimization.

Employee onboarding program become the first step to introduce geothermal industries and company itself to new employees. This program helps new employees integrate smoothly into their roles and the organizational culture, policies and also knowing some challenges in geothermal industries as well.

Every new hire in company will be assessed based on their individual competencies to see their gap competencies between individual skill and required skill on their position. This assessment program become framework to create various training programs to minimize the gap.

Coaching and mentoring programs are also established to foster a culture of learning and growth within the organization. Experienced professionals mentor younger employees, passing on valuable knowledge and insights gained over the years. This not only helps develop technical skills but also cultivates leadership and problem-solving abilities.

The company emphasizes the continuous development of its workforce through training programs, workshops, and knowledge-sharing platforms. These initiatives enhance employees' technical skills, leadership abilities, and industry knowledge.

PT Geo Dipa Energi has great commitment to develop its talent by collaborating with a lot of credible third party to conduct training, certification, and development program. As of today, the company has made collaboration with more than 50 training and certification organizers such as Succofindo, Patrari Jaya, Surveyor Indonesia, DDI, Dale Carnegie, DNV, GML, PPM, Delloite, Korn Ferry, etc. for both soft skills and technical skills as shown in Figure 1.

2.1.3 Collaborations with Educational Institutions

Collaboration between geothermal institutions and geothermal industries is the bridge that connects theory and practice. These partnerships ensure academic curricula align with industry requirements, facilitating seamless transitions for graduates into the workforce. By incorporating real-world experience and exposure to the latest technologies and industry practices, geothermal institutions can produce highly skilled professionals who are well-prepared for the demands of the industry.

PT Geo Dipa Energi believes in the transformative potential of industry-academia collaboration. The company actively engages with geothermal institutions, providing inputs on curriculum development and participating in joint research projects. This collaboration ensures that the skills and knowledge imparted to students are in line with industry needs.

Through guest lectures and workshops conducted by industry professionals, students gain valuable insights into the geothermal industry's current trends and challenges. This exposure enhances their ability to think critically and develop innovative solutions to real-world problems. As a result, graduates from these institutions are better equipped to contribute effectively to the geothermal industry from day one of their careers.

To get more practical experiences in geothermal field, PT Geo Dipa Energi unit Patuha offering 3 months long practical field work, internship, and workshop in Patuha field to student as part of collaboration with educational institution. This program ensures every student not only have theorical skills but also practical skill to face problems in geothermal field. Currently the company has collaboration with more than 100 students over past 2 years from more than 15 educational institutions as shown in Figure 2.

No	Nama Training & Sertifikasi	Jumlah Pegawai	Penyelenggara Training/Sertifikasi	Jenis
1	Certified Contract Management Specialist (CCMS)	3	Lembaga Pengembangan dan Konsultasi Nasional (LPKN)	Sertifikasi
2	Certified HR Program Executive (CHRPE)	3	PT GML Performance Consulting	Sertifikasi
3	ITC Category 1 Thermography cource	1	Smartgate Training and Consulting	Sertifikasi
4	Perpanjangan Sertifikasi Manager Energi	1	Arya Bangkit Widya-ABW	Sertifikasi
5	Perpanjangan Sertifikasi Penanggungjawab Pengendalian Pencemaran Air (PPPA)	1	LSP Lalinsa	Sertifikasi
6	Perpanjangan Sertifikasi Pengelolaan Limbah B3 (PLB3)	1	LSP Lalinsa	Sertifikasi
7	Perpanjangan Sertifikasi Petugas K3 Kimia	1	ISC Safety School	Sertifikasi
8	Perpanjangan Sertifikasi Skema Spektrometri	1	LSP Telapi	Sertifikasi
9	Perpanjangan Sertifikasi Skema Volumetri	1	LSP Telapi	Sertifikasi
10	Perpanjangan Sertifikat Teknisi Perancah	14	ISC Safety School	Sertifikasi
11	Sertifikasi Accident Investigator	1	PT Patrarijaya Utama	Sertifikasi
12	Sertifikasi Ahli K3 Umum	2	ISC Safety School	Sertifikasi
13	Sertifikasi Auditor Energi	2	Arya Bangkit Widya-ABW	Sertifikasi
14	Sertifikasi Instrumentasi dan Kalibrasi Tingkat 1	2	PT Patrarijaya Utama	Sertifikasi
15	Sertifikasi Keahlian Perhitungan Nilai Daur Hidup (LCA)	2	PT Patrarijaya Utama	Sertifikasi
16	Sertifikasi Penanggung Jawab Operasional Air Limbah (POPAL)	3	PT Patrarijaya Utama	Sertifikasi
17	Sertifikasi Penanggung Jawab Operasional Instalasi Pengendalian Pencemaran Udara (POIPU)	1	PT Patrarijaya Utama	Sertifikasi
18	Sertifikasi Penanggung Jawab Operasional Instalasi Pengendalian Pencemaran Udara (POIPU)	1	PT Patrarijaya Utama	Sertifikasi
19	Sertifikasi Pengawas Operasional Madya (POM)	10	LSP Energi Mandiri	Sertifikasi
20	Sertifikasi Pengawas Operasional Pertama (POP)	36	LSP Energi Mandiri	Sertifikasi
21	Sertifikasi Pengawas Operasional Utama (POU)	1	LSP Geologi Pertambangan Panas Bumi - GPPB	Sertifikasi
22	Sertifikasi Pengelolaan dan Pengolahan Limbah Non-B3	2	PT Patrarijaya Utama	Sertifikasi
23	Sertifikasi Skema petugas pengambil Contoh Air	1	LSP Telapi	Sertifikasi
24	Sertifikasi Supervisor Perancah	2	PT Patrari jaya Utama	Sertifikasi
25	Wakil Ketua Teknik Panas Bumi (WKTPB)	2	EBTKE	Sertifikasi
26	Sertifikasi Asesor Uji Alir	1	LSP Geo Mineral Batubara & Energi	Sertifikasi
27	Sertifikasi Ahli K3 Umum	2	PT Mutiara Mutu Sertifikasi	Sertifikasi
28	Sertifikasi Penanggung Jawab Pengendalian Pencemaran Udara (PPPU)	1	PT Patrarijaya Utama	Sertifikasi
29	Sertifikasi Manager Energi	1	PT Patrarijaya Utama	Sertifikasi
30	Sertifikasi Kompetensi Pengambilan data Penilaian Daur Hidup (LCA)	2	PT Patrarijaya Utama	Sertifikasi
31	Operator Pesawat Angkat Angkut (Forklift Kelas II)	3	PT Patrarijaya Utama	Sertifikasi
32	Sertifikasi Pengawasan Pengelolaan Limbah Padat Non B3	1	PT Patrarijaya Utama	Sertifikasi
33	Sertifikasi Petugas P3K	5	PT Patrarijaya Utama	Sertifikasi
34	Advance Vibration Analysis Course	1	PT Tiara Vibrasindo Pratama	Training
35	Analisa Tan Delta dan Partial Discharge	2	PT Patrarijaya Utama	Training
36	Awareness Sistem Manajemen K3 dan Sistem Manajemen Lingkungan ISO 14001:2015	11	Sucofindo	Training
37	Deklarasi Kondisi dan Indeks Kinerja Pembangkit (DKIKP)	4	Srikandi Nusantara Jaya Consultant	Training
38	Drilling for Non Driller	5	PT Geo Dipa Energi (Persero)	Training
39	Geothermal Well Workover for Non Driller	12	PT. Srikandi Nusantara Jaya Consultant	Training
40	HR Business Process Design Awareness Level	4	Pungki Purnadi Associate	Training
No	**Nama Training & Sertifikasi**	**Jumlah Pegawai**	**Penyelenggara Training/Sertifikasi**	**Jenis**
41	Information Security Awareness (ISA)	68	Kementretian Keuangan-BPPK	Training
42	Instrument Process Control	2	PT Patrarijaya Utama	Training
43	Introduction to Geothermal 102	5	New Zealand Support for Training in Geothermal Support (NZSTIGS)	Training
44	Inventory and Warehouse Management	2	PT Patrarijaya Utama	Training
45	ISO 37001:2016 Anti bribery Managemen System Requirements	4	BSI Training Academy	Training
46	ISO 37001:2016 Anti bribery Management System Implementing	3	BSI Training Academy	Training
47	ISO 37001:2016 Anti bribery Management System Internal Auditor	3	BSI Training Academy	Training
48	ISO 9001 Sistem Manajemen Mutu	18	PT Denvegraha	Training
49	Kontrak Manajemen	2	Powerindo NS Training Development	Training
50	Machinery Lubricant Analyst Level 1	1	PT Tiara Vibrasindo Pratama	Training
51	Manual Valves (Detail Design dan Parts dari Gate, Ball, Plug, Butterfly dan Check Velves)	4	PT Varley Indonesia	Training
52	Operasional Pengelolaan Limbah B3 Level Operator	1	Adhiwiyata Bina Bestari	Training
53	Operational and Maintenance Repairs to Mechanical Pumps	7	New Zealand Support for Training in Geothermal Support (NZSTIGS)	Training
54	Pelatihan Keanekaragaman Hayati	3	PT Patrarijaya Utama	Training
55	Pengelolaan Sampah Berbasis 3R	1	PT Patrarijaya Utama	Training
56	Principles of Operation of a Geothermal Steam Turbine & Principles of Operation of a Generator	1	New Zealand Support for Training in Geothermal Support (NZSTIGS)	Training
57	Project Management with Microsoft Project	2	PJB Academy	Training
58	Prosedur Implementasi Penggunaan Produk Dalam Negeri (TKDN) dan Tata Cara Perhitungan TKDN	10	Surveyor Indonesia	Training
59	RAM Analysis for Geothermal Power Plant	14	D & G Advancetech	Training
60	Refreshment IT Service Management (ITSM)	1	Veda Praxis	Training
61	Reliability User Conference	2	PT Tiara Vibrasindo Pratama	Training
62	Root Cause Analysis for Team Members	8	New Zealand Support for Training in Geothermal Support (NZSTIGS)	Training
63	Short Term Training Scholarship (STTS) on Geothermal Energy Project Management di New Zealand	3	New Zealand Schollarship	Training
64	Short Term Training Scholarship (STTS) on Geothermal Energy Project Management di New Zealand	3	New Zealand Schollarship	Training
65	Short Term Training Scholarship (STTS) on Geothermal Energy Project Management di New Zealand	3	New Zealand Schollarship	Training
66	Sistem manajemen Mutu ISO 9001	1	PT Patrarijaya Utama	Training
67	Software GWB	1	Aqueous Solutions	Training
68	The Training and Study Tour Program for Geothermal Power Plant	9	AOTS Japan	Training
69	Tracer Flow Test (TFT)	2	PT Mustikabumi Indonesia	Training
70	Uninterruptible Power Supply (UPS) Power Supply Analysis & Troubleshooting	1	Mairodi Mandiri Sejahtera	Training
71	Well Control	2	PT Crew Petro Indonesia	Training
72	Basic Instrumentation & Control System	5	PT Patrarijaya Utama	Training
73	Petugas Penanganan Bahaya Gas H2S	5	PT Patrarijaya Utama	Training
74	Generator Excitation System	4	PT Patrarijaya Utama	Training
75	Automatic Voltage Regulator : Operation and Maintenance	4	PT Patrarijaya Utama	Training
76	Risk Management In Surface Production Facilities	3	PT Patrarijaya Utama	Training
77	Generator Governor Control System	4	PT Patrarijaya Utama	Training
78	Fault, Failure and Problem Prevention with Root Cause Analysis	4	PT Patrarijaya Utama	Training
79	Sistem Proteksi Petir & Grounding	4	PT Zeus Prima Garda	Training
80	Principle of Operation of Geothermal Binary Powerplant	6	New Zealand Support for Training in Geothermal Support (NZSTIGS)	Training
81	Advanced Operations of Steam Gathering Network	9	New Zealand Support for Training in Geothermal Support (NZSTIGS)	Training
82	Penanganan Kebakaran	20	PT Resik Training Center	Training
83	Pengadaan Lahan	2	PT Equator Global Internasional	Training
84	Maintenance principles of electrical equipment	2	New Zealand Support for Training in Geothermal Support (NZSTIGS)	Training

Figure 1: List of Training and Certification.

No	Institution Name	Major
1	SMK NEGERI 1 Soreang	Teknik Pengelasan
2	SMK Prakarya Internasional	Teknik Pemesinan
3	Universitas Majalengka	Managemen
4	PEM Akamigas	Teknik Produksi Migas
5	Universitas Gajah Mada	Teknilk
6	TEDC Bandung	Teknik Otomasi
7	PENS	Sistem Pembangkit Energi
8	Politeknik Negeri Bandung	Teknik Elektro
9	Politeknik Negeri Bandung	Teknik Mesin
10	Politeknik Negeri Bandung	Teknik Konversi Energi
11	Politeknik Negeri Bandung	Managemen Aset
12	SMK Katapang	Teknik Mekatronika
13	Universitas Lampung	Teknil Mesin
14	Politeknik Perkapalan Negeri Surabaya	Teknik Mesin
15	Institut Teknologi Bandung	Geologi
16	Institut Teknologi Bandung	Teknik Industri
17	Universitas Brawijaya	Teknik Kimia
18	Taylor University Malaysia	Management

Figure 2: List of Institution.

Other than those programs, PT Geo Dipa Energi also collaboration with international educational institutions. This initiative come from New Zealand and Iceland as part of their commitment to develop renewable energy all over the world. PT Geo Dipa Energi has been collaborated with Jacobs's program New Zealand Support for Training in Geothermal Support (NZSTIGS) for over 4 years and continuously sending employees to New Zealand to learn from experts in geothermal industries and get another perspective regarding development in geothermal industries. Every year the company will send 1 or 2 its employees to study in New Zealand for 3 months long and back with new knowledge to share through sharing knowledge programs. Besides New Zealand, the company also made a collaboration with Iceland through The Geothermal Training Programme (GRÓ GTP) which aims to strengthen organizational, institutional and individual, capacities with each Programme working towards the Sustainable Development Goals.

2.2 The Importance of Government, Regulators, and Industry Collaboration to build a Robust Well-Connected Ecosystem

Collaboration between the government, regulators, and the geothermal industry is pivotal in ensuring the sector's sustainable development. Through collaboration, the government and regulators can provide support and incentives that foster the growth of the industry. By developing policies and regulations aligned with the geothermal sector's needs, they can encourage investments and advancements in geothermal resources.

PT Geo Dipa Energi recognizes that a conducive regulatory environment is essential for the geothermal industry's growth. The company actively engages with government agencies and regulators to provide insights on policy development and the regulatory framework. These engagements ensure that policies are tailored to promote investments in geothermal exploration and development while addressing environmental and social considerations.

2.3 The Role of the Penta Helix Model: A Connected Ecosystem

The Penta helix model, consisting of government, industry, academia, media, and the community, promotes collaboration, knowledge sharing, and innovation. This model establishes a well-connected ecosystem that supports talent development and drives the growth of the geothermal industry. By bringing together key stakeholders, the Penta helix model creates a unified front in tackling challenges and seizing opportunities in the renewable energy landscape.

PT Geo Dipa Energi is a firm believer in the power of the Penta helix model. The company actively engages with various stakeholders, including government agencies, research institutions, the media, and local communities. By collaborating with the government and academia, the company stays informed about the latest developments in geothermal technology and research. This knowledge informs the company's strategies and helps it stay ahead in the geothermal sector.

The media plays a crucial role in promoting awareness about renewable energy and geothermal technologies. PT Geo Dipa Energi engages with media organizations to disseminate information about its talent development programs, sustainable practices, and community engagement initiatives. This fosters public support for the geothermal industry and helps create a positive perception of renewable energy solutions.

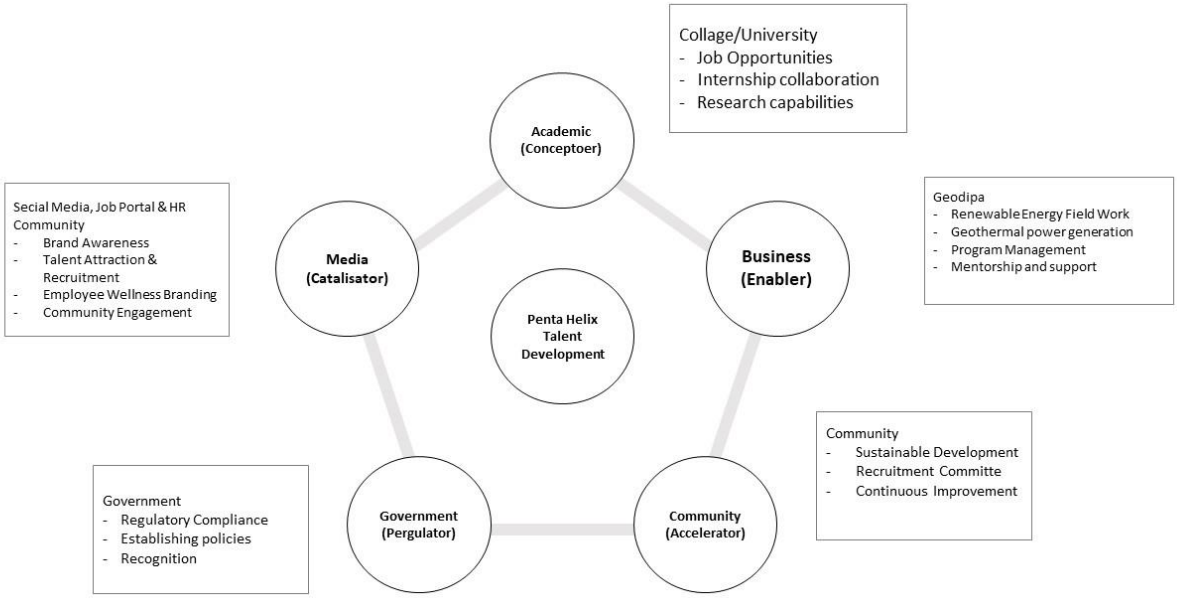


Figure 3: Penta Helix Talent Development model on Geo Dipa Energi.

In the context of the geothermal area, a Penta Helix approach could lead to significant advancements in geothermal technology, talent development, and overall industry growth. Here's how each stakeholder in the Penta Helix model could contribute to the geothermal sector:

1. **Government:** The government plays a critical role in creating a conducive policy and regulatory environment for geothermal energy development. Additionally, governments can fund research and development initiatives, promote geothermal energy in the national energy mix, and provide supportive infrastructure.
2. **Business:** Geo Dipa as a private sector geothermal energy companies and related businesses, brings expertise, capital, and operational capabilities to develop and implement talent development. They can invest in research, and collaborate with other stakeholders to increase the efficiency and cost-effectiveness of geothermal operations.
3. **Academic:** Institutions, Collage, University and research organizations can contribute by conducting research on geothermal technology, exploration methods, and environmental impact assessments. They can train and produce skilled professionals through specialized geothermal engineering and geosciences programs, meeting the industry's workforce needs.
4. **Community:** The local communities living near geothermal resources are important stakeholders. In a Penta Helix model, their involvement is vital to ensure social acceptance and sustainable development. Engaging with the community and considering their perspectives can lead to win-win solutions that benefit both the industry and the people.
5. **Media:** The function of a media platform like a job portal is to connect job seekers with potential employers and facilitate the process of job searching and hiring. Job portals serve as online platforms where job seekers can browse and apply for various job openings, and employers can post job listings to attract qualified candidates. And then, social media platforms serve various functions and play a significant role in modern society. Social media serves as a platform to build and maintain professional networks and relationships. Users can connect with like-minded individuals, colleagues in the same industry, or even potential business partners.

3. CONCLUSION

Geothermal industries can play a key role in accelerating talent development and building a robust well-connected ecosystem. By providing training and education programs, creating internship and apprenticeship opportunities, collaborating with universities and other educational institutions, working with government agencies, research institutions, and other stakeholders, and collaborating with other industries, geothermal industries can help to ensure that the geothermal industry has the skilled workforce it needs to meet the world's growing energy needs.

PT Geo Dipa Energi's program in the Patuha Geothermal Area serves as an exemplary model for fostering collaboration between key players in the industry. By investing in talent development and promoting collaboration between industries, academia, and the government, the geothermal sector can meet the demands of renewable energy and contribute to a sustainable future for generations to come. The concerted efforts of all stakeholders, guided by the Penta helix model, will propel the geothermal industry forward, ensuring a greener and more sustainable energy landscape for the world.

The future of the geothermal industry looks promising, with PT Geo Dipa Energi's efforts serving as a benchmark for sustainable growth, technological advancements, and talent development within the sector. In conclusion, PT Geo Dipa Energi's commitment to talent development and ecosystem building has made a significant impact on the geothermal industry, providing valuable insights for the industry's sustainable growth and development.

REFERENCES

Aguilar, A., & Zubielqui, I. (2019). The pentahelix model of innovation and the role of public policy in renewable energy. Energy Policy, 128, 209-215.

Daniel A. Jones, David J. Hill, and Michael J. O'Leary (2014). Building a Geothermal Workforce for the Future: Challenges and Opportunities. 1-12

I.B. Fridleifsson (1995). Human Resource in Geothermal Development.

Indonesia Geothermal Association. (2022). Geothermal Industry Outlook 2022. Retrieved from http://www.inaga.or.id/public/content/Geothermal-Industry-Outlook-2022.pdf

United Nations Environment Programme (UNEP). (2019). Promoting Skill Development for Green Jobs in the Renewable Energy Sector. Retrieved from https://www.unenvironment.org/resources/report/promoting-skill-development-green-jobs-renewable-energy-sector

World Bank Group. (2021). Indonesia - Accelerating Sustainable Geothermal Energy Program Project. Retrieved from https://projects.worldbank.org/en/projects-operations/project-detail/P167821

Towards Sustainable Development: Evaluating the Environmental Impact of Renewable Energy Technologies Worldwide

Adika Bagaskara[1,2], M. Rizqi Al Asyari[1,2], Daniel W. Adityatama[1,2], Dorman Purba[2], and Fatkhur Rahman[3]

[1]Geoenergi Solusi Indonesia (Geoenergis), Cibis Nine 11th floor, Jakarta 12560, Indonesia
[2]Enerka Bhumi Pratama, Cibis Nine 11th floor, Jakarta 12560, Indonesia
[3]Petrosea, Indy Bintaro Office Park, CBD Bintaro Jaya, South Tangerang, Indonesia

adika.bagaskara@outlook.com

Keywords: Renewable Energy, Environmental Impact, Water Consumption, Land Use, Carbon Emissions

ABSTRACT

The transition to renewable energy sources has gained significant momentum worldwide, driven by the need to mitigate climate change and reduce reliance on fossil fuels. This study examines the current condition of renewable energy in Indonesia and worldwide, specifically focusing on its environmental impact. The analysis comprehensively evaluates three key aspects: water consumption for various electricity generation technologies, land use comparison in power plant electricity production, and typical carbon emissions associated with different types of renewable energy.

To assess water consumption, various life cycle assessments are conducted for different renewable energy technologies, including geothermal, solar, wind, and hydropower. The findings provide insights into the water intensity of each technology and its implications for water resources. Furthermore, the study compares land use requirements among different renewable energy technologies employed in power plants. The aim is to provide an understanding of the land footprint associated with each technology and its implications for land availability and ecosystems.

In addition to water consumption and land use, this paper explores the carbon emissions associated with renewable energy technologies. Typical emission factors are presented for various renewable sources, enabling a comprehensive comparison and assessment of their carbon footprint. The implications of these emissions on climate change mitigation strategies are discussed. The paper contributes to the ongoing dialogue on sustainable energy transition by providing a comprehensive analysis of the environmental impact of renewable energy in Indonesia and worldwide. The results highlight the water consumption, land use, and carbon emissions associated with different technologies, aiding policymakers, researchers, and industry stakeholders in making informed decisions towards a more sustainable energy future. The findings underscore the need for strategic planning and effective environmental management to ensure the long-term viability and sustainability of renewable energy deployment.

1. INTRODUCTION

1.1 Indonesia Renewable Energy Potential Capacity, Installed Capacity, and Utilization Rate

To begin the discussion, it is important to have an understanding on how large Indonesia's renewable energy potential is, and what the utilization rate is in the country. Based on data or information from RUPTL and ESDM, the first renewable energy power plant that Indonesia built was for hydropower and since then the country has utilized this type of energy rather highly. Geothermal has a much higher utilization rate compared to solar and wind energy, in which both solar and wind are still very rarely utilized. Details of the potential each renewable energy possess is presented in the table below. The utilization percentage shows how Indonesia have taken longer to increase its installed renewable energy capacity; despite of how renewable energy is expected to become the key energy source.

As a start, there needs to be an understanding of renewable energy potential in Indonesia, along with its utilization rate. Based on the utilization data below, hydropower and geothermal are the ones that have

rather high utilization. This is quite reasonable considering that hydropower is a type of renewable energy power plant that is first owned by Indonesia. Geothermal energy is even higher in percentage, compared to solar and wind energy, which percentage are still small. The detail of the potential capacity of each renewable energy sources has, installed capacity as well as the utilization rate in Indonesia is shown in the following table. The data shows that several renewable energy sources that are expected to become Indonesia's key energy source in the future actually have great potential but are still small or have low levels of utilization.

Table 1: Breakdown of land use for a variety of electricity generation technologies (global case, in square-meter/MW) (PLN, 2021; ESDM, 2021).

No.	Type of energy	Potential capacity (MW)	Installed capacity (MW)***	Utilization (%)
1	Geothermal	23,965*	2,286.05	9.54%
2	Solar	207,898**	225.04	0.11%
3	Hydro	75,091**	5,988.67	7.98%
4	Mini or micro-Hydro	19,385**	613.08	3.16%
5	Wind	60,647**	154.31	0.25%

1.2 Different Locations or Large Renewable Energy Potential in Indonesia

Proof of potential estimates of geothermal energy still needs to be done through exploration drilling. Current documentations present information that large potentials are mostly in the island of Sumatera and Jawa, as seen in figure below, with the installed capacity mainly focused in Jawa. Various factors for consideration are required, especially non-technical ones such as tariffs, demand, etc. Indonesia's solar energy potential is enormous, given its location on the equator, which is the main reason for the country's hot climate temperature. Indonesia's island of Kalimantan has the largest potential of this renewable energy. The figure below shows that the west part of the Kalimantan province possesses the largest solar potential, which covers approximately 10% of the total capacity.

In terms of wind energy, Indonesia has certain risks and wind characteristics that suggests areas for wind development is to have the wind speed of 6-8 m/s, higher than recommendations suggested by several literature studies and best practices that have been conducted globally. Such areas in Indonesia with this speed magnitude is known to be mostly in south coast of Jawa, as shown Figure 1.

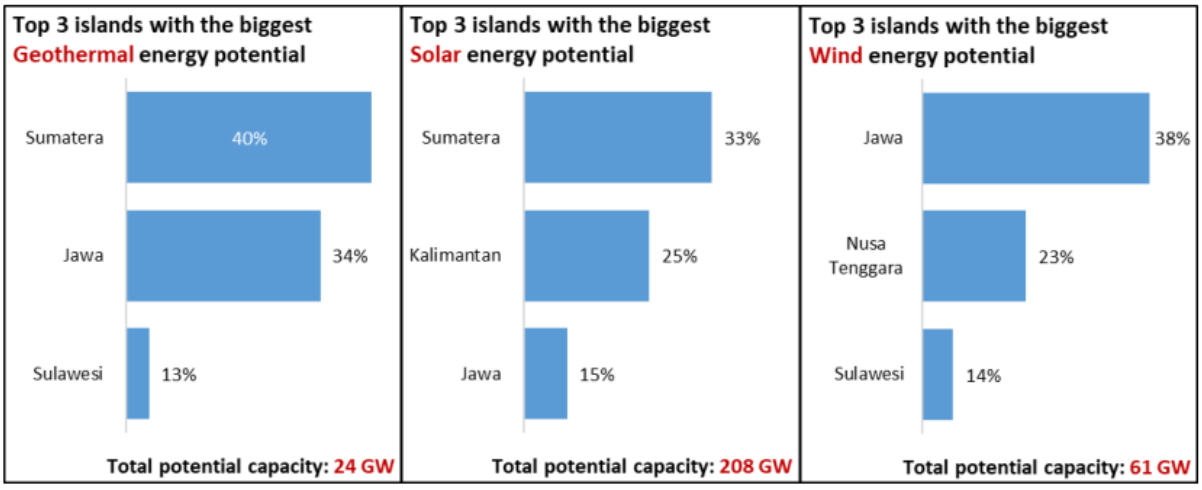


Figure 1: Location in Indonesia with the biggest Geothermal, Solar and Wind energy potential (PLN, 2021; RUEN, 2017).

For geothermal energy, potential estimates still need to be proven through exploration drilling. The biggest potential is currently documented on the Sumatera and Jawa Island, as shown in Figure 1. However, installed capacity is still focused on Jawa Island. The low utilization is related to various factors that need to be considered, especially non-technical ones such as tariffs, demand, etc. The potential for solar energy in Indonesia is enormous, given its location on the equator.

In terms of temperature, Indonesia is also quite hot, mainly due to radiation. The biggest potential is currently documented on Kalimantan Island, as shown in the following figure. The biggest potential for solar energy is mainly in West Kalimantan Province which covers about 10% of the total potential capacity. Some literature and global best practice state that areas for the development of wind energy should have at least a wind speed of 4 m/s. However, in Indonesia, with all the risks and the intermittent nature of the wind, the recommended wind speed is at least 6-8 m/s. Wind speeds of this magnitude can be found mostly on the Jawa Island, as shown in Figure 1, especially on the south coast.

Hydro energy potential could be located within the forest and residential area, as documented by several studies. Due to the difficulties, only a limited amount of hydropower can be built over time. Initiatives by the government to allow the utilization of government-owned dams (PUPR) can help to accelerate hydro energy installed capacity and reduce risks in the management process.

In Indonesia the island of Papua has a sufficient amount of hydro energy potential, with a 1% difference compared to Kalimantan (see figure below). The development of mini and micro hydro power plants is expected to grow competitively through regulatory support. With the issuance of a regulation from Ministry of ESDM, it is expected that the development of mini and micro hydro power plants will increase by involving private developers. The biggest potential is currently documented on Kalimantan Island, as shown in the following figure.

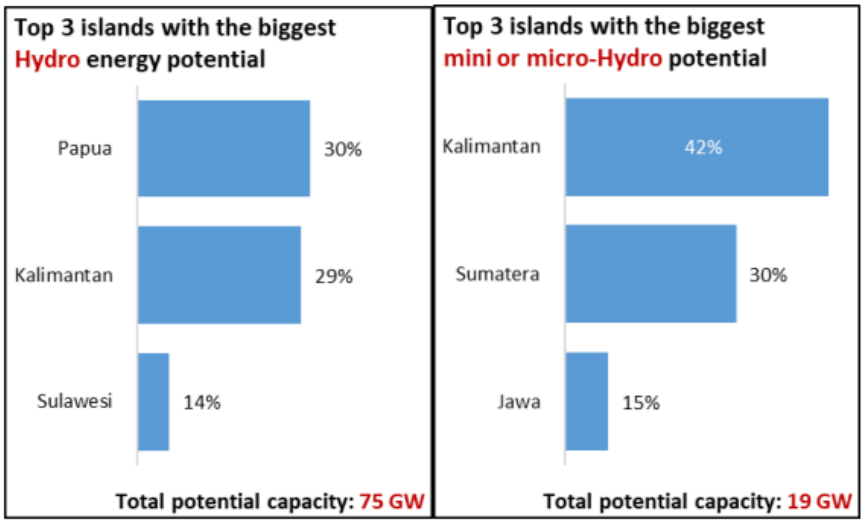


Figure 2: Location in Indonesia with the biggest Hydro energy potential (RUEN, 2017).

1.3 Typical Use of Energy Sources

For electrical generation, the use of coal still dominates the majority of power plants in the world, even in Indonesia. The illustration below also represents the conditions in Indonesia, where the grid contribution of renewable energy is still relatively small. This is detailed in the following discussion. Except for electricity generation; geothermal, solar and mini or micro-hydro energy is also adequate to fulfil the electricity demand in residential. For commercial and industrial use, geothermal and hydro energy are still the best option, considering their characteristic to provide baseload.

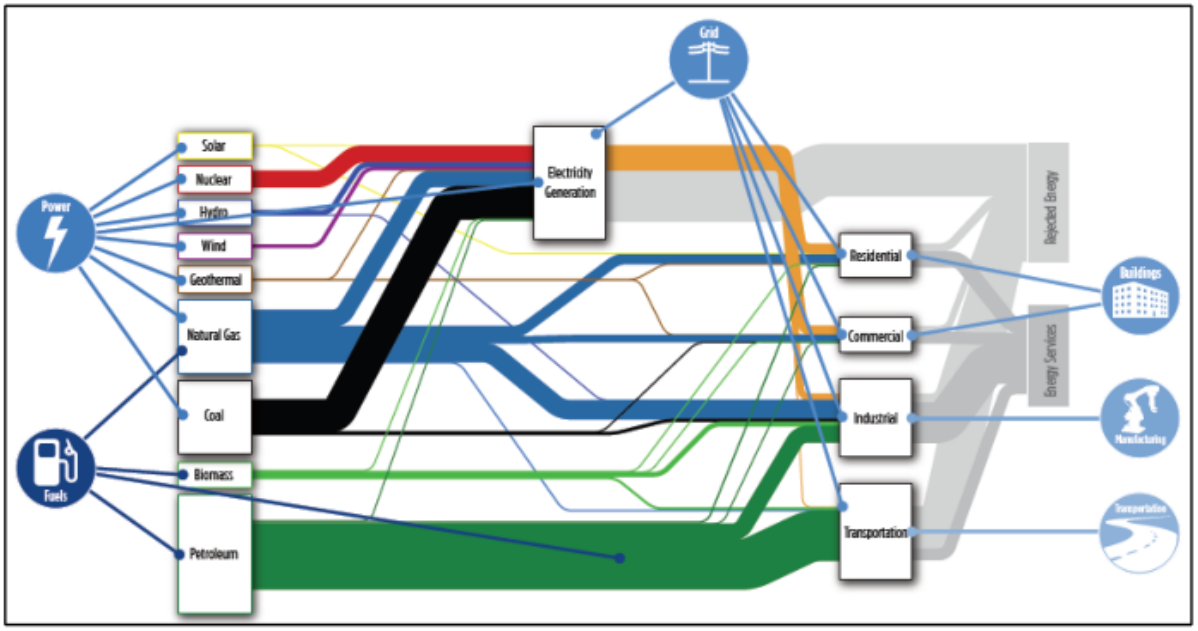


Figure 3: Estimated energy use (global case) (DOE USA, 2015).

1.4 Importance of Evaluating Environmental Impacts of Renewable Energy

The annual increase in worldwide energy demand and its environmental consequences play a crucial part in the extensive shift toward sustainable and eco-friendly global energy practices. Renewable energy solutions have garnered significant economic, environmental, and technical focus over the past decade, with some being available for nearly a century. Nonetheless, even renewable energy sources can have adverse environmental effects, although they are generally perceived as less harmful than fossil fuels (Sayed et al, 2022).

Evaluating the environmental impacts of renewable energy is crucial for sustainability and informed decision-making. It helps in optimizing technologies, ensuring they don't create new environmental challenges. Such evaluations also foster transparency, building public trust in renewable technologies. By understanding the full environmental footprint of these sources, we can work towards a genuinely sustainable energy future.

1.5 Research Objectives and Methods

Through literature review, the purposes of this study are:

1. To examine the current condition and growth of renewable energy in both Indonesia and on a global scale, specifically highlighting its environmental implications.
2. To conduct life cycle assessments for renewable energy technologies like geothermal, solar, wind, and hydropower, with the objective of evaluating their water consumption patterns and their potential implications on water resources.
3. To make a comparative analysis of the land use requirements associated with various renewable energy technologies in power plants, aiming to shed light on their land footprints and the resultant implications for land availability and ecosystem health.
4. To explore and present the typical carbon emission factors of different renewable energy technologies, thereby facilitating a comprehensive comparison of their carbon footprints.

Finally, this paper is expected to:

1. Offer a holistic understanding of the environmental impact associated with various renewable energy technologies, both in Indonesia and globally.
2. Equip policymakers, researchers, and industry stakeholders with concrete data and insights, enabling them to make informed decisions for a sustainable energy transition.
3. Reinforce the importance of strategic planning and robust environmental management practices in ensuring the long-term viability of renewable energy projects.
4. Drive home the point that while renewable energy sources are essential for mitigating climate change, their deployment must be carefully managed to ensure minimal adverse environmental impacts.

2. WATER CONSUMPTION FOR RENEWABLE ENERGY GENERATION TECHNOLOGIES

One of environmental impacts of power plant that must be considered is water resources usage. Water is used in many phases of energy life cycle from resource extraction to electricity generation. With changes in climate and society, it is important to understand the consumption of water. While some technologies use very little water (e.g., wind and solar energy), others are far larger consumers, with hydropower being among the highest consumers per unit of useful output energy. Wind energy has negligible water use. Solar energy also uses very little water with maximum 77 gallons/MWh. Geothermal power plants fall somewhere in the middle. The following figure (in logarithmic scale) compares water consumption among electricity generation technologies as a range of values. Due to these extremely low values, wind and solar are highly sustainable with respect to water consumption.

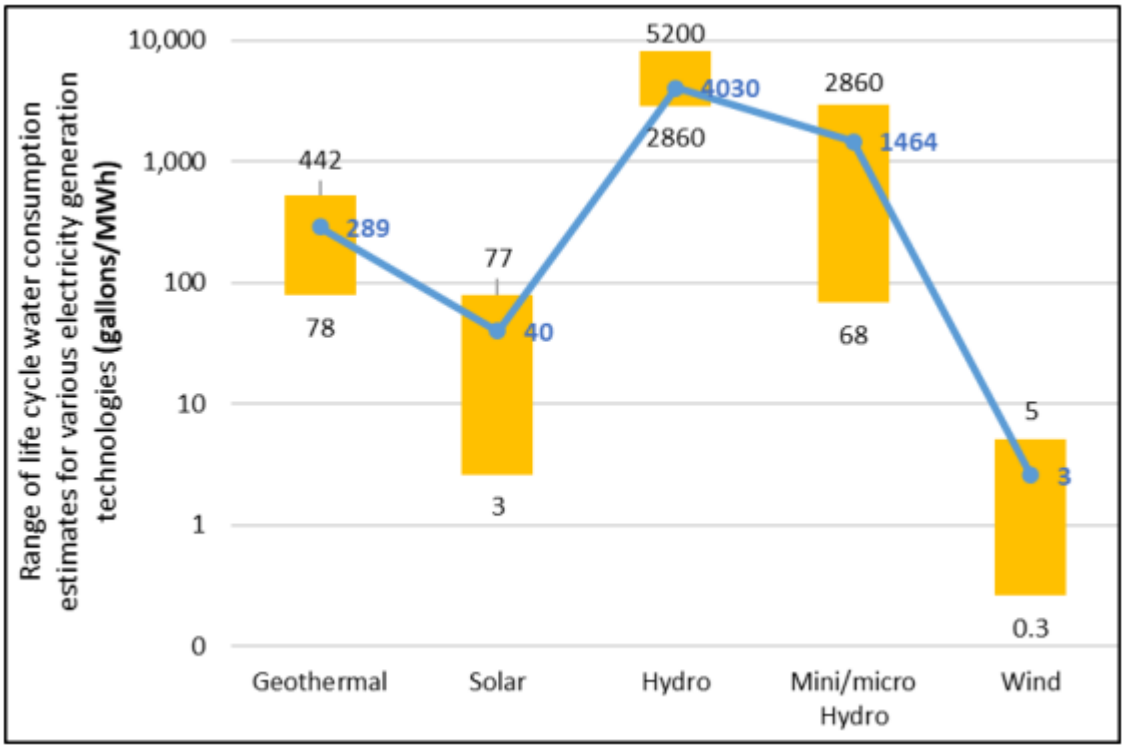


Figure 4: Range of life cycle water consumption estimates for various electricity generation technologies (global case) (DOE USA, 2015; Evans, 2009).

3. LAND USE FOR RENEWABLE ELECTRICITY GENERATION TECHNOLOGIES

Electricity generation is energy intensive, and each source leaves its own environmental and ecological footprint. This section discussed the various land requirements for renewable electricity generation. The land used by each source was approximated to account resource production, energy plants, transport and transmission, and waste materials storage. The final assessment can be seen below as the chart shows how many square meters per megawatt each source of electricity uses.

In geothermal, land use is mainly for power plants and steam fields. Other than mini or micro-hydro, geothermal is the lowest in terms of land use. Solar and wind are much more land intensive technologies. In solar energy, land use is mainly for the placement of solar panels. In wind energy, land use is mainly for the placement of wind turbines. Hydroelectricity generated by large water reservoirs has a significantly the largest use of land than any other generation technology.

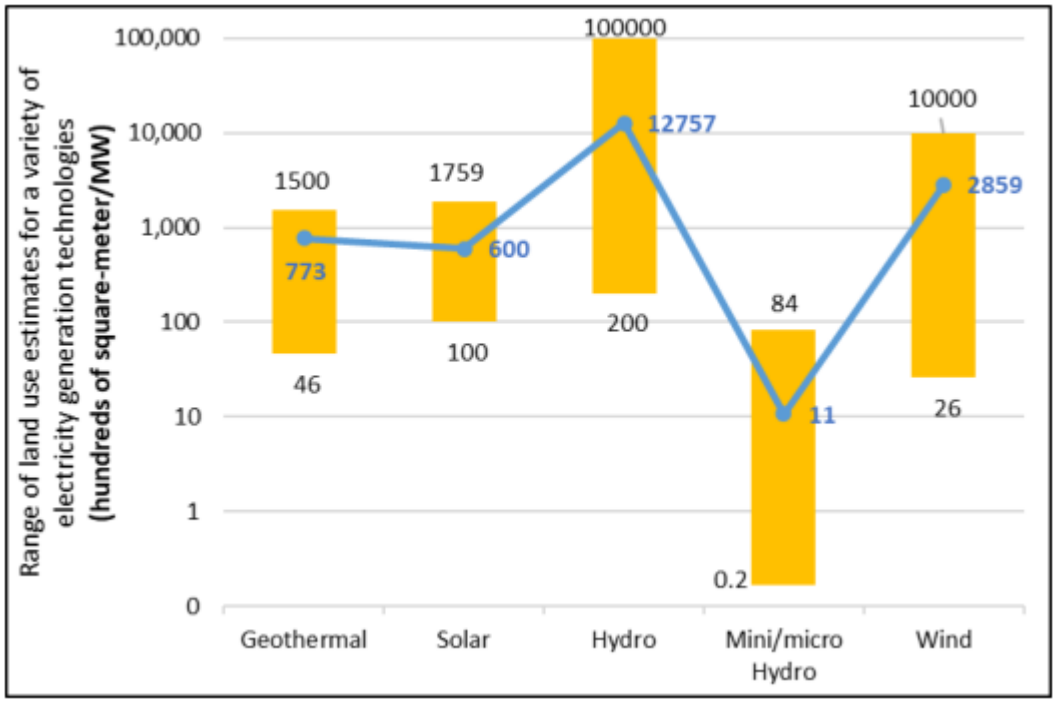


Figure 5: Range of life cycle water consumption estimates for various electricity generation technologies (global case) (DOE USA, 2015; Evans, 2009).

Comparing the required land areas can inform decision making for development and prioritization of R&D efforts to reduce technology or process footprints. Also, by understanding the physical footprint impacted by electricity production, effective policy can be taken that hopes to balance environmental impact, reliability, economy, and security. Realizing that these impacts go further than just the visible activities taking place onsite at generating power plants is essential for understanding larger picture.

4. BREAKDOWN OF LAND USE FOR RENEWABLE ELECTRICITY GENERATION TECHNOLOGIES

The previous discussion regarding the land use for electricity generation technologies will be followed up. In this section, the land use for each type of renewable energy will be broken down and compared. For the global average, in terms of overall land use, a geothermal power plant requires quite a small land use per MW, in fact the value only reaches around 60% compared to hydropower, as shown in the following table. Even so, this value is still smaller than the need for land use in wind energy. The value used in the following table comes from the median value from the previous section.

Table 2: Breakdown of land use for a variety of electricity generation technologies (global case, in square-meter/MW) (DOE USA, 2015; STRATA, 2017).

Category	Geothermal	Solar energy	Hydropower	Mini/micro-Hydro	Wind energy
Energy plant	59,100	43,276	961,332	808	242,812
Resource prod.	1,200	2,732	272,596	229	1,129
Transmission	17,000	13,992	41,723	35	41,934
Total land use	**77,300**	**60,000**	**1,275,651**	**1,072**	**285,874**

The percentage of land use for each type of renewable energy is illustrated by the following figure. The use for the placement of electricity generators is dominated by all types of energy, ranging from 70%-85%. Hydro and mini or micro-hydro also use the land for resource production, around 20%. Additionally, around 15%-25% of land use in geothermal, solar and wind energy is for transmission.

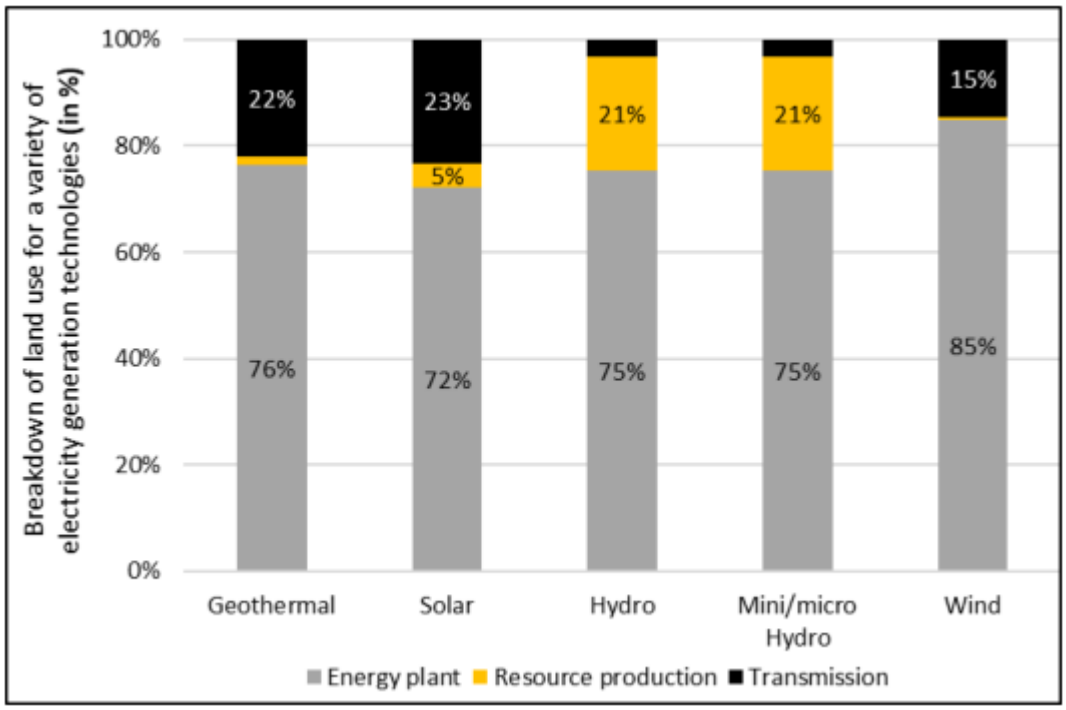


Figure 6: Breakdown of land use for a variety of electricity generation technologies (global case) (DOE USA, 2015; STRATA, 2017).

5. GREENHOUSE GAS EMISSIONS FOR RENEWABLE ENERGY GENERATION TECHNOLOGIES

The use of renewable energy sources to generate electricity will lead to fossil fuel conservation and environmental improvements because of reducing greenhouse gases (especially CO2) emitted. As for the transmission network, smart grid optimizes the use of existing lines and substations for maximum efficiency and minimum losses. As for consumption, introducing smart meters, along with the use of smart house facilities and extended penetration of hybrid plug-in electric vehicles will lead to reducing greenhouse gases emissions, energy conservation, and preserving our environment. The following figure shows a comparison among greenhouse gas emissions from the various energy sources. It shows how renewable power plants emit minimum emissions. For geothermal and solar energy, the maximum number is quite high compared to other renewable energy. However, the maximum emission of 245 g-CO2/kWh is still lower than electricity generated from natural gas, oil and coal.

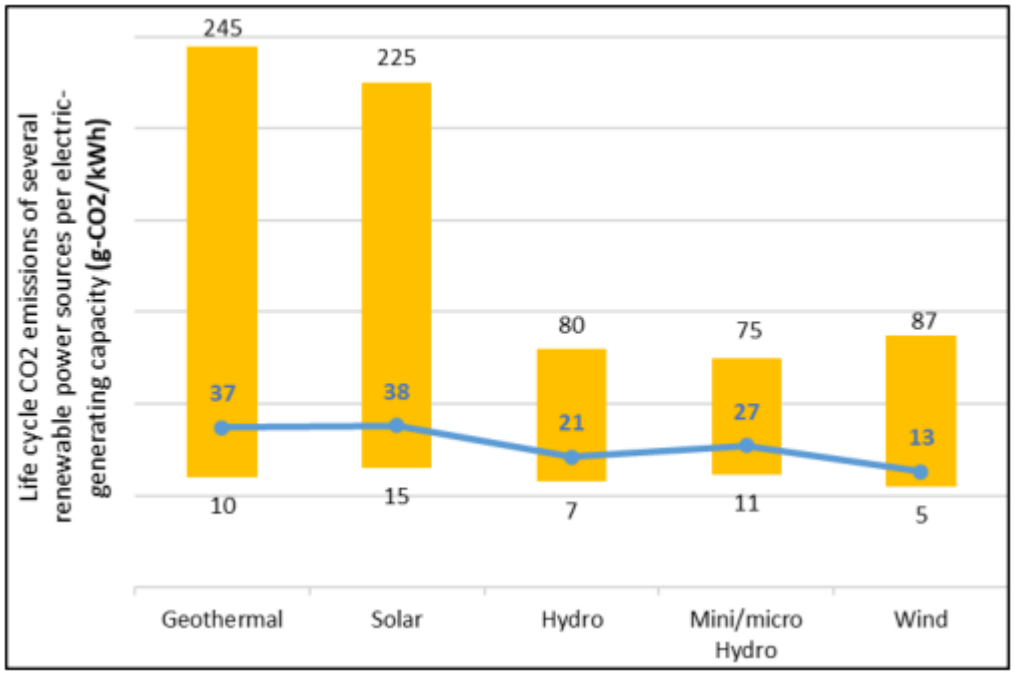


Figure 7: Life cycle CO2 emissions of several renewable power sources per electric-generating capacity (global case) (Prakash, 2012; Abdallah, 2013; NREL, 2021).

6. CONCLUSION AND WAY FORWARD

Based on the findings regarding water consumption, land use, and greenhouse gas emissions for renewable energy generation technologies, it is clear that there are significant environmental differences among these technologies. Renewable energy technologies vary widely in their water consumption. Wind and solar energy have negligible water use, making them highly sustainable with respect to water consumption. Hydropower, on the other hand, is a significant consumer of water resources. Geothermal power falls in between, with moderate water usage. Land use also varies significantly among renewable energy sources. Geothermal power has the smallest land footprint per megawatt, followed by solar and wind energy. Hydropower, particularly large reservoir-based hydroelectricity, requires the most land. Renewable energy sources have significantly lower greenhouse gas emissions compared to fossil fuels, making them crucial for mitigating climate change. While geothermal and solar energy may have higher maximum emissions compared to other renewables, they are still much cleaner than fossil fuels.

Here's a way forward based on these findings:

1. Promote Low-Water Technologies: Given the growing concerns about water scarcity, there should be a concerted effort to promote renewable energy technologies with minimal water consumption, such as wind and solar. In regions facing water stress, policymakers should prioritize these technologies for energy development.
2. Sustainable Land Use Planning: When planning renewable energy projects, consider the land use requirements carefully. Optimize land use by choosing appropriate locations and minimizing ecological impacts. Focus on repurposing non-arable or degraded land for solar and wind installations.
3. Diversify Energy Portfolios: A balanced energy mix that includes a variety of renewable sources can help mitigate environmental impacts. By diversifying the sources of renewable energy, we can reduce the pressure on any one resource (e.g., water or land) and improve overall sustainability.
4. Enhance Geothermal Efficiency: Geothermal energy has relatively low water consumption and land use compared to hydropower, but it can be made even more efficient. Research and development efforts should aim to increase the output per unit of land and water used in geothermal power generation.

5. Continued Emissions Reduction: While renewable energy sources emit fewer greenhouse gases than fossil fuels, continuous efforts to reduce emissions from all renewable technologies are essential. This could involve technological advancements, better materials, and improved maintenance practices.
6. Transition to Smart Grids: As mentioned, smart grids can optimize energy transmission and reduce losses. Governments and utilities should invest in upgrading existing grids to improve efficiency and reduce emissions.
7. Consumer and Industrial Engagement: Encourage consumers and industries to adopt energy-efficient practices, such as using smart meters and embracing hybrid plug-in electric vehicles. Government incentives and education campaigns can drive these initiatives.

The findings of this study highlight the importance of considering water consumption, land use, and greenhouse gas emissions when choosing renewable energy technologies. A holistic approach to renewable energy development, combined with ongoing innovation and sustainable practices, can help us achieve a cleaner and more sustainable energy future while minimizing environmental impacts.

REFERENCES

Abdallah, L., & El-Shennawy, T.: Reducing carbon dioxide emissions from electricity sector using smart electric grid applications. Journal of Engineering, (2013).

DOE USA: Quadrennial technology review: an assessment of energy technologies and research opportunities, (2015).

ESDM: Handbook of energy & economic statistics of Indonesia, (2021).

Evans, A., Strezov, V., & Evans, T.: Comparing the sustainability parameters of renewable, nuclear and fossil fuel electricity generation technologies, (2010).

NREL: Annual technology baseline: the 2022 electricity update, (2022).

Peraturan Presiden Nomor 22 Tahun 2017 tentang Rencana Umum Energi Nasional, (2017).

PLN: Rencana usaha penyediaan tenaga listrik (RUPTL) 2021-2030, (2021).

Prakash, R., & Bhat, I. K.: Life cycle greenhouse gas emissions estimation for small hydropower schemes in India. Energy, 44(1), 498-508, (2012).

Sayed, E. T., Wilberforce, T., Elsaid, K., Rabaia, M. K. H., Abdelkareem, M. A., Chae, K. J., & Olabi, A. G.: A critical review on environmental impacts of renewable energy systems and mitigation strategies: Wind, hydro, biomass and geothermal. Science of the total environment, 766, 144505, (2021).

STRATA: The footprint of energy: land use of US electricity production, (2017).

Exploring the Impact of Lender Procurement Guidelines on Geothermal Project Exploration Planning: Indonesia's GREM Perspective

Aryani Amir[1], Agung Hardinugroho[1], Chandra Hasudungan Panjaitan[1], Dorman Purba[1,2], Desak Inten Nyoman Apriani[1], and Ery Surandaru[1]

[1]PT Sarana Multi Infrastruktur (Persero), Sahid Sudirman Center 49th floor, Jakarta, Indonesia
[2]PT ENERKA Bhumi Pratama, Cibis Park 11th floor, Jakarta, Indonesia

aryani.pmugeothermal@ptsmi.co.id, dorman.purba@enerklaz.com, desak@ptsmi.co.id

Keywords: geothermal, exploration, GREM, SMI, resource, risk, drilling, cost, procurement, budget, finance, fund, market, contractor, bidding

ABSTRACT

Geothermal developers in Indonesia face a challenging financing landscape, particularly during the exploration phase of geothermal projects. The availability of financing products specifically designed for geothermal exploration remains limited. However, Geothermal Resource Risk Mitigation (GREM) financing emerges as the pioneering and currently the only available solution to help geothermal developers manage risks during this crucial phase. Understanding the lender's procurement guidelines becomes paramount in harnessing the potential benefits of GREM financing.

This paper aims to provide geothermal developers in Indonesia with valuable insights into the importance of comprehending lender procurement guidelines in the context of limited financing options, highlighting the role of GREM as a risk management solution. By comprehending these guidelines, geothermal developers in Indonesia might gain insights into the specific requirements and procedures set by lenders, enabling them to align their project planning and implementation accordingly. This understanding enhances the developers' ability to navigate the procurement process effectively, increasing their chances of accessing GREM financing. Moreover, familiarity with the lender's procurement guidelines empowers developers to proactively address potential challenges and demonstrate compliance, ultimately improving their project's viability and reducing the risks associated with geothermal exploration.

On the other hand, complying with lenders' procurement requirements can present challenges for geothermal project developers as borrowers. These challenges include navigating complex and rigorous procurement procedures, ensuring transparency and accountability throughout the process, meeting stringent eligibility criteria, and managing the administrative burdens associated with documentation and compliance. Additionally, developers may face difficulties in accessing the necessary resources and expertise to meet the specific procurement guidelines set by lenders.

Finally, this paper aims to provide developers with a clear understanding of the benefits of following the lender procurement process and strategies for managing administrative burdens, ultimately yielding positive outcomes for the exploration project.

1. INTRODUCTION

1.1 Geothermal Energy Development in Indonesia

The utilization of geothermal as green energy is become critical component in Indonesia's efforts to achieve 23% renewable energy by 2025 and additional 21% of renewable power generation by 2030 (DEN, 2022a). Indonesia is the nation that has enormous geothermal potential (approx. 23 GWe) and is one of the top two geothermal producers (approx. 2,356 MW) globally (Darma, Imani, Shidqi, Riyanto, & Daud, 2021; ADB, 2018). Unfortunately, the potential is still under-utilized since current utilization is only 8% of the total potential (Fadhillah, et al., 2022). Indonesia is targeting geothermal utilization to reach 5,799 MW in 2030, which equals 259% addition to the current capacity (PLN, 2021). Figure 1 shows the existing and targeted Indonesia geothermal development.

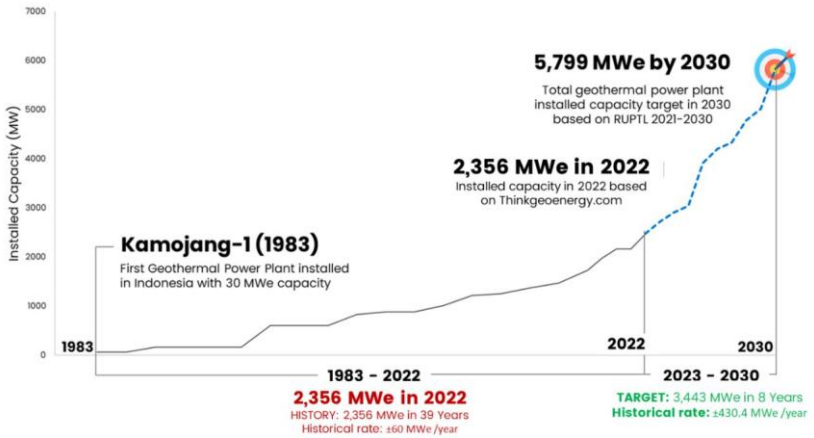
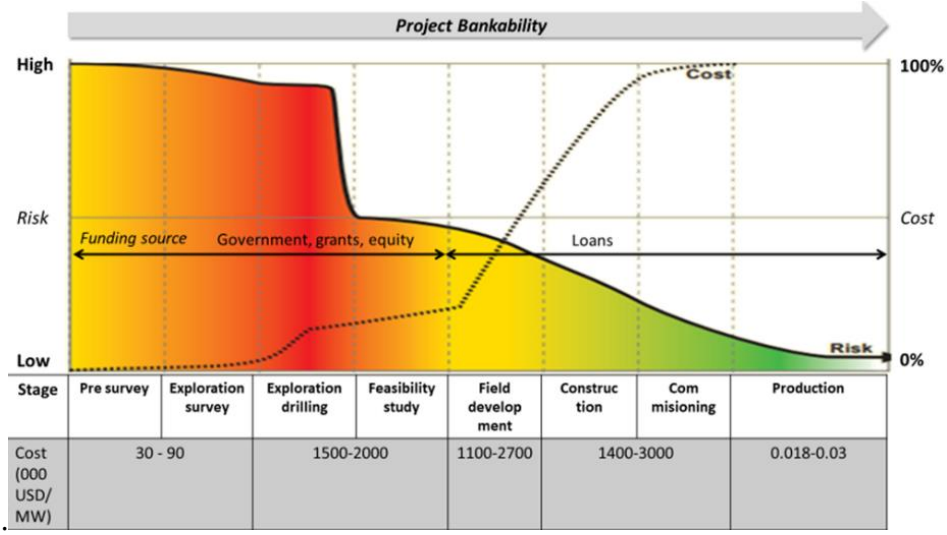


Figure 1: The historical and projected Indonesia geothermal development (PLN, 2021; EBTKE, 2022; ThinkGeoenergy, 2023).

Currently, Indonesia's geothermal industry operates 16 power plants under either the management of state-owned enterprises (SOE) or Independent Power Producers (IPP). Additionally, there are 63 areas designated as "geothermal working areas" in the exploration-development phases and 15 areas classified as "preliminary survey-exploration areas" in the pre-exploration phases (MEMR, 2022). Despite these efforts, the present condition of geothermal development poses significant challenges to achieving the government's targets by 2030. To accelerate geothermal development, it is imperative to focus on promoting exploration activities while also addressing associated exploration risks to enhance investment attractiveness.

1.2 Importance of Effective Geothermal Project Exploration Planning

The geothermal sector faces substantial initial financial investment that is accompanied by high risk due to uncertainties related to resources, social-environmental factors, finances, and technical challenges (IRENA, 2022). Research by GeothermEx (2010) and Castlerock (2010) emphasizing that the main barrier to geothermal development in Indonesia lies in the significant risk involved during extensive investments, particularly in the preliminary survey and test drilling stages. These stages encounter limited data and rely on interpretations by geoscientists, leading to uncertainties about critical resource conditions, such as reservoir temperature, fluid characteristics, and permeability, which directly affect to the development strategy and financial performance. The cost-risk curve and funding source of each phase shown in Figure 2 modified from IGA (2014) and Purwanto (2019), while Table 1 summarize the identified risk of general geothermal project based on ESMAP (2021).



Stage	Pre survey	Exploration survey	Exploration drilling	Feasibility study	Field develop ment	Construc tion	Com misioning	Production
Cost (000 USD/ MW)	30 - 90		1500-2000		1100-2700	1400-3000		0.018-0.03

Figure 2: Geothermal projects' risk, cost, and funding source modified from IGA (2014) and Purwanto (2019).

1.3 Financing Options for Geothermal Exploration Project in Indonesia

As mentioned earlier, financing the geothermal exploration project is still considered a high-risk business for lenders as the resource uncertainty is still high. This section will further discuss the funding options for the geothermal exploration project that is currently available in Indonesia.

1.3.1 Own Equity

Most developers use their equity as the financing source for the geothermal exploration project. The cost estimate of a geothermal exploration project in Indonesia is around USD 15-50 million (Table 4), which depends mainly on the drilling strategy and little dependency on the size of the development project. Typically, the developers raise the equity from parent company loans and shareholder loans. The other options are issuing bonds and shares, but they can only do this after the resource is confirmed.

The primary consideration in using developer's own equity is the risk borne solely by the developers. With such a considerable capital cost, there is still a high possibility that the exploration found no economic geothermal resource. Or in some cases, the resource characteristic needs to be more attractive to be developed, which requires the developers to spend more capital to drill more exploration wells. In this stage, the developer has a high risk of losing all the equity spent on exploration activities.

1.3.2 Infrastructure Financing for Geothermal Sector (Pembiayaan Infrastruktur Sektor Panas Bumi, or PISP) Fund

The government of Indonesia has allocated around IDR 3.1 trillion (equivalent to approximately USD 200 million) from the government budget to support geothermal development in Indonesia. This fund will be leveraged with another funding source from international financial institutions, donors, and other stakeholders to collaborate in the de-risking funding scheme of geothermal exploration. This fiscal incentive is regulated by Ministry of Finance Regulation No.80/PMK.08/2022 Regarding Geothermal Development Support using Pembiayaan Infrastruktur Sektor Panas Bumi (PISP) Fund at PT Sarana Multi Infrastruktur ("PT SMI").

PT SMI is a state-owned enterprise (SOE) under the Ministry of Finance (MoF) assigned to manage the PISP fund. Ministry of Energy and Mineral Resources (MEMR) will use this fund to support a geothermal exploration program called Government Drilling. Other than that, the fund will be used as a financing facility for SOE and private developers with the de-risking feature for SOE developers. This feature allows the developer to not fully bear the risks and costs of exploration in the event of an exploration failure.

The overview of geothermal exploration de-risking facilities available in Indonesia that just discussed is illustrated in Figure 3.

1.3.3 Geothermal Energy Upstream Development Project (GEUDP) or Government Drilling

Geothermal Energy Upstream Development Project (GEUDP) is a government-sponsored exploration drilling collaboration program between the Government of Indonesia and the World Bank. The program aims to develop greenfield geothermal areas that have yet to be tendered, especially in eastern Indonesia, where the area's electrification ratio is low compared to the other parts of Indonesia (Apriani et al., 2018). The source of funds for the GEUDP program comes from the PISP Fund of USD 49 million, with matching grants from the Clean Technology Fund (CTF) of USD 49 million and the Global Environment Facility of USD 6.25 million. The program also received grants from the New Zealand Ministry of Foreign Affairs and Trade (NZ MFAT) in the form of technical assistance that equals the amount of NZD 2.13 million.

MEMR, as the beneficiary of this program, will propose a geothermal prospect area to MoF to seek exploration support under the GEUDP program. Then, the technical implementing agency, PT Geo Dipa Energi ("GDE") will conduct a preliminary assessment to see whether the proposed area is feasible to continue exploration drilling. Suppose the result shows that the proposed prospect area is viable; MoF will issue an assignment letter to GDE as the technical implementing agency and PT SMI as the financial manager to conduct the exploration drilling activities, which is supported under the GEUDP scheme.

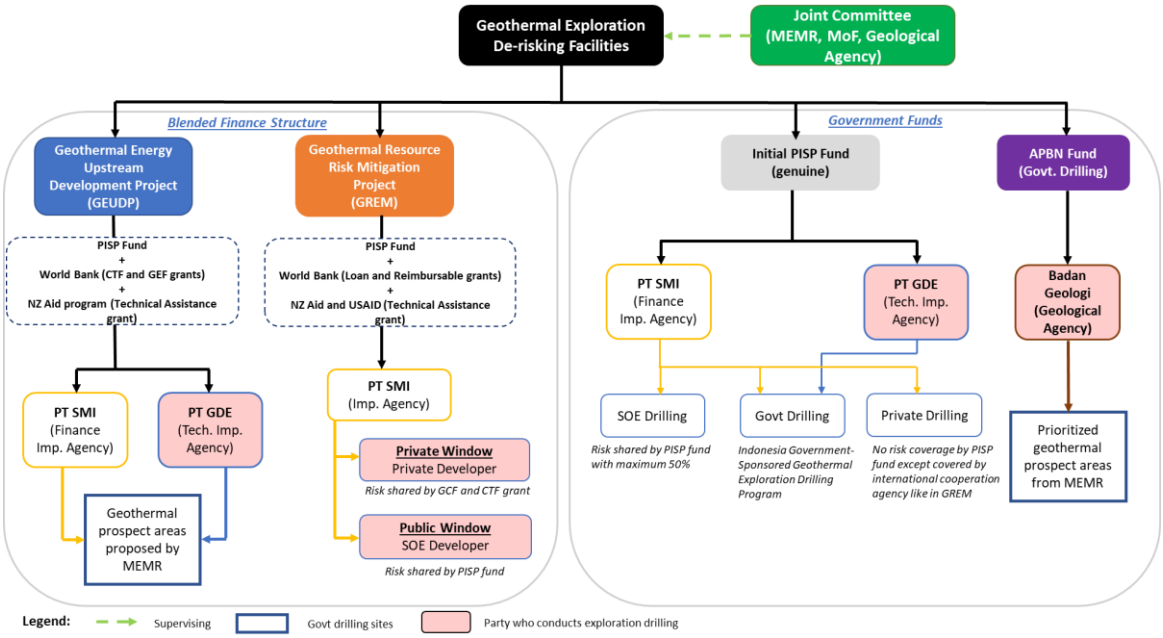


Figure 3: Overview of Geothermal Exploration De-Risking Facilities in Indonesia (PT SMI, 2022a).

The data acquired in the exploration drilling will be assessed by an independent party and discussed in the Joint Committee meeting to decide if the geothermal resource in the prospect area is proven and sufficient to be tendered by MEMR. Assuming that resource is now de-risked, then MEMR will proceed with the tender process of WKP. In this stage, the participation of both public and private sector geothermal developers in the tender process is expected to increase as the geothermal resource risk has significantly reduced. Suppose the drilling exploration result shows that the resource is not economically attractive enough to be further developed; the government funds and donor funds will cover the exploration cost. Figure 4 shows the business model of GEUDP.

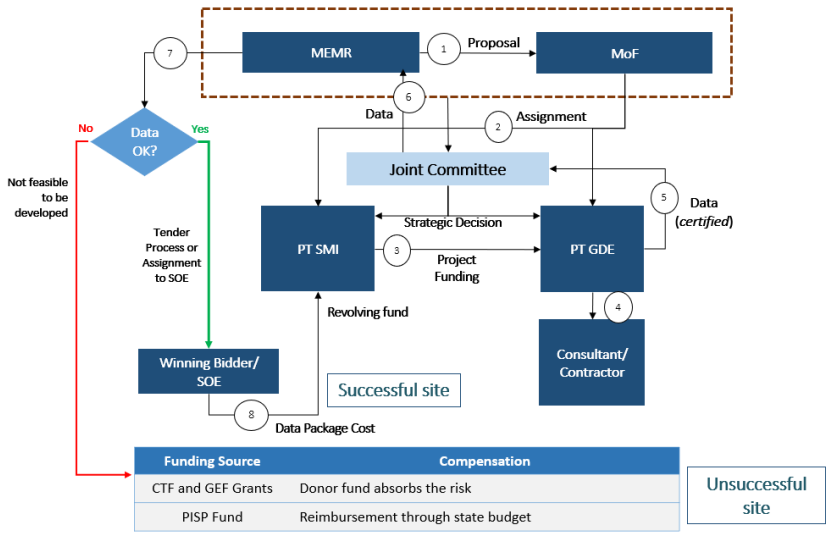


Figure 4: GEUDP Business Model (modified from PT SMI, 2022b).

However, since most of the geothermal prospect area under GEUDP has yet to be tendered and awarded to the geothermal developers, the beneficiary of this facility is MEMR. MEMR will use the fund to undertake the exploration drilling to improve the quality of information available at the time of tender. The winning geothermal developer will reimburse the exploration costs at the time of the concession award. In other words, GEUDP is designated for something other than a geothermal developer who already holds a geothermal working area license or concession.

Aside from GEUDP, the Geological Agency of Indonesia, under MEMR, also conducted exploration drilling in several geothermal prospect areas in Indonesia, namely Nage, Bittuang, and Cisolok-Cisukarame. The activities include preliminary survey, land acquisition, permits, infrastructure construction work, drilling, well testing, and pre-FS document updating. The source of funds to support these activities comes from the state budget (APBN), and the risks are covered 100% by the government.

1.3.4 Geothermal Resource Risk Mitigation (GREM)

The Geothermal Resource Risk Mitigation (GREM) Project is developed by the Government of Indonesia (GoI) through PT SMI together with the World Bank with the objective to foster the development of geothermal power generation projects in Indonesia. The new facility shall enable early-stage financing of geothermal projects for public and private developers to enable the increase of geothermal power generation capacities in the country. The Facility is envisaged to include three windows:

1) Government drilling,
2) Public developer window, and
3) Private developer window.

The first window has already been explained in the earlier sub section. While the remaining two windows are being established under the GREM Facility, where publicly owned and private developers are provided with financing for resource confirmation drilling with a view to achieve financial close for the exploitation (construction and operation) phase. The funds will be disbursed over two phases, in which the first phase was expected to be started effectively in 2020 and with a Project Closing Date of October 31, 2029.

The two windows are planned to be capitalized with a total of US$651.25 million in the aggregate towards investments in geothermal exploration drilling. The funds will be disbursed over two overlapping phases, that will start at Year 1 and Year 3 respectively. The overlapping of phases ensures that essential activities in Phase 1 and Phase 2 continue without there being a gap in program roll-out while the next phase is prepared. The first phase will start up the program and introduce the proposed innovative financing mechanism. The second phase will scale up while reflecting the changes and streamlining from the learning. The design of the future phase(s) will consider developing the capacity of institutions and stakeholders, market response, risk appetite of key stakeholders, and learning from technical challenges. However, both phases are designed to have the same components and outcomes, but with a different scope and targets. Developers under the GREM Facility are to put in equity toward the exploration program for the sub-projects.

The GREM Facility also includes a US$6.25 million grant from GCF, CTF, and GIF for technical assistance and capacity building for PT SMI and relevant stakeholders. PT SMI will be the executing entity for the GREM Facility in a financial intermediary function. GREM shall facilitate the mobilization of private and public funds with the objective of fostering the development of the geothermal market.

Procurement procedures are solely applicable to the public developers and will guide PT SMI's supervision of procurement by public developers. Private sector developers will not have the obligation to comply with the Procurement Regulations.

1.4 Significance of Lender Procurement Guidelines

Lender procurement guidelines for geothermal exploration projects in Indonesia are important for several reasons:

1. These guidelines establish a transparent and fair procurement process, fostering healthy competition and reducing corruption risks.
2. They facilitate the efficient selection and evaluation of goods and services, ensuring the engagement of qualified and reliable contractors.

3. These guidelines effectively manage project risks by ensuring compliance with industry standards, environmental regulations, and social considerations.
4. Furthermore, adherence to these guidelines enhances project governance, accountability, and optimal resource management. Ultimately, lender procurement guidelines are pivotal in driving the efficiency, sustainability, and success of geothermal exploration projects in Indonesia.

On the other hand, the absence of lender procurement guidelines for geothermal exploration projects can have several negative impacts on the project. Firstly, without clear guidelines, the procurement process may lack transparency and fairness, potentially leading to favoritism, inefficiency, and increased corruption risks. This can result in the selection of contractors or suppliers who may not possess the necessary expertise or qualifications, compromising the quality of goods and services provided.

Furthermore, the absence of guidelines can lead to inconsistent evaluation criteria, making it challenging to compare proposals and select the most suitable vendors. This lack of standardization can hinder project progress, delay procurement activities, and increase project costs. Additionally, without guidelines, it becomes difficult to ensure compliance with environmental regulations, social considerations, and industry standards, which can lead to negative environmental and social impacts. In summary, the absence of lender procurement guidelines can impede project efficiency, jeopardize quality, increase corruption risks, and undermine the project's overall success.

In geothermal exploration, goods and services are sourced globally and as such require international level procurement guidelines which can be provided by lenders, especially international financial institutions. They often have their own procurement guidelines that align with international best practices. By following these guidelines, borrowers can ensure that their procurement processes meet internationally recognized standards of transparency, fairness, and efficiency, which in the end resulting in achieving the most appropriate procurement output that leads to fulfillment of value for money principle.

From GREM perspective, the significance of lender procurement guidelines is indispensable. Funds disbursement to GREM could be re-evaluated if lender procurement guidelines is not adhered to. It is crucial to fulfill the loan agreement and maintain a positive relationship with the lender because lenders often impose procurement guidelines as a condition for providing funds or financial assistance. These guidelines often demonstrate commitment to transparency, accountability, and efficient use of funds. By complying with the guidelines, borrowers can increase the chances of securing financing or financial assistance from the lender which will in the end facilitating project implementation. Failing to adhere to lender procurement guidelines will lead to mis-procurement and as such will jeopardize the funds disbursement.

The act of demonstrating a track record of following procurement best practices and meeting lender's requirements can also increase the chances of accessing future funding or assistance from the lender or other financial institutions because it builds trust and confidence in the borrower's ability to manage funds effectively. It also enhances the borrower’s reputation and credibility.

Another advantage of adhering to lender procurement guidelines is that they often require borrowers to develop and strengthen their procurement capacities. This can include training of staff, adopting standardized processes, and implementing monitoring and evaluation mechanisms. Compliance with these guidelines helps borrowers build internal capabilities, improve procurement practices, and enhance overall organizational capacity.

1.5 Paper Objectives and Method

The objectives of this paper are to:

1. Understand the significance and benefits of GREM financing as a risk mitigation solution for geothermal developers in the limited financing context of exploration projects.
2. Investigate the impact of lender procurement guidelines on geothermal project exploration planning in Indonesia.

3. Offer insights and recommendations to geothermal developers for understanding and navigating lender procurement guidelines to improve project planning and implementation.
4. Identify the challenges faced by geothermal developers in complying with lender procurement requirements and propose strategies to overcome these challenges.

This paper is the result of a literature study and interviews with relevant stakeholders, including geothermal developers, financial institutions, and industry experts. The literature study involved an extensive review of research articles, publications, and reports on geothermal project exploration planning, lender procurement guidelines, and GREM financing. The stakeholder interviews provided valuable firsthand insights and perspectives on the practical aspects, challenges, and experiences related to lender procurement guidelines and the implementation of GREM financing in geothermal exploration projects.

2. GOODS AND SERVICES TO BE PROCURED IN GEOTHERMAL EXPLORATION

2.1 Procurement Process and Potential Challenges

The procurement process involves the systematic and strategic acquisition of goods, services, or works from external suppliers or contractors. It typically includes a series of steps, starting with the identification of procurement needs and specifications, followed by supplier selection, contract negotiation, and contract administration. The process involves activities such as market research, supplier prequalification, issuing requests for proposals or bids, evaluating proposals or bids, negotiating contracts, and managing supplier relationships.

Effective procurement processes aim to ensure transparency, competition, value for money, and adherence to legal and regulatory requirements. The process may vary depending on the organization, industry, and specific project requirements, but the overarching goal is to procure the right goods and services, at the right time, in the right quantities, and at the right cost, while maintaining quality and mitigating risks.

The procurement process entails a series of challenges and risks that organizations often confront. Here are some major risks and challenges associated with the procurement process:

1. Identifying Reliable Suppliers: The task of identifying suppliers who possess the necessary competence to meet quality, quantity, and timing requirements can be intricate. The failure to secure dependable suppliers might lead to project delays, substandard products, and escalated expenses.
2. Legal and regulatory compliance: Compliance with various laws, regulations, and procurement policies is crucial to avoid legal issues and potential penalties. Failure to adhere to these requirements can lead to disputes, contract cancellations, and reputational damage.
3. Procurement timeline: For procurement packages which require the lender’s prior review, an additional number of days for receiving no objections from the lender before continuing the next steps of the procurement process need to be added.
4. Fraud and Corruption: The procurement process remains susceptible to fraudulent activities like bid rigging, bribery, and kickbacks. These unethical practices can inflict financial losses and tarnish an organization's reputation, compromising its integrity.
5. Effective Risk Management: Navigating risks linked to supplier reliability, delivery delays, quality discrepancies, and unpredictable market dynamics demands proactive measures. Developing comprehensive risk mitigation strategies and well-structured contingency plans is a complex undertaking.
6. Ethical and Sustainable Procurement: Balancing ethical considerations, encompassing environmental and social aspects, within the supply chain poses a considerable challenge. Ensuring responsible practices while managing cost-efficiency necessitates a delicate equilibrium.
7. Navigating Compliance and Regulations: Complying with intricate legal and regulatory frameworks, both domestically and internationally, constitutes a substantial challenge.

Successfully navigating procurement laws, intricate trade agreements, and industry-specific regulations necessitates meticulous attention to detail.

8. Promoting Transparency and Fairness: Upholding transparency and impartiality in the procurement process is pivotal to curbing favoritism, bias, and corrupt practices. Striving for consistent, objective evaluations while mitigating conflicts of interest presents a formidable challenge.

Comprehending procurement guidelines holds utmost significance for every project stakeholder, driven by essential factors. These guidelines serve as a framework ensuring adherence to legal and ethical norms, creating an environment of transparency and impartiality during supplier selection. This grasp of guidelines not only expedites efficient decision-making but also fosters seamless communication channels, allowing stakeholders to align their efforts coherently.

Moreover, this understanding becomes a pivotal tool in preemptively addressing potential risks through well-defined risk management strategies. It establishes a system of accountability, aiding stakeholders in carrying out their roles responsibly while optimizing the allocation of resources. This collective comprehension not only cultivates an atmosphere of trust amongst stakeholders but also stands as a cornerstone for the project's triumphant culmination, as it harmonizes efforts towards project objectives, timelines, and overall success.

2.2 Identification of Essential Goods and Services Required in the Exploration Phase

Understanding the goods and services essential for a geothermal exploration project holds pivotal significance for successful project outcomes. Precise comprehension aids in meticulous project planning by accurately assessing required resources for tasks like drilling and geological assessments. This knowledge is crucial for effective budgeting, preventing financial constraints and ensuring optimal allocation of funds for procurement, equipment rental, and specialized services.

Furthermore, understanding necessary goods and services streamlines procurement planning, enabling early supplier engagement and fostering healthy competition among potential providers. This in-depth awareness also promotes seamless communication and collaboration among project teams, ensuring alignment with project goals, reducing misunderstandings, and enhancing overall project coordination. In summary, grasping the specific goods and services needed in geothermal exploration projects is paramount for efficient resource management, transparent procurement processes, and cohesive teamwork, all contributing to the project's ultimate success.

2.2.1 Drilling Infrastructure Construction

Typically, the construction of drilling infrastructure to facilitate an exploration project encompasses a range of elements, including but not limited to:

1. Construction of any access roads required for transportation of drilling rigs, materials and labor;
2. Construction of drilling pads, sumps, and drilling laydown areas;
3. Provision of water supply for drilling;
4. Construction of a suitable area for drilling camp; and
5. Provision of a site office suitable for managing the site before, during, and after drilling activities.

2.2.2 Well Material

Goods & services required for Well Materials include but not limited to:

1. Cementing
2. Tubular inspection
3. Casing
4. Wellheads
5. Casing accessories

2.2.3 Drilling Operation

Goods & Services required in Drilling Operation include but not limited to:

1. Casing
2. Surface Equipment (Wellhead)
3. Subsurface Equipment (Casing accessories, Shoes and Liner)
4. Bit
5. Rig Integrated Services, including Rig Services (Rig Equipment, Rig Personnel, Cooling Tower, Heavy duty equipment, Light vehicle, VSAT, Mini and base camp, top drive, medic), Mud logging, H2S Services, Waste management, Solid Control equipment, Drill string maintenance & hard banding, Casing running & drive system, Water distribution system
6. Cementing
7. Directional Drilling
8. Drilling Fluid
9. Wireline Logging & Explosive Handling
10. Aerated Drilling
11. Fishing Services
12. Coring Services
13. Completion Tools
14. Rig Inspection
15. Casing Inspection
16. Fuel

2.2.4 Well Testing

Well testing services include but not limited to:

1. Well testing Facilities
2. Well testing Services
3. Welding Services
4. Geochemistry Services
5. Brine Pump Services
6. Light Vehicle Services

2.2.5 Consultant and Contractors

Consultants & Contractors required in a geothermal exploration phase include but not limited to:

1. Civil Infrastructure Front-End Engineering Design (FEED) Consultant
2. Environmental and Social Consultant
3. Safeguards Consultant
4. Environment & Social Safeguard Consultant
5. Exploration Management Consultant
6. Manpower Services Consultant
7. Site Services Consultant
8. Land Appraisal Consultant
9. Environmental & Social Impact Assessment Consultant
10. Legal Consultant for Land
11. Leasing Consultant
12. Engineering Design (DED) Consultant
13. Civil & Infrastructure Contractor
14. Lidar Survey Consultant
15. Geological Survey Consultant
16. Geochemical Survey Consultant

3. OVERVIEW OF LENDER'S PROCUREMENT GUIDELINES

3.1 Examination of existing lender procurement guidelines for geothermal projects

Lender procurement guidelines are a set of standardized instructions and principles established by lending institutions to govern the procurement process for various projects and initiatives. These guidelines aim to ensure transparency, fairness, and efficiency in the selection of suppliers, contractors, and service providers involved in projects funded by the lending institution. The guidelines are designed to cover a wide range of procurement processes that occur on a global scale.

Lender procurement guidelines can vary depending on the lending institution, the type of project, and the specific sector or industry involved. While there may not be a universally recognized set of guidelines specifically tailored for geothermal exploration projects, certain lending institutions, development organizations, or countries might have guidelines or recommendations that apply to such projects.

The first geothermal financing mechanism is solely funded by international financing institution, such as the International Bank for
Reconstruction and Development (IBRD), the Asian Development Bank (ADB), Japan Bank for International Cooperation (JBIC),
World Bank (WB) and Japan International Cooperation Agency (JICA) (World Bank & ADB, 2015).

For geothermal exploration projects, procurement guidelines would likely encompass aspects unique to the geothermal sector, such as drilling equipment, geophysical surveys, resource assessment, and environmental considerations. These guidelines could address challenges like geological uncertainties, technical complexities, and the specialized expertise required in geothermal exploration.

Lenders rate borrowers' countries based on certain requirements which are usually related to global issues such as gender, environment, social, conflict prone countries. Disqualification for contractors not meeting lender's global issues requirements such as gender-based violence, gender biases and discrimination issues can be imposed following a certain examination and necessary assessment.

In lenders procurement guidelines, screening of contractors and consultants to make sure they do not engage in any terrorism activities is an action of risk mitigation by the lenders. Before signing a contract with a winning bidder, lenders need to make sure that winning bidders/recommended consultants are not on the debarred list. Contract can be postponed or even canceled if the winning bidders/recommended consultants are on the blacklist. Make sure to check the status of winning bidders/recommended consultants are free from debarred by finding out the information on lender's online platforms and/or offline platforms as provided by lenders.

Lenders often manage several, if not, many projects under their financing mechanism. In order to monitor the procurement process of each borrower, lenders use online systems to properly monitor the procurement process. Borrowers are required to record every procurement step from identification of needs to contract award and contract management and upload relevant procurement documentation such as request for bids, supplier bids, bid evaluation result, signed contract, etc. For procurement packages requiring lender's prior review, no objection is obtained through the system.

3.2 Requirements and implications for project developers

A set of requirements is often proposed by lenders to the developers as borrowers as a prerequisite of securing fundings. Some of the procurement related requirements that should be fulfilled by the developers, among others, are as follows:

1. Preparation of a procurement strategy for the project being funded and the plan for procurement activities. The strategy should lay out the developers' strategic analysis to identify the best

procurement approach for the project. The developers will have the flexibility of designing the best procurement approach that will increase the chances of achieving the value for money principle and fit to purpose results. The best procurement approach yielded from this exercise will give developers a solid foundation to navigate within the project to deliver a successful project implementation.

2. Contractors and consultants to be selected from a procurement process should not be on the lenders' list of debarred firms and consultants. If any of the contractors or consultants are identified to be on the list, they should be banned from signing a contract or even excluded from the procurement process. This action will free the developers from any consequences that may arise from engaging an incompetent contractor or consultant and opens opportunities for the developers to find the right contractor or consultant for the work to be carried out.
3. Waiver of local content requirement that contradicts with lenders' procurement principle of fairness. Local content requirement prevents developers from importing long lead items from abroad even though they are relatively cheaper comparing to those produced in Indonesia. This government requirement has been a challenge in the oil and gas industry and nowadays in geothermal exploration.

4. SYNERGIES BETWEEN LENDER AND GEOTHERMAL DEVELOPER

4.1 Streamlining Procurement Processes and Enhancing Stakeholder Collaboration

Streamlining refers to the process of optimizing and simplifying a system, process, or operation to make it more efficient, effective, and streamlined. It involves eliminating unnecessary steps, reducing redundancies, and enhancing workflow to achieve greater productivity and cost savings. Streamlining aims to remove bottlenecks, minimize delays, and improve overall performance by focusing on essential activities and utilizing resources more efficiently. The goal is to create a streamlined process that is streamlined, agile, and aligned with organizational objectives, resulting in improved outcomes, reduced waste, and enhanced customer satisfaction. To streamline the procurement process between lenders and borrowers in the context of geothermal exploration financing, several actions can be taken (Table 1):

Table 1: Procurement Process between Lenders and Borrowers.

No.	Action	Example
1.	**Clear and Transparent Communication:** Establish clear channels of communication between lenders and borrowers to facilitate effective information exchange and prompt decision-making.	This can include regular meetings, progress reports, and dedicated points of contact to address queries and provide updates on procurement activities.
2.	**Standardize Procurement Procedures:** Develop standardized procurement procedures and guidelines that are aligned with industry best practices and regulatory requirements.	This ensures consistency in the procurement process and reduces the need for unnecessary customization or negotiation for each project.
3.	**Prequalified Supplier Database:** Create a prequalified supplier database that includes reputable and qualified contractors, suppliers, and service providers with relevant expertise in geothermal exploration.	This database can be regularly updated and shared between lenders and borrowers to expedite the supplier selection process.
4.	**Streamlined Bid Evaluation:** Implement a streamlined bid evaluation process that incorporates clear evaluation criteria, weightings, and a structured scoring system.	This enables efficient evaluation of bids, reduces subjectivity, and ensures fair and objective supplier selection.
5.	**Utilize Technology and Digital Solutions:** Leverage digital procurement platforms, electronic document management systems, and online bidding portals to automate and streamline various procurement tasks.	This includes issuing requests for proposals, receiving and evaluating bids, and managing contract documentation.
6.	**Risk-Based Approach:**	This includes assessing the financial stability of suppliers, conducting due diligence on their past performance, and considering risk

No.	Action	Example
	Adopt a risk-based approach to procurement, focusing on identifying and mitigating key risks specific to geothermal exploration projects.	allocation mechanisms in procurement contracts.
7.	**Continuous Improvement and Lessons Learned:** Establish a feedback loop and process for continuous improvement by capturing lessons learned from each procurement process.	This includes evaluating performance, identifying areas for enhancement, and implementing corrective actions to optimize future procurement activities.
8.	**Collaborative Relationship:** Foster a collaborative relationship between lenders and borrowers, promoting open dialogue, trust, and shared goals.	Engage in joint planning, regular progress reviews, and knowledge-sharing to enhance mutual understanding and streamline the procurement process.

4.2 Opportunities for Improved Transparency and Accountability in Procurement

Improved transparency and accountability in procurement present significant opportunities for organizations. By enhancing transparency, organizations can provide stakeholders with clear visibility into the procurement process, ensuring fairness, and mitigating the risk of corruption or unethical practices. Transparency enables stakeholders to assess the legitimacy and integrity of procurement decisions, fostering trust and confidence in the organization's operations.

Accountability in procurement ensures that responsible parties are answerable for their actions, decisions, and the outcomes of the procurement process. It establishes clear lines of responsibility and consequences for non-compliance or misconduct. Accountability promotes adherence to ethical standards, encourages good governance, and helps prevent fraud or misuse of resources.

4.3 Maximizing the Benefits of GREM Financing in Geothermal Project Exploration Planning

Maximizing the benefits of GREM financing in geothermal project exploration planning offers significant advantages for geothermal developers. GREM financing, as provided by the World Bank, serves as a valuable risk mitigation solution, particularly in the limited financing context of geothermal exploration projects in Indonesia. By understanding and effectively leveraging GREM financing, geothermal developers can optimize their exploration planning and achieve positive outcomes.

Procurement plays a crucial role in maximizing the benefits of GREM financing in geothermal project exploration planning. Geothermal developers need to strategically align their procurement processes with the lender's procurement guidelines to fully leverage GREM financing and its associated advantages.

By effectively managing the procurement process in line with GREM financing requirements, geothermal developers can optimize the utilization of funds, enhance risk management, attract competitive suppliers, and achieve the desired outcomes of the exploration project. Effective procurement practices not only support the successful implementation of the project but also contribute to the overall sustainability, accountability, and transparency of geothermal development in Indonesia.

5. DISCUSSION

Geothermal projects provide relatively clean and constant production profiles compared to other renewable energy technologies. The electricity production from geothermal energy in Indonesia is still a long way from the ambitious 2030 target. One of the crucial factors of the slow progress in the geothermal sector in Indonesia is caused by high resource risk and high upfront investment costs which are faced in the newly tendered or green field projects. The uncertainty is decreased after the resource availability has been confirmed during the drilling phase.

The procurement aspect has an important role in the geothermal business process; thus, the geothermal developers need to increase their awareness about the issues related to procurement process when choosing the financial source as it may affect the requirement process. Failure to understand the procurement requirement of the selected financing scheme may lead to prolonged delay, higher cost, and reduced discounted value of the project’s revenues.

REFERENCES

Adityatama, D. (2020). Mengenal Tahapan Proyek Panas Bumi di Indonesia. www.enerklaz.com

Apriani, D. N. I., Randle, J. B., & Paripurna, A. (2018). Government Drilling Program for Geothermal Exploration in Indonesia. 14–16.

Asian Development Bank (ADB), & The World Bank. (2015). Unlocking Indonesia's Geothermal Potential. ASIAN DEVELOPMENT BANK.

Asokawaty, R. F., Purba, D. P., Adityatama, D. W., Muhammad, F., & Umam, M. (2020). Indonesia's Geothermal Development Comp are to World Top Geothermal Producers. 45th Workshop on Geothermal Reservoir Engineering.

Darma, S. (2016). Indonesia: Vast geothermal potential, modest but growing exploitation. In Geothermal Power Generation: Developments and Innovation (pp. 609–643). Elsevier Inc. https://doi.org/10.1016/B978-0-08-100337-4.00021-8

Direktorat Panas Bumi. (2022). Buku Pintar Umum Panas Bumi.

GeothermEx (2010). An assessment of geothermal resource risks in Indonesia.

GGGI (2023). A Guideline to Differentiate Cost Type in Geothermal Development Project in Indonesia: Blawan-Ijen Geothermal Prospect Area Case. Global Green Growth Institute report to PT SMI (unpublished).

Ibrahim, R. F., & Fauzi, A., Suryadarma. (2005). The progress of geothermal energy resources activities in Indonesia. Paper presented at the Proceeding World Geothermal Congress 2005, 1-7.

IGA. (2014). Best practices guide for geothermal exploration. Bochum, Germany: International Geothermal Association.

Jacobs, & PT SMI. (2022). GREM Evaluation Framework Criteria.

Kristianto, B. (2018). Discussion on 3G surveys cost and duration in geothermal exploration in Indonesia. Personal communication.

PT SMI. (2022a). Indonesia Geothermal Resource Risk Mitigation Project Developer Manual. https://ptsmi.co.id/strategiccooperation/grem

PT SMI. (2022b). De-risking of Geothermal Exploration from Lender's Perspective.

Purba, D.P (2018).: Energy 785 Research Project Report: Investigation on Geothermal Resource Assessment Methods in Reducing Exploration Risk in Indonesia Geothermal System. The University of Auckland, New Zealand. Unpublished manuscript.

Purba, D.P., Adityatama, D.W., Umam, M.F., and Muhammad, F. (2019). Key Considerations in Developing Strategy for Geothermal Exploration Drilling Project in Indonesia, Proceedings, 44th Workshop on Geothermal Reservoir Engineering, Stanford University, Stanford, California, United States.

Purba, D.P., Adityatama, D.W., Agustino, V., Fininda, F., Alamsyah, D., and Muhammad, F. (2020). Geothermal Drilling Cost Optimization in Indonesia: A Discussion of Various Factors, Proceedings, 45th Workshop on Geothermal Reservoir Engineering, Stanford University, Stanford, California, United States.

Purba, D.P., Adityatama, D.W., Nugraha, R. P., Ayuningtyas, R. R., Chandra1, V. R., Al-Hassan, M. A., Ramadhan, R. F., Rizqy, M. M. (2021). Resource Assessment Methods Selection for Geothermal Exploration Project in Indonesia: What Are the Considerations? Proceedings, 46th Workshop on Geothermal Reservoir Engineering, Stanford University, Stanford, California, United States.

Poernomo, A. S. (2015). An overview of Indonesia Geothermal Development – Current Status and Its Challenges. Pp. 1 – 11. In: Proceedings of World Geothermal Congress, Melbourne, Australia.

Purwanto, E. H., Suwarno, E., Lukman, R. F., and Herdiyanto, B. (2018). Geothermal Drilling in Indonesia: A Review of Drilling Operation, Evaluation of Well Cost and Well Capacity, Proceedings, 6th Indonesia International Geothermal Convention & Exhibition, Jakarta, Indonesia (2018).

ThinkGeoEnergy. (2023, January 11). Top 10 Geothermal Countries 2022 – Power Generation Capacity (MW). https://Www.Thinkgeoenergy.Com/Thinkgeoenergys-Top-10-Geothermal-Countries-2022-Power-Generation-Capacity-Mw/Amp/.

Türkiye Kalkınma ve Yatırım Bankası (TKYB), & The World Bank. (2021). RSM Geothermal Resource Validation - Beneficiary Manual 2.0. https://rpmjeoturkiye.com/en/homepage/

Umam, M., Adityatama, D., & Purba, D. (2018): Tantangan Pengembangan Energi Panas Bumi Dalam Perannya terhadap Ketahanan Energi di Indonesia. Swara Patra, 8(3), 48-65.

Utami, P. (2010). High-temperature Geothermal Area and its Challenges for Civil Engineering Works. PERTEMUAN ILMIAH TAHUNAN XIV HATTI. Indonesia.

Geothermal resource optimisation: Exergy's 500 MWe local production experience and know how in Turkey

Erdogan Arpaci and Chee Aun Kok

EXERGY

e.arpaci@exergy.it, c.kok@exergy.it

Keywords: geothermal resource exploitation, Turkey, Radial Outflow Turbine, binary system, tailor-made power plant design, geothermal local production

ABSTRACT

3% of electricity and majority of the heating in Turkey are geothermal powered. There are now 63 geothermal power plants reflecting nearly 22 GWe of capacity with majority located in the Western Anatolia regions. Western Anatolia and the Western Anatolian Graben systems (Büyük Menderes and Gediz Grabens which cover over 4000 sq. km) hold the potential between 5 to 16 µW/m3.

2/3 of the installed capacity are binary power plants which use hot water/low enthalpy steam from the ground to evaporate a lower boiling fluid to drive the turbine, while the remaining units are from conventional steam flash configurations. The hot water and low enthalpy resources bear certain similarities to the resources available in Indonesia.

There was only 100 MWe of installed capacity in 2010 but by 2017 there was more than 1 GWe of capacity built up. The growth of geothermal power generation was due to a combination of improved feed in tariff, favorable government legislation, local content manufacturing incentives and also improvements in the binary technology.

Exergy is one of the main binary power plant suppliers in Turkey and the goal of this paper is to share the lessons we have learnt as a company investing in Turkey and translate this into success with future partners in Indonesia. Through the valuable experience of establishing a factory, hiring the right people, setting up the equipment and manufacturing flow, Exergy was able to formulate both technological and manufacturing strategy that can bring value to Indonesia in view of her available manufacturing, supply chain and also geothermal resources sizes available.

1. GEOTHERMAL MARKET IN TURKEY VS INDONESIA

In 1965, the government's Directorate of Mineral Research and Exploration began the first geological and geophysical surveys in southwestern Turkey. The Kizildere geothermal reservoir, on the western branch of the Buyuk Menderes Graben, was found in 1968 to be suitable for electricity generation. A small 500 kW pilot power plant was built in 1974 and free electricity distributed to nearby households. The state-owned Electricity Generation Company enlarged the plant in 1984, to average around 10 MW.

In 2007, Turkey passed the Law on Geothermal Resources and Natural Mineral Waters, which accelerated geothermal exploration by making investment easier for the private sector.

In 2009, government announced the renewable energy support scheme (YEKDEM) and the feed-in tariff was 105 USD/MWh, guaranteed for ten years. In addition to this government was giving additional incentives for made in Turkey turbine and made in Turkey generator up to 20 USD/MWh. These incentives were valid for the geothermal power plants that were installed between 2010 to 2020. By the help of this YEKDEM mechanism, the number of geothermal power plants increased from 3 to 49 in 10 years and the installed power changed from 90 MWe to 1.500 MWe. Please see figure 1 showing the installed power of geothermal power in Turkey by years.

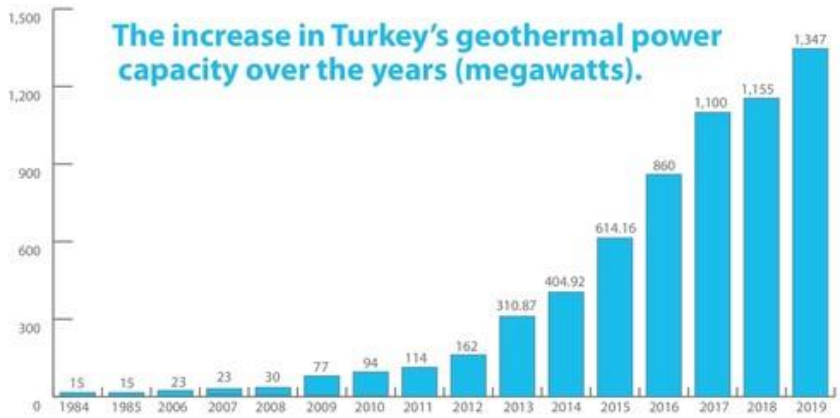


Figure 13: Turkey Geothermal Power Capacity by Years.

In 2023, government announced a new renewable energy support scheme (YEKDEM) and the minimum feed in tariff is 94.5 USD/MWh and maximum is 115.5 USD/MWh for a period of 15 years for the geothermal power plants to be installed between 2023 to 2038. In addition to this government was giving additional incentives for made in Turkey turbine, made in Turkey generator, made in Turkey cooling system and made in Turkey heat exchangers up to 10 USD/MWh.

By the end of 2022, the total geothermal installed power in Turkey is 1.682 MW and that generates 3.5% of the country's electricity demand. 63 power plants are in operation on 27 geothermal fields. Turkey is fourth in the world for geothermal power; with about half that of the United States, and slightly less than Indonesia and the Philippines. Please see Figure 2 for the top 10 geothermal Countries as of 2022.

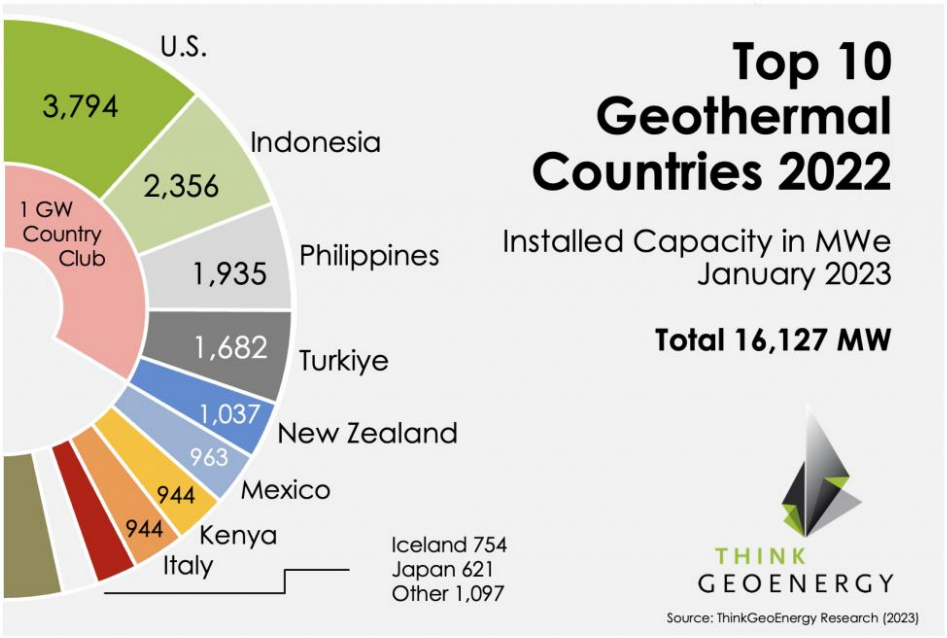


Figure 2: Top Ten Geothermal Countries as of 2022.

Exploration levels have reached from 2,000 meters to 5,000 meters. The probable heat potential of Turkey is 31,500 MWt. For electricity generation, this rate is at the level of 5.000 MW.

Indonesia has potentially 28 GWe of geothermal capacity however as of 2021, only around 2.88 GWe of this capacity has been installed. Currently geothermal makes up 12% of the country's total generation and the government aspires to increase this capacity to 25% by the year 2025. Pertamina, which is the

National oil company of Indonesia, is one of the major stakeholders of this segment. Pertamina plans to double their current 700 MWe of geothermal capacity to 1400 GWe by 2025. Binary power plants are part of the strategy for Pertamina to reach this target. Binary plant investments are significantly lower as they do not need to dig new well for retrofitting to existing flash plant, thus avoiding the single most expensive component of geothermal power plant. Binary power plants can also be developed much faster.

Indonesian President Joko Widodo has issued the Presidential Regulation Number 112/2022 in order to attract more investors to developed the domestic renewable energy market. The new regulation sets better prices for the prices of power to be sold to the single buyer local utility PT PLN (Persero)

The prices are as follows:

Geothermal power plants (wholly built by business entities and wholly or partially built by the central and regional governments)

- 10 MW capacity, the highest benchmark price is 9.76 cents/kWh x F (location), in the first 10 years. Meanwhile, the price for the 11th – 30th years reaches 8.30 cents/kWh.
- Capacity 10 – 50 MW, the price is 9.41 cents/kWh x F in the first 10 years, while in years 11 – 30 years the price becomes 8.00 cents/kWh.
- Capacity 50 MW – 100 MW, the price is 8.64 cents/kWh x F in the first 10 years. While the 11th – 30th years are only 7.35 cents/kWh.
- Capacity of 100 MW and above, the price is 7.65 cents/kWh x F in the first 10 years. While the 11th – 30th years are only 6.50 cents/kWh.

Geothermal steam power equivalent to electricity:

- Capacity – 10 MW, the highest benchmark price is 6.60 cent/kWh x F (location), in the first 10 years. While the price for years 11 – 30 reaches 5.60 cent/kWh
- Capacity 10 – 50 MW, the price is 6.25 cents/kWh x F in the first 10 years, while in years 11 – 30 years the price becomes 5.31 cents/kWh
- Capacity 50 MW – 100 MW, the price is 5.48 cents/kWh x F in the first 10 years. While the 11th – 30th years only 5.31 cents/kWh.
- Capacity of 100 MW and above, costs 4.48 cents/kWh x F in the first 10 years. While the 11th – 30th years are only 3.81 cents/kWh.

The magnitude of the location factor F depends on the location. The lowest values are in Java, Madura, and Bali (1.00) and the highest are in Papua (1.50). The Indonesian Government has a Domestic Component Level (TKDN) requirement for power generation equipment (Regulation of the Minister of Industry No. 54 of 2012). For the geothermal sector the TKDN of Geothermal Power Plant EPC has to be > 35% now.

Comparing the 2 countries, Indonesia does not have any PPA premium incentives tied to domestic manufacturing. Nevertheless, as a company Exergy has looked into the manufacturing infrastructure, supply chain, skilled labor capability and availability in Indonesia and this remains a country that is very interesting for Exergy to have their 3rd factory.

2. GEOTHERMAL PROJECTS FINANCING IN TURKEY

Geothermal has high upfront costs and is financially risky.

The World Bank announced on August 25, 2016, that Turkey had applied for up to US$ 290 million to fund the “Turkey Geothermal Development Project.” US$ 40 million of the US$ 290 million sought to be covered by the Bank’s Clean Technology Fund. The Turkey Geothermal Development Project, to be implemented by a public development bank, Türkiye Kalkınma Bankası A.Ş. (the Development Bank

of Turkey), and Turkey's first private development bank, Türkiye Sınai Kalkınma Bankası A.Ş. (the Industrial Development Bank of Turkey), was announced by the World Bank on November 1, 2016.

The Turkey Geothermal Development Project, which has two components, aims to boost the geothermal sector by helping to minimize developer risk at the exploration stage and by providing long-term financing for the development and operation stages. The first component of the project, a Risk-Sharing Mechanism funded by the Clean Technology Fund's US$ 40 million contribution, is designed to support geothermal investments early in the exploration and resource verification stages. The second component of the program focuses on the financing of geothermal investments made by the private sector companies throughout Turkey. The Development Bank of Turkey and the Industrial Development Bank of Turkey will both use the credit line provided by the World Bank specifically to support geothermal developers. Loans will be granted at market rates but with longer tenors than currently available. As of end of February 2020, almost US$ 200 million under the second component have been disbursed to the Turkish banks.

In 2022 the World Bank loaned $300 million for geothermal energy, some to private companies via the state industrial development bank Türkiye Sınai Kalkınma Bankası (TSKB).

European Bank for Reconstruction and Development, the Asian Infrastructure Investment Bank and the Black Sea Trade and Development Bank provided financing of US$ 350 million for three new geothermal power plants.

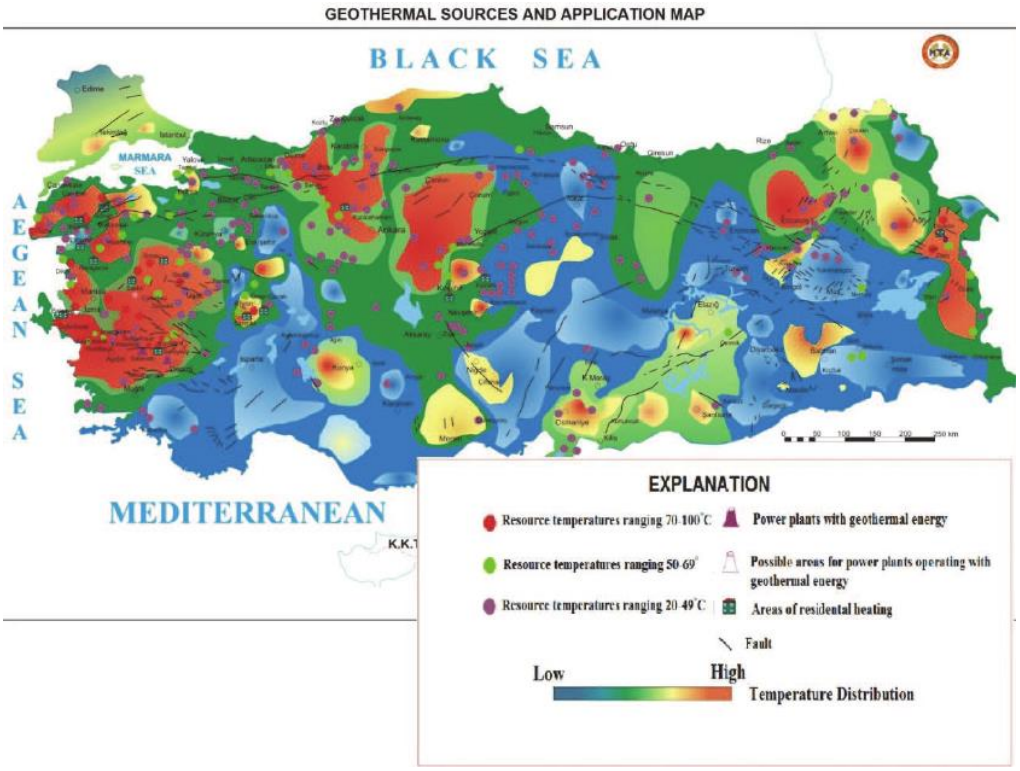


Figure 3: Geothermal Resources and Application Map of Turkey.

3. GEOTHERMAL RESOURCE CHARACTERIZATION IN TURKEY

Down to a few kilometers under the surface, Due to extensional tectonism the highest temperatures are in the west. There are 16 fields hotter than 130 °C, one in the Marmara Region and the rest in the Aegean Region. There are a few high-temperature resources in the Menderes Massif up to almost 300 °C. The high geothermal potential is due to the geology of Turkey, such as the radiogenic granites of western Anatolia and the Western Anatolian Graben systems. Please see Figure 3 – Geothermal Sources and Application Map of Turkey.

Turkey has a significant geothermal potential, with 78 percent of potential areas in Western Anatolia, 9 percent in Central Anatolia, 7 percent in the Marmara Region, 5 percent in Eastern Anatolia, and 1% in other regions. 90% of geothermal resources are low and medium temperature, appropriate for binary power plant application.

Figure 4: Distribution of geothermal possible reserves in Indonesia.

The resources available in Indonesia are a mix of Steam Flash Power plants and Low Enthalpy reserves. Most of the steam power plants in the country has been developed. Interestingly what remains to be developed in the country bears similarity with the resources in Turkey. Low enthalpy steam and hot water form the steam separators of such plants; together with the hot water from within the local geothermal working area, has been evaluated and proven to be technically suitable for ORC Binary solutions.

4. BINARY POWER PLANTS AND EXERGY TECHNOLOGY

90% of geothermal resources are low and medium temperature, appropriate for binary ORC power plant application.

4.1 Binary Power Plants

Binary power plants are expected to be the most used type of geothermal power plant in the future, as they can make use of lower temperature water but more importantly, they can guarantee no water consumption, zero emission and 100% resource reinjection. The geothermal fluid from the well flows through shell-and-tube heat exchanger which transfers its heat to the secondary fluid which vaporizes due to its low boiling point. It is then passed through a turbine coupled with an electric generator. At the end the secondary fluid is condensed with air or water as cooling and pumped again with a feed pump, in a completely closed loop. Please see Figure 5 for a binary cycle.

4.2 Exergy Organic Rankine Cycle (ORC) Technology

Around 25% of the installed 16 GW capacity is ORC power plants. But the important trend for the recent developments shows that around 65% of the new installed capacity since 2015 is ORC power plants. So, ORC technology will be the key to generate more power from geothermal in the future.

Organic Rankine Cycle (ORC) systems are closed loop with no interaction with geothermal fluid and used for power production from low to medium temperature heat sources and for small-medium applications at any temperature level. This technology allows for exploitation of low-grade heat that otherwise would be wasted. Having the unique advantage of operating under several conditions, Organic Rankine Cycle engines perform with higher efficiency and flexibility with respect to traditional Rankine cycle technologies on medium enthalpy resources.

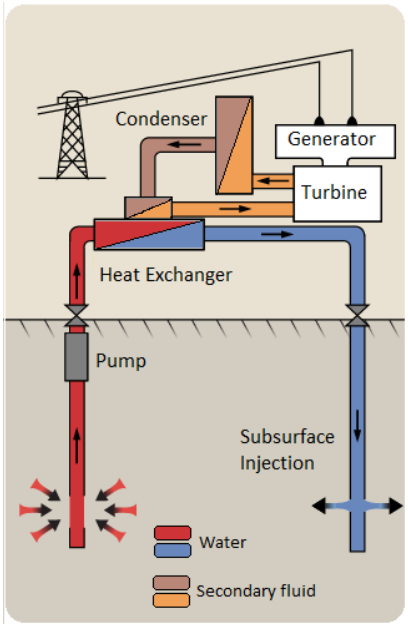


Figure 5: ORC Binary Power Plant (lighter brown – vaporized secondary fluid & darker brown – liquid secondary fluid).

The main components of an Organic Rankine Cycle power plant design are:

Turbine

It's the key component of the entire ORC power plant, which determines most of the ORC system performance. It expands the working fluid producing mechanical energy that is converted into electricity by a generator coupled with the turbine shaft.

Heat Exchangers

The working fluid flows through the heat exchangers, extracting the heat from the heat source. Shell and tube heat exchangers are usually applied but they can vary geometry and configuration depending on the energy source and the total thermal input.

Condenser

With the direct air to fluid heat exchanger, the organic fluid is cooled and liquefied before entering the pump. The use of air eliminates the requirement for water to treatment and make up. It is possible to use also a water-cooled condenser where water is easily available

Feed Pump

Brings the organic fluid from the condensation pressure to the maximum pressure of the Organic Rankine Cycle. The pump is usually driven by an electric motor at variable rotating speed.

The advantages of the ORC over the traditional Rankine cycle are;

- Suitable for lower temperature hot source applications
- Design flexibility with the option to utilize the most efficient working fluid available
- Operational flexibility; superior off-design performances
- Compact and automated; no need for operators
- Long-lasting expander, with simple and low-cost maintenance
- Low costs for foundation and assembly
- Simple and reliable system maintenance with higher availability

With more than 20 years' experience in the power industry, Exergy design, engineer, produce and maintain Organic Rankine Cycle (ORC) systems for electricity production. ORC systems are used for power production from renewable energy sources including geothermal, biomass and concentrated solar power as well as from waste heat.

Exergy undertakes the development and manufacturing process of the ORC turbine and plant internally. This includes in-house R&D, engineering, project management, testing and after-sales service. Exergy also operates a central control room to provide remote monitoring of the plants of its customers.

Exergy is operated by a team of experienced and skilled experts that include energy and mechanical engineers, product managers, technology specialists and designers, sales and marketing professionals, service and quality managers and support staff. Today Exergy counts 61 power plants in its portfolio for a total capacity of more than 500 MWe and owns the second largest geothermal binary fleet worldwide.

4.3 Exergy Radial Outflow Turbine (ROT) Technology

Designed by EXERGY, The Radial Outflow Turbine (ROT) was launched in the market in 2009, becoming a world first in the ORC industry and recognizing Exergy as a game changer in the marketplace. This technology is covered by current and pending patents and is the first turbine of its kind to be utilized in an ORC system.

The key feature of the Radial Outflow Turbine configuration is the capacity to convert the energy contained in the organic fluid into mechanical power with higher efficiency than any competing technologies present in the market.

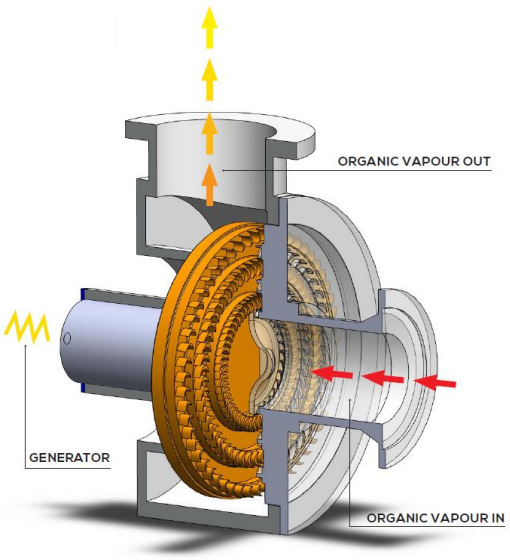


Figure 6: Exergy's Radial Outflow Turbine.

Most of the characteristics of Radial Outflow Turbine technology, covered by multiple IP rights, entail several advantages:

- Suitable for low temperature heat resources, as low as 90 °C
- Thanks to straight blades and radial design, outward movement of fluid leading to minimum 3D effects and minimum turbulence, means maximum efficiency
- Higher efficiency than any competing turbines in the market
- Multiple pressure admissions possible on a single disk; cost effective solution, less limitation on cycle pressure and 20% more power than a single level system
- Thanks to low-speed turbine; no gearbox, higher reliability, low noise and longer life of the bearings

- Thanks to patented mechanical group technology; no fluid loss or drainage, easy and fast maintenance, no overhaul maintenance on the turbine
- Large increase in volumetric flow achieved without the need for extreme changes in blade height
- Up to 9 stages on a single disk turbine; better exploitation of high enthalpy resources, extreme flexibility for changing geothermal fluid conditions

5. EXERGY'S SUCCESS IN TURKISH GEOTHERMAL MARKET AND WHAT CAN BE REPLICATED IN INDONESIA

Exergy International Srl entered Turkish market in 2013 by and in 2014 opened the local subsidiary Exergy Turkey Turbin Enerji Teknolojileri A.S. to manufacture made in Turkey turbine to benefit its customer from additional incentives and also created a dedicated maintenance and service team to provide high availability to its plants. Within less than 10 years, Exergy achieved to supply more than 500 MW geothermal power plants in Turkey and being the fastest growing geothermal ORC supplier in the market.

Our experience in Turkey allows us to have a view of what is ahead and what we can execute in Indonesia. Looking at the Indonesia market as a whole these are the fundamental technical requirements for success in Indonesia:

1. Efficient turbine design: the Radial Outflow Turbine remains a crucial part of the technology that must be maintained;
2. Modular design: product design and manufacturing must be made within a factory and able to be replicated in high volume with minimum changes;
3. Easy site erection, commissioning and maintenance: the product has to be designed in a way that is easily and swiftly erected and installed by the EPC partner. The overall package must also be easily maintained locally by a domestic team.

5.1 Exergy ORC History

In 2009: conceptualized by Exergy's founder Claudio Spadacini after years of research and development,

Exergy launches the Radial Outflow Turbine on the market.

In 2011: Exergy becomes part of the Maccaferri Industrial Group and firing up the first high-enthalpy 1 MW Radial Outflow Turbine in September.

In 2012: Exergy installs the world's first Radial Outflow Turbine in a geothermal plant at the Bagnore III plant for Enel Green Power in Tuscany. This plant is still the first and only geothermal binary plant in commercial operation in Italy.

In 2014: Exergy wins key contracts in Turkey for the supply of more than 10 ORC power plants, becoming a market leader for geothermal binary power plant equipment. In July, EXERGY establishes a Turkish subsidiary company, based in the city of Izmir.

In 2015: Exergy launches the world's first geothermal power plant equipped with a 2-pressure level cycle featuring a single-disk turbine in Denizli, Turkey. This 4 MWe plant represents a unique technological milestone confirming EXERGY's leadership at the forefront of innovation and earning the company the 2016 European Geothermal Innovation Award from the EGEC.

In 2016: Exergy starts up its first 12 MW and 25 MW large scale geothermal plants in Turkey

In 2017: First performance results on plants in operation register average availability above 99%.

In 2018: Exergy enters the Oil & Gas market with a WHR ORC unit for an LNG regasification plant in Thailand.

In 2019: On September 25, Exergy is acquired by Nanjing TICA Thermal Technology Co. Ltd.

In 2021: Exergy supplies the first geothermal brine recovery project in the Philippines for the Energy Development Corporation.

5.2 Exergy Approach to Turkish Geothermal Market

Due to the resource characteristics of Turkey, Turkey was the biggest target market for Exergy since the establishment of the company.

Innovation and Tailor-Made Solutions: Exergy sold its first power plant in Turkey in 2013. The plant was in operation in 2014 and it is the world's first geothermal power plant equipped with a 2-pressure level cycle featuring a single-disk turbine in Denizli, Turkey. Plant's inlet brine temperature was designed as 105°C and Exergy was the only ORC supplier proposed a feasible commercial and technical offer. This 4 MWe plant represents a unique technological milestone confirming Exergy's leadership at the forefront of innovation.

Exergy Turkey Subsidiary: In July 2014, Exergy took a very strategic decision to open a subsidiary company in Turkey to manufacture turbine. By manufacturing turbine in Turkey, Exergy customers were benefiting from an additional feed in tariff and able to make 10% more profit annually. By the support of this advantage Exergy was able to sell app. 500 MW power plants between 2014 to 2020.

Wide Range of Plant Applications: as of today, Exergy has 28 geothermal power plants in operation and 5 geothermal power plants in construction. Among these, 25 power plants are in operation in Turkey and 2 power plants are under construction in Turkey. Power plant designs are all tailor-made to give the optimum commercial and technical proposal to customers and plant inlet temperatures are varying between 105° C to 175° C and plant sizes are varying between 1 MW to 28 MW. Working in such a wide range with a tailor made design mentality, Exergy has the experience to supply highest efficient power plants in the market.

Maintenance and Service: Exergy has its own maintenance and service crew based in Italy and Turkey. All power plants are being monitored 7/24 online and in case of any alert first approach is being made through Scada system. If it cannot be solved online, Exergy technicians and engineers are ready to approach the plants physically whenever needed. That enables Exergy to reach above 99% availability values for the geothermal plants and that is another selection criteria among competition.

In House Expertise: Exergy is capable of development and design of ORC systems, engineering, manufacturing and testing, project management, long terms after sales service and operation of plants. All are done by in house expertise by Exergy personnel in Turkey and that brings the down time of the plants down and smooth operation of the power plants.

5.3 Exergy Approach to Indonesia Market

While Exergy is reputable for its custom-made high performance, high availability ORC units, the team has embarked on a process to manufacture the new modular ORC units in Indonesia as an extension of its current facilities. These modular plug-and-play units will be in the sizes of 280 kWe and 1.2 MWe. The success of the company depends on its people, that has been the key element of its investment in Turkey. Exergy would be manufacturing its modular units in Indonesia mainly for:

- Domestic supply chain. Indonesia has a network of local fabricators that is ASME U, R and S which already exports both pressure and non -pressure parts to the global market. The heat exchanger for superheaters, economizer, preheaters and recuperators can be built domestically. The company is now pre-qualifying supplier for this. Bandung is Indonesia's center for the maintenance, service and overhaul center for prominent global aviation, gas turbine and steam turbine companies. This is an area that the company is evaluating for the turbine production for the modular units.
- Skilled workforce and knowledge transfer. Many Indonesians are now involved in the manufacturing, deployment, erection, installation, commissioning within the country and

beyond. It is our intention to train to build a skilled workforce that is able to produce our product.

- Local Workshop for repairs and maintenance: PT Power Perdana, Exergy's representative partner, comes from the oil and gas rotating equipment sales and services background. They have an operational workshop now undertaking tasks for rotating equipment for both power generation and compression. This allows the upcoming new to work together immediately. For the end users, this can assure that anomalies are attended to in real time.

6. CONCLUSION

Turkey is mostly composed of low-medium enthalpy resources and it is very convenient for ORC application. Exergy is the leading geothermal ORC supplier in Turkey by more than 500 MW references by its power plants in operation with above 99% availability. Thanks to the renewable energy support scheme (YEKDEM), finance support from World Bank, development banks, European Bank for Reconstruction and Development and local banks, local presence of Exergy in Turkey by a complete subsidiary company capable of manufacturing and providing after sales service and tailor-made solutions that give customers the optimum solutions, Exergy will continue to lead the geothermal market in Turkey. The remaining resources to be developed in Indonesia bears similarities to those in Turkey. The technical prowess needs to be working well with domestic skilled personnel for a winning solution. Exergy is thinking globally and acting locally to better serve the market needs.

REFERENCES

Cariaga, Carlo: Development of geothermal in Turkey – UNESCO Science Report, Fusun Servin Tut Haklidir. Think GeoEnergy. (23 March 2022)

Chandrasekharam, Dornadula; Baba, Alper: Carbon dioxide emissions mitigation strategy through enhanced geothermal systems: western Anatolia, Turkey. (18 April 2022).

Eröcal, D; Yegorov: Countries in the Black Sea Basin. In UNESCO Science Report: the Race Against Time for Smarter Development (1 July 2022).

Husin Setia Nugraha; Husin Setia Nugraha; Yunus Saefulhak; Bintara Pangaribuan: A Study on the Impacts of Incentives to the Geothermal Energy Electricity Price in Indonesia using Production-based Cost Approach (PDF), Proceedings of the IIGCE 2017, Jakarta (2 August 2017)

Kaya, Nuran Erkul: EBRD launches €500M financing facility to support green transition in Turkiye. (23 June 2022)

Richter, Alexander: ThinkGeoEnergy's Top 10 Geothermal Countries 2021 – installed power generation capacity (MWe). (23 January 2022).

Resettlement Policy Framework for the Turkey Geothermal Development Project – Component 2 – Financial Intermediaries (TSKB) – draft (6 July 2022)

Serpen, Umran; Aksoy, Niyazi; Öngür, Tahir: 2010 Present Status of Geothermal Energy in Turkey" (PDF). *Proceedings* of the Thirty-Fifth Workshop on Geothermal Reservoir Engineering. Stanford, California: Stanford University (31 March 2011).

Serpen, Umran; DiPippo, Ronald : Turkey – A geothermal success story: A retrospective and prospective assessment (1 May 2022).

Turkey to Scale-up Renewable Geothermal Energy Generation with World Bank Support. World Bank. (23 January 2022).

Economic Assessment of Lithium Extraction from Geothermal Brine: Comparative Analysis Worldwide and Indonesia's Prospects

Candra Sri Sutama[1], Ali Ashat[2], Desti Alkano[1], and Syarif Riyadi[1]

[1]ECADINE
[2]Geothermal Master ITB

candra.sutama@outlook.com, candra.sutama@ecadin.org,
labgeothermal@yahoo.com, d.alkano@ecadin.org, sy.riyadi@gmail.com

Keywords: lithium, geothermal, DLE, Indonesia

ABSTRACT

Lithium is a crucial element in renewable energy storage systems and electric vehicle batteries. Hence, it is regarded as an essential metal in the context of energy transition. As a result, the demand for lithium is anticipated to increase by more than ten times over the course of two decades. During the last few years, there has been a notable increase in global demand for lithium, accompanied by restricted supply, which has led to a substantial price increase and the colloquial term "white gold" being attributed to this valuable metal. Currently, the global lithium supply chain is heavily concentrated, raising concerns about energy security in many countries, prompting the need to explore alternative lithium sources. In response, the pursuit of alternative lithium extraction methods has intensified. Recent advancements in Direct Lithium Extraction (DLE) technology have made it possible to extract lithium from various brine sources, including geothermal brine. The utilization of geothermal brine for lithium extraction not only provides a viable alternative for meeting the increasing demand but also minimizes environmental impact and addresses energy security concerns.

This paper aims to conduct an economic assessment of extracting lithium from geothermal brine by analyzing various geothermal lithium projects worldwide. Subsequently, it focuses on the case of Indonesia, to evaluate the potential of lithium extraction from Indonesia's geothermal brine and the important areas to support it.

To achieve these objectives, the research methodology involves a comparative analysis of several geothermal lithium projects worldwide, assessing their economics and identifying common methods. The specific case of Indonesia is examined through an overview of its resources, then simulating the economic performance of lithium extraction from geothermal brine, sensitizing several technical and operational parameters. In the end, the study analyzes policy and investment climates to provide insights into the challenges and opportunities associated with extracting lithium from geothermal brine.

Ultimately, the assessment presented in this paper aims to facilitate informed decision-making regarding lithium extraction from geothermal brine. By evaluating several geothermal lithium projects globally and analyzing Indonesia's prospects, this study offers valuable insights into the potential of geothermal brine as an alternative source for lithium extraction, thereby contributing to the development of a sustainable and resilient lithium supply chain in the context of the energy transition.

1. INTRODUCTION

1.1 Lithium, the Critical Metal for Energy Transition

Lithium is an alkali metal denoted by the chemical symbol Li. In the form of lithium carbonate (Li_2CO_3) or lithium hydroxide monohydrate ($LiOH.H_2O$), it is one of the main components of Lithium-ion (Li-ion) batteries, a type of battery that is vastly used in renewable energy storage systems and electric vehicle batteries. Hence, it is regarded as an essential mineral in the context of the energy transition.

In the brief span of half a decade from 2017 to 2022, the global lithium demand has escalated markedly. This demand surge, coupled with a constrained supply, has catalyzed an over six-folds expansion in the lithium market size. Furthermore, the demand for lithium is projected to multiply by more than ten times

in the next two decades. In the clean energy sector, more than 90% of this demand will come from electric vehicle battery requirements and the rest from grid battery storage needs (IEA, 2023).

Today, global lithium production is dominated by a few countries. Around half of global lithium is produced in Australia by mining spodumene, a mineral ore containing lithium aluminum inosilicate. The rest of global lithium are mostly produced in the lithium triangle (Chile, Argentina, Bolivia) by concentrating lithium-rich brine pumped from salars (underground brine lakes), through months-long or even years-long natural evaporation process in large ponds. China also contributes to approximately 15% of world lithium production. However, interestingly, nearly 60% of global lithium is processed in China while 40% is distributed between Chile and Argentina (IRENA, 2023).

Due to this highly concentrated supply chain, the urgent need for securing steady critical material supplies for energy transition, including lithium, has driven the emergence of numerous policy actions in recent years. Lithium is listed in 26 out of 35 Critical Material Lists for Energy Transition published by various countries and regions, ranking second only to cobalt. Notably, Lithium is included in the European Union's Critical Raw Materials Act, the United States' Inflation Reduction Act (IRA), and the Critical Minerals Strategies of both Australia and Canada, among others (IEA, 2023). Countries and regions are actively seeking alternative sources and methods to produce lithium, ensuring energy security is attained in the efforts to reach their decarbonization goals.

1.2 Environmental footprint of current lithium production

Strikingly, despite lithium's vital role in the energy transition, the process of lithium production leaves a considerable environmental impact. Currently, nearly all the spodumene originating from Australia, after being transformed into lithium concentrate, is shipped to China to undergo refining. This whole process is responsible for the emission of over 15 tons of carbon dioxide per ton of lithium hydroxide monohydrate produced (Kelly et al., 2021). This carbon footprint highlights the paradox of relying on a material essential for a green energy transition that, in its production process, significantly contributes to greenhouse gas emissions.

On the other hand, while the carbon intensity of producing lithium hydroxide monohydrate from salar brine is roughly half compared to that from Australian spodumene, it is important to note that this method requires substantial quantities of water. A study conducted by Jerez et al., in 2021 has elucidated the environmental implications of this extraction method, particularly in terms of water justice for indigenous communities in the vicinity of lithium extraction sites. Focusing on the case of Salar de Atacama, the study discusses the detrimental effects of lithium extraction on the local water ecosystems. With lithium companies drawing more than two million liters of water (both fresh and saline) daily from the Salar de Atacama, the surrounding water ecosystem has been significantly disrupted. This massive extraction has resulted in water depletion observable in the main rivers supplying the Salar de Atacama basin. The subsequent reduction in available water has led to a discernible decrease in agricultural activities in the Salar, further underscoring the intricate connection between lithium production and environmental implications. This scenario highlights the urgent need for sustainable extraction methods to balance the demand for this critical energy transition metal with the well-being of our natural ecosystems and communities.

2. DIRECT LITHIUM EXTRACTION (DLE) FROM GEOTHERMAL BRINE

Considering the concerns raised earlier, efforts to identify alternative lithium sources and develop novel extraction methods have significantly increased. The recent advancement in mineral extraction technology has enabled lithium extraction directly from a range of brine sources. Unlike the traditional methods requiring months to years of natural evaporation, Direct Lithium Extraction (DLE) technology allows lithium to be concentrated from a solution through a technical procedure. The optimal DLE technology would enable quicker lithium extraction, reduce water and energy consumption, and minimize surface land use, thereby providing a more sustainable approach to lithium extraction.

One of the brine types that hold promising potential as a source of lithium is geothermal brine. After the hot brine from a geothermal reservoir is brought to the surface for heating or generating electricity,

the lithium is extracted, then subsequently the brine is injected back into the earth. The resulting lithium concentrate is then processed on-site into lithium carbonate and/or lithium hydroxide monohydrate. This method allows to produce low-carbon lithium while simultaneously generating renewable electricity from geothermal energy.

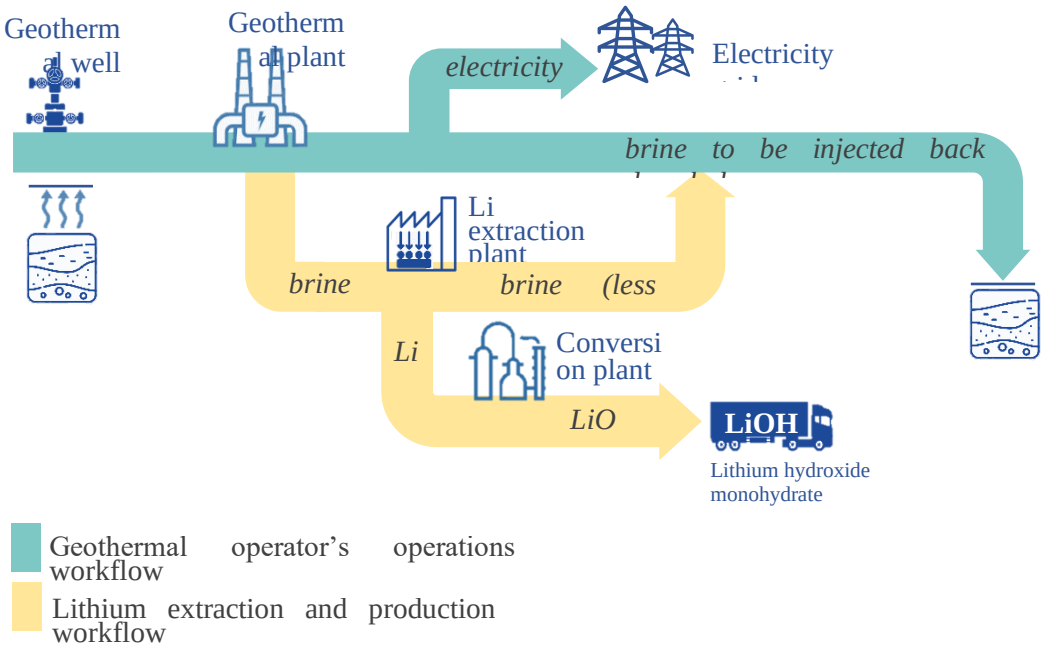


Figure 1: Simplified workflows of a combined geothermal electricity – lithium production plant.

There are numerous approaches to extraction and recovery of lithium from brines, explained in detail and grouped by several researchers including by Ighalo et al. (2022), Murphy and Haji (2022), Stringfellow and Dobson (2021). Used by many industry players is this simple technology classification: Adsorption, Ion Exchange, and Solvents Extraction (Warren, 2021). The adsorption process physically absorbs LiCl molecules onto the surface of a sorbent from a lithium-loaded solution with water as a potential stripping solution. Ion exchange takes lithium ions from the solution by trading lithium ions for protons or other cations within the sorbent's structure. An acid solution is typically required for stripping and recovering the lithium. Solvent extraction exchanges LiCl molecules or lithium ions between brine and an organic liquid phase containing an extractant that complexes with lithium or lithium compounds in the brine. Most of the technology used by the companies described in the following chapter is based on Adsorption and Ion Exchange.

3. DLE FROM GEOTHERMAL BRINE ACTIVITIES AROUND THE GLOBE

While there are ongoing explorations and advancements in DLE from geothermal brine in various parts of the world, the epicenter of these activities, the most researched, and widely discussed, primarily falls within two key geographical locations. These are the Salton Sea region in California, the United States, and adjacent sites in Europe including Upper Rhine Graben and Cornwall.

3.1 Salton Sea, California, US

In the Salton Sea, the geothermal brine has lithium concentrations from 200 mg/kg to 400 mg/kg and could potentially produce 600,000 tons of lithium carbonate per year (Ventura et al., 2020, Neupane and Wendt, 2017). Currently, there are three geothermal-lithium companies operating in the Salton Sea: Energy Source Minerals, Controlled Thermal Resources, and BHE Renewables. The first company that tried out lithium extraction in the Salton Sea, Simbol Materials, ceased operations in 2015, despite having been considered for a $325 million acquisition by Tesla the year before (CNBC, 2022).

The California government strongly backs lithium extraction efforts in the Salton Sea, as evidenced by the passage of Assembly Bill 1657 and the subsequent creation of the Blue Ribbon Commission on Lithium Extraction in California, also known as the Lithium Valley Commission. The commission's mandate includes exploring and analyzing lithium extraction practices in California and formulating recommendations to help realize its potential. California Energy Commission has also provided research and demonstration grant funding, with a total amount of approximately US$ 13 million, to all current lithium recovery project developers (Paz et al., 2022).

EnergySource Minerals (ESM) operates project ATLiS on geothermal brine associated with the John L. Featherstone geothermal power plant, using their own proprietary ILiAD technology to extract lithium. Several patents related to ESM indicate that the technology used falls under the inorganic adsorption process (Stringfellow & Dobson, 2021). Currently, EnergySource Minerals is expected to be commercial by 2025, producing 20,000 metric tons of lithium hydroxide monohydrate per annum. Nevertheless, in May 2023, ESM has already signed a binding lithium supply contract with Ford Motor for a non-disclosed amount (Energy Source Minerals, 2023).

Controlled Thermal Resources (CTR) operates the Hell's Kitchen Lithium and Power project using lithium extraction technology from Lilac Solutions (CTR, 2020). Patents associated with Lilac Solutions indicate that the type of technology used is an ion exchange process using coated material (Snydacker et al., 2019). CTR also plans to start delivering lithium in 2025, at an initial capacity of 25,000 metric tons of lithium hydroxide monohydrate per annum. Even if planned commercialization is still in the future, in June 2022, CTR has signed a 10-year agreement with car maker Stellantis to supply up to 25,000 metric tons of lithium hydroxide monohydrate per year (Stellantis, 2022). CTR also signed an agreement with General Motors in 2021 (General Motors, 2021).

BHE Renewables is a subsidiary of Berkshire Hathaway Energy which currently owns 10 geothermal power plants in Imperial Valley. BHE Renewables is currently working on two demonstration pilot projects and could start construction of the commercial plant as early as 2024 (BHE Renewables, 2022). BHE Renewables uses its own proprietary adsorption extraction technology, with an expectation to produce up to 90,000 tons of lithium carbonate equivalent per annum (Financial Times, 2019).

3.2 Europe: Upper Rhine Graben and Cornwall

The French Geological Survey (BRGM) and the European Institute for Energy Research (EIFER) database indicates that there are six geothermal locations in Europe rich in lithium. Two prominent regions showing promising prospects for lithium extraction from geothermal brines include the Upper Rhine Graben (URG) straddling the northern frontier of France and Germany, and Cornwall in the United Kingdom.

The URG region already has several geothermal sites, operating on both the French and German sides (Sanjuan et al., 2022). Meanwhile, in Cornwall, although no geothermal plants are currently operational, several are being developed, including the United Downs Project and the Eden Project (Financial Times, 2023). Currently, there are three geothermal-lithium companies operating commercially in these areas: Vulcan Energy Resources, Lithium de France, and Cornish Lithium.

Vulcan Energy Resources, originally an Australian-based company, is operating in the Upper Rhine Valley area in southwest Germany. It is the only company discussed in this paper that is publicly traded. Vulcan is using Vulsorb, their own in-house sorbent for extracting lithium. The pre-feasibility study (PFS) of the Phase 1 Project was published in January 2021, followed by a definitive feasibility study (DFS) report in January 2023. In Phase One, Vulcan targets to produce 24,000 ton of lithium hydroxide monohydrate per annum by end of 2026. Vulcan has signed several binding offtake agreements in 2021, including with Stellantis, Volkswagen, Renault, LG Energy Solution, and Umicore (Vulcan Energy Resources, 2023)

Lithium de France is operating in Alsace, north of France, the French part of URG. Lithium de France started exploration activity by the end of 2022, with investors from oil & gas players including Arverne Drilling and Equinor (Lithium de France, 2022). The planned production capacity is mentioned as

15,000 tons of lithium hydroxide monohydrate per year by 2026 (Le Figaro, 2023). The extraction technology is not disclosed.

Cornish Lithium is operating in Cornwall, UK, at the United Downs Deep Geothermal Project Site. Cornish Lithium is using GeoLith, an ion exchange technology to extract lithium (Cornish Lithium, 2021). Through its subsidiary, GeoCubed, Cornish Lithium commissioned its pilot plant in April 2023, which received US$ 3.7 million in funding from the UK Government's Getting Building Fund (International Mining, 2022). From late 2026, the commercial plant is expected to deliver 7,000 tons of lithium carbonate equivalent (Financial Times, 2023)

3.3 Other parts of the world

This part discussed other geothermal-lithium projects everywhere else, and listing some non-geothermal direct lithium extraction project from brine.

Geo40 is a New Zealand-based company who are working to produce both silica and lithium extraction from geothermal brine. The silica extraction plant itself has gone commercial since 2018 (NZ Herald, 2018) while the lithium extraction pilot is currently ongoing, after receiving funding of NZ$ 2 million from the New Zealand government. The extraction technology is using mineral sorbent (Geo40, 2023).

Several non-geothermal direct lithium extractions from brine projects warrant attention due to their significant similarity to the economic models of geothermal-lithium projects. Those include Compass Minerals (Great Salt Lake, US), Standard Lithium (Smackover, US), Lake Resources, and E3 Lithium (Canada).

4. ECONOMIC ASSESSMENTS OF DLE AND GEOTHERMAL-LITHIUM PROJECTS AROUND THE GLOBE

As of the time of writing this paper, no geothermal-lithium project has reached commercial scale. All current undertakings are still under development or undergoing pilot stage. Adding an additional layer of complexity to the task of economic assessment is the limited availability of comprehensive data. Many of the companies have held back from publicly disclosing specific operational and financial details, possibly due to proprietary considerations or ongoing strategic assessments. Therefore, the economic evaluations presented in this chapter are derived from publicly available information and should be seen as approximations and indicative trends rather than definitive predictions.

4.1 Lithium price

The financial viability of a geothermal-lithium project is intrinsically tied to the price of lithium, a figure that can significantly fluctuate over the duration of the project. Predicting the trajectory of lithium prices is a complex task. Multiple analysts adopt a bullish outlook, premised on the assumption that the supply of lithium will remain constrained in the upcoming years. The lithium bulls are led by Macquarie (2022), which calls for prices to reach an average of 62,586 US$/ton in 2023 and remain steady at around 72,500 US$/ton until 2026 on a supply deficit. On the other hand, Goldman Sachs (2022) is bearish and predicted a sharp price correction to 16,372 US$/ton in 2023.

In 2022, the average price for fixed contracts in the U.S. stood at $37,000 USD per ton of lithium carbonate. In the same year, the lithium carbonate spot price (c.i.f. China) varied dramatically, oscillating between $35,000 USD per ton in January to $67,000 USD per ton in November (USGS, 2023). As of July 2023, the spot price of lithium carbonate is around $34,500 USD per ton (Argus, 2023). It is important to note that lithium hydroxide monohydrate consistently commands a higher price than lithium carbonate, and nearly all lithium producers operate under fixed-term contracts as opposed to spot pricing.

Obviously, there is always a risk that Lithium price falls due to various reasons, including excess supply from new sources and mass commercialization of non-lithium battery system. While, in general, lithium price predictions still tend to be bullish, it shows that Lithium market forecasting is not an easy task. Therefore, in every analysis, it is important to sensitize project performance to lithium price.

4.2 DLE Projects Economics – Publicly Available Datasets

The following table shows publicly disclosed data of several DLE projects, whether they utilize geothermal brine or other types of brine. The authors have selected to display solely the projects that employ adsorption or ion exchange techniques for lithium extraction. The most advanced data originates from Vulcan Energy Resources' DFS (Definitive Feasibility Study) data set, as this calculation was constructed following the pilot phase. Conversely, the SRI International data is fundamentally anchored in laboratory results, which were subsequently integrated into process design, courtesy of the support from EnergySource Minerals and Ormat (Ventura, 2020). The remaining data, stemming from non-geothermal brine projects, was constructed during the preliminary economic assessment phase. It is crucial to emphasize that the lithium price, as represented across all data sets, is significantly lower than the market price registered in 2022, a fact emphasized in the preceding subsection.

Table 1: Summary of Several DLE Project Economics.

Company	**Vulcan Energy Resources[(a)]**		**Standard Lithium[(b)]**	**E3 Metals[(b)]**	**SRI International[(c)]**
Project	Upper Rhine Valley		Smackover	Clearwater	Salton Sea
Location	Germany	Germany	Arkansas, US	Canada	California, US
Document	**PFS[(d)] (2021)**	**DFS[(e)] (2023)**	PEA[(f)]	PEA[(f)]	CEC Report
Brine type	Geothermal	Geothermal	Evaporite	Oilfield	Geothermal
Li concentration (mg/L)	181	181	168	75	400
Product	$LiOH.H_20$		Li_2CO_3	$LiOH.H_2O$	Li_2CO_3
Production (ton/yr)	15,000	24,000	20,900	20,000	20,000
Production cost ($/ton)	2,904	4,795	4,319	3,656	3,845
CAPEX ($ 1000)	521,400	922,891	437,162	602,000	52,300
OPEX ($ 1000/yr)	47,916	126,585	90,259	73,200	76,900
Modeled product price ($/ton)	13,714	28,124	13,550	15,160	12,000
Pre-tax IRR	27%	46%	42%	32%	-
Li recovery	90%	Not mentioned	90%	90%	90%

(a) Vulcan Energy Resources (2023), adjusted with US$ 1.1 = € 1, (b) Warren, 2021, (c) Ventura et al., 2020
(d) Pre-feasibility study, (e) Definitive feasibility study, (f) Preliminary economic assessment

Table 1 illustrates a general pattern in the capital expenditure (CAPEX) necessary for a DLE project. An exception to this is the CAPEX estimation provided by SRI International, which is noticeably different from the average - although it should be noted that this estimation was made at a very preliminary stage. This trend is also mirrored in operating expenditure (OPEX), which typically approximates US$ 4,100 per ton of lithium produced. This excludes data from Vulcan's PFS and does not differentiate between the production costs of lithium hydroxide monohydrate and lithium carbonate. It is crucial to mention that the production of lithium hydroxide monohydrate tends to be pricier than that of lithium carbonate. Further, it should be highlighted that the main variations between non-geothermal brine processes and geothermal brine ones lie in the pre-processing measures necessary for handling silica or other minerals (Warren, 2021).

5. SIMULATING THE ECONOMICS OF A GEOTHERMAL-LITHIUM PROJECT IN INDONESIA

There are several available data and studies concerning lithium in Indonesia's geothermal brine, including research conducted by Herdianita et al. (2019), Salafudin (2021), and Mahon et al. (2000). However, most of the data available is taken from surface manifestation sample, instead of wellbore sample. The currently operating geothermal fields offer limited public access to data regarding the lithium content of the produced brine. Dieng field stands as the sole operating geothermal field that has been thoroughly documented for its high lithium content, reaching approximately 70 ppm (Herdianita et al., 2019) and with estimated total lithium production of 360 tons/year (Badan Geologi, 2020). The Dieng geothermal field has drawn the attention of numerous researchers, aiming to devise methods for extracting lithium from its brine. This includes noteworthy contributions by Mustika et al. (2021), Suud et al. (2022), Tangkas et al. (2023), and Wahyudi et al. (2023).

To simulate the economics of a geothermal-lithium project in Indonesia, no specific geothermal field will be chosen. Instead, authors assume a certain lithium production capacity. In this case, it is simulated that lithium hydroxide monohydrate will be produced, as it is the main form of lithium product required by the Electronic Vehicle industry. It is worth noting that the assumed capacity is relatively small compared to other global projects, and the project's CAPEX (capital expenditure) does not increase linearly with production capacity. Several other basic assumptions are taken, including lithium recovery percentage, lithium hydroxide monohydrate price, and cost of capital. These assumptions are based on international benchmarks from the previous chapter's DLE (Direct Lithium Extraction) projects, which are adjusted to suit the conditions in Indonesia when applicable (as shown in Table 2). The parameters considered in the analysis are referred to as "base case" parameters. As the objective of this simulation is not giving definitive number, but rather, providing approximation and indication, sensitivity analysis is performed on some of the important parameters. This analysis helps to understand how each parameter affects the project's economic performance (Figures 2 and 3).

Subsequently, the economic performance of the Direct Lithium Extraction from the geothermal brine project is modeled, focusing solely on the lithium production and conversion part. The calculation does not include the geothermal electricity production component. Table 3 presents the main economic performance indicators resulting from the simulated DLE from the geothermal brine project, using the base case parameters in Table 2.

Afterward, a series of sensitivity analyses are conducted to gain deeper insights into how the project's performance is influenced by various operational and economic parameters. The sensitivity analysis shows parameter variations, in percentage, from each parameter's base case value, presented against Net Present Value (NPV) and Internal Rate of Return (IRR).

To keep the analysis simple and organized, the sensitivity tests are categorized into two groups. The first group is technical parameters, including lithium content, extraction efficiency, and plant efficiency. The variations of those parameters essentially will affect the amount of lithium produced, hence the variation from the base case will provide exactly the same trend toward NPV and IRR. Therefore, the sensitivity trend of the technical parameter variations is the same and will be presented *only with lithium content parameter variation*.

The second group is economic parameters, comprising Lithium price, CAPEX, and OPEX. While these divisions serve as a helpful framework, it is important to note that some parameters, such as OPEX, have a strong connection to technical aspects but are represented in monetary values, making the boundaries between the two categories less distinct. An additional graph is added to observe the influence of lithium prices to the economic performance of the DLE project.

Table 2: Operation and economic parameter assumptions – base case.

Parameter	Base case value	Note
Plant capacity	4,500 tons Lithium hydroxide monohydrate/year	Based on brine flowrate 416 L/sec, Li content 70 mg/L, Li = 744 ton/ year 1 ton Li produces 6.048 tons Lithium hydroxide monohydrate (Warren, 2021) Li content, plant & extraction efficiency using base case
Lithium content	70 mg/L	Technical parameter- to be sensitized
Plant efficiency	90%	Technical parameter- to be sensitized
Extraction efficiency	90%	Technical parameter- to be sensitized
Lithium hydroxide monohydrate price	US$ 20,000/ ton	To be sensitized
CAPEX (Capital expenditure)	US$ 400 million	To be sensitized
OPEX (Operating expenditure)	$ 4,700/ton	To be sensitized
Tax rate	22%	Flat
Cost of capital	10%	Flat
Project life cycle	20 years	Flat

Table 3: Base Case Economic Performance of a Simulated DLE from Geothermal Brine Project.

Financial indicator	Value
NPV (Net Present Value)	US$ 378 M
IRR (Internal Rate of Return) – post tax	29%
Payback Period	5 years

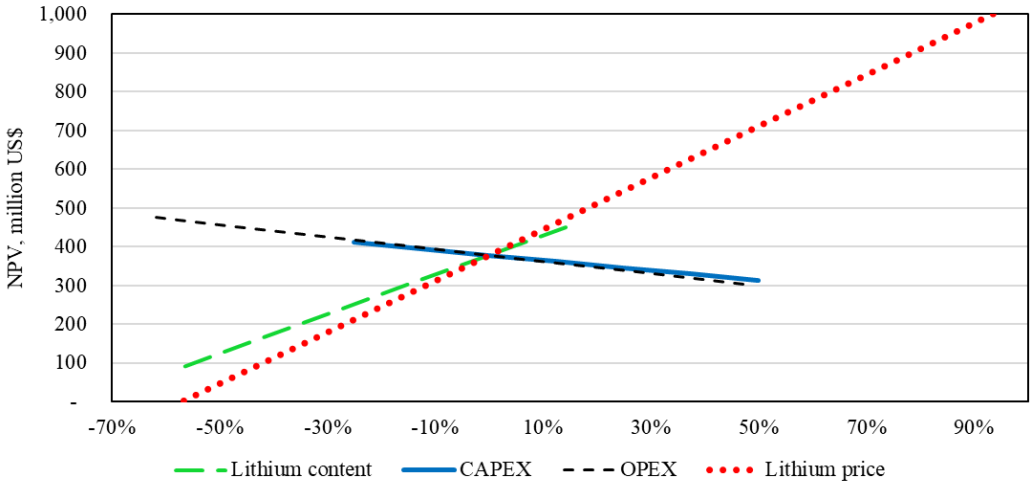


Figure 2: Simulated technical and economic parameter variations sensitivity plotted against NPV.

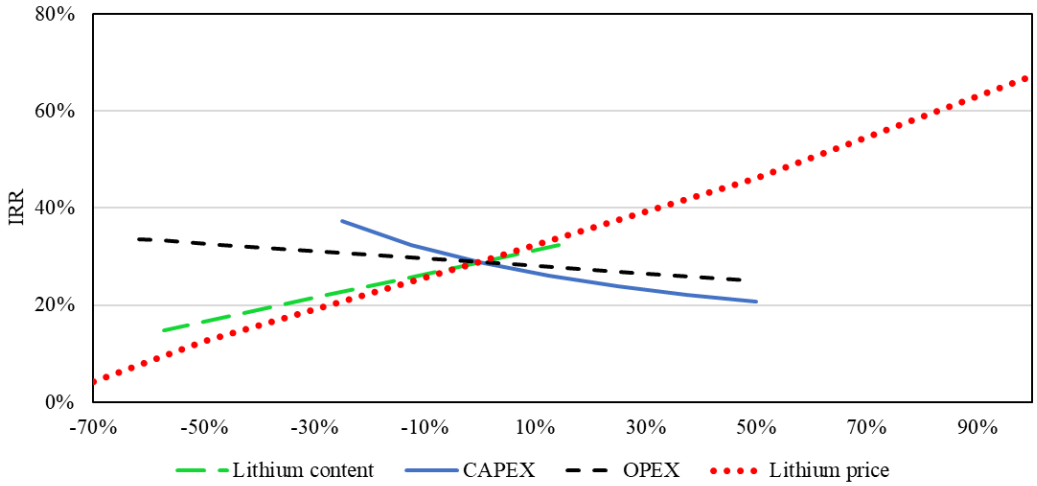


Figure 3: Simulated technical and economic parameter variations sensitivity plotted against IRR.

From the sensitivity graphs above, a consistent agreement is observed between the NPV and IRR graphs regarding the impact of each parameter. Among all the parameters, the one with the highest potential to influence the economic performance of the project is the lithium price. This is evident from its steep slope against both NPV and IRR values, and its susceptibility to significant changes, which are largely driven by market mechanisms beyond the control of the DLE project owner. The base case assumes a conservative Lithium price of US$ 20,000 per ton. To put this into perspective, as of July 2023, the spot price of Lithium hydroxide monohydrate, reported by the Fastmarkets price reporting agency, fluctuates between US$ 46,000 and US$ 40,000. If the Lithium price remains at this level throughout the lifetime of the project, it would significantly boost both NPV and IRR to exceptionally high levels. Conversely, in the worst-case scenario, if the price of lithium hydroxide monohydrate falls below US$ 10,000 for the entire duration of the project, the project loses its attractiveness and viability. To manage price volatility, both lithium producers and off-takers are typically signing long-term contracts: it is a common practice in the industry.

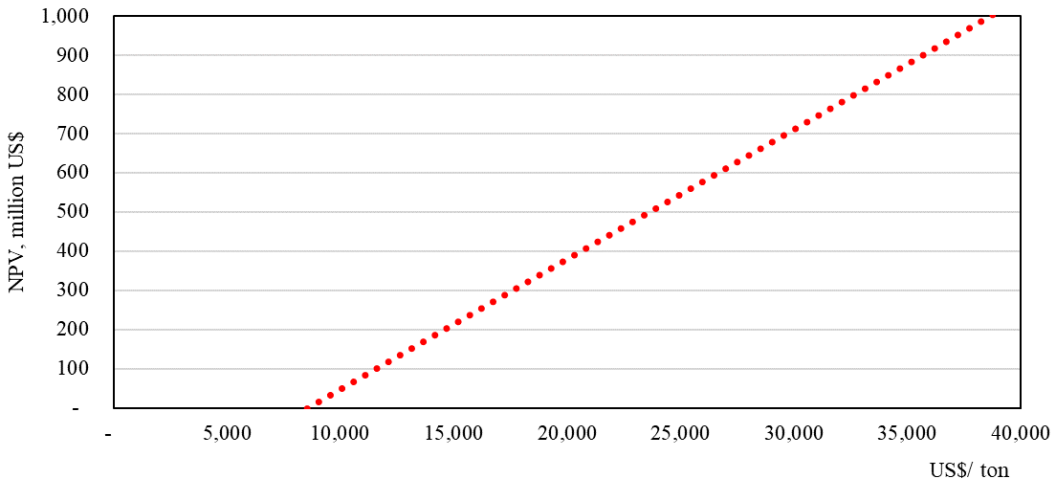


Figure 4: Simulated lithium hydroxide monohydrate price against NPV.

In the other hand, the technical parameters, CAPEX and OPEX, will not show very large variations, especially because they are already known within a certain degree of control, and provided that the planning and execution are well-managed. These factors are more controllable by the project owner, as they are related to the project's implementation and operational efficiency. For instance, CAPEX and OPEX increase up to 50% does not significantly hinder economic performance. Meanwhile, technical parameters such as lithium concentration, plant efficiency, and extraction efficiency are well-understood and established during the project planning phase, therefore in actual execution should have

relatively small variations. In the base case, the brine's lithium concentration is assumed to be 70 mg/L and the sensitivity analysis also simulates lower concentrations, going as low as 30 mg/L, which basically means simulating reduction in plant production capacity. It is worth mentioning that no prior project feasibility study has been reported with such concentration, but research indicates the technological developments for Direct Lithium Extraction (DLE) in such conditions (Murphy & Haji, 2022). On a different note, higher lithium concentrations are not assessed, given the lack of studies suggesting concentrations beyond the 70 mg/L levels in Indonesia's geothermal brine.

6. ENABLING THE DEVELOPMENT OF GEOTHERMAL-LITHIUM PROJECTS IN INDONESIA

As observed in the preceding chapter, the Direct Lithium Extraction (DLE) from the lithium brine project proves to be a highly appealing undertaking from an economic perspective, even though it demands relatively substantial initial capital expenditure and a long time to production. It is also important to acknowledge that not all geothermal plants are suitable for conducting DLE activities. In order to make this project a reality, several crucial aspects require careful consideration.

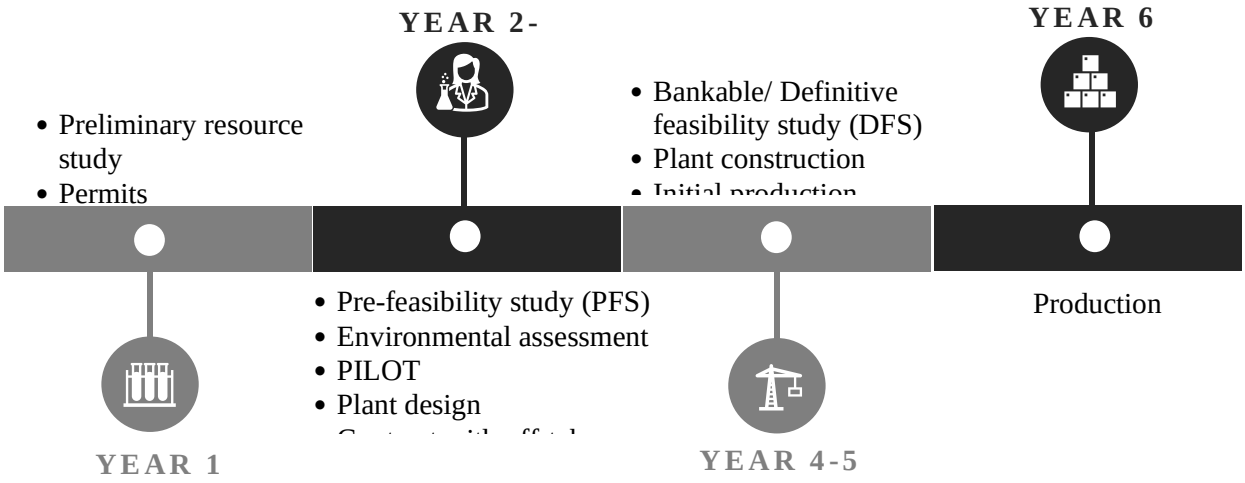


Figure 5: An approximative simplified timeline of DLE from Geothermal Brine Project, compiled from various sources.

6.1 Regulation

Currently, there is no regulatory framework governing mineral extraction activities from geothermal brine. Such regulations are essential to oversee non-electricity-related operations conducted by geothermal field operators, who already have a binding contract with electricity off-taker (PLN, Indonesia's National Electricity Company). Regulations are also important to ensure sustainable practices, both environmentally and socially. Establishing this regulatory framework is crucial to attract investor interest, as they require clear rules and guidelines to assess the potential risks and benefits of their investments.

6.2 Funding

Until the Definitive Feasibility Study (DFS) phase is completed, DLE projects typically require funding through equity. DLE companies have the option to either self-finance or seek funding from investors and/or government grants to support the study and pilot stages. Chapter 3 highlights that a majority of DLE companies have received substantial financial backing from the government. Similarly, in Indonesia, government support can play a crucial role in significantly advancing progress in DLE activities.

6.3 Technology

Direct Lithium Extraction technology is developing very fast, encouraged by the high global lithium demands. As mentioned in the previous chapter, in Indonesia, several researchers have already explored DLE methods from geothermal brine, such as Mustika et al. (2021), Suud et al. (2022), Tangkas et al. (2023), and Wahyudi et al. (2023). Internationally, several companies, including Lilac Solutions (US), EnergySource Minerals (US), Eon Minerals (Canada), Adionics (France), GeoLith (France), and Tenova (Italy), have commercially offered DLE methods. However, due to the unique compositions and characteristics of each geothermal brine, careful testing and subsequent piloting are essential to determine the most suitable DLE technique for each specific brine.

7. CONCLUSION

Direct Lithium Extraction (DLE) from geothermal brine has emerged as a sustainable alternative source for lithium production, addressing energy security concerns. Internationally, several DLE projects are underway, with a focus on locations like California in the US and various areas in Europe. These projects are expected to commence lithium production from 2025 onwards, utilizing adsorption or ion exchange technology. Some of these projects have publicly available economic models that can serve as reference points for simulating similar projects.

In Indonesia, there is limited published data on the lithium content of geothermal brine from producing wells, except for the extensively studied Dieng field. With the limited data, a simulation of the economic performance of a DLE project from geothermal brine, with a capacity of 4,500 tons of Lithium hydroxide monohydrate per year, shows encouraging results. Sensitivity analysis is conducted to understand the impact of various parameters on the project's economic performance. Notably, the lithium price emerges as the most critical parameter, as it is subject to market fluctuations and can significantly influence the project's viability.

To enable the development of lithium-geothermal projects in Indonesia, certain aspects must be carefully addressed. The establishment of a regulatory framework is crucial to oversee mineral extraction activities from geothermal brine and ensure sustainable practices. Government funding and support play a pivotal role in advancing DLE projects through the study and pilot stages. Additionally, the selection and implementation of the most suitable extraction technology tailored to the unique characteristics of each geothermal brine are essential for successful project execution.

REFERENCES

Argus (2023) "Prices & data – Lithium: Lithium carbonate min 99.5% cif China prices USD/kg". Available at: https://www.argusmedia.com/metals-platform/price/assessment/lithium-carbonate-min-99-5--cif-china-prices-PA00233610000, [accessed July 2023]

Badan Geologi (2020) "Potensi lithium di Indonesia", in Webinar Potensi Pemanfaatan Lithium untuk Baterai Ion-Li di Indonesia" Bandung: Badan Geologi.

BHE Renewables (2022) "Geothermal: Lithium Development". Available at: https://www.bherenewables.com/projects/geothermal, [accessed July 2023]

CNBC (2022) "The Salton Sea could produce the world's greenest lithium, if new extraction technologies work". Published May 4 2022. Available at: https://www.cnbc.com/2022/05/04/the-salton-sea-could-produce-the-worlds-greenest-lithium.html [accessed 26 July 2023]

Controlled Thermal Resources (2020) "CTR and Lilac Solutions set to unlock massive clean lithium resource in the U.S.". Available at: https://www.cthermal.com/latest-news/ctr-and-lilac-solutions-set-to-unlock-massive-clean-lithium-resource-in-the-us, [accessed July 2023]

Cornish Lithium (2021) " GeoCubed selects GeoLith's Li-Capt® DLE Technology for United Downs Pilot Plant and Deep Geothermal Water Samples Successfully Obtained Following GEL Pump Test". Available at: https://cornishlithium.com/company-announcements/geocubed-selects-geoliths-li-capt-dle-technology-for-united-downs-pilot-plant-and-deep-geothermal-water-samples-successfully-obtained-following-gel-pump-test/ [accessed July 2023]

EnergySource Minerals (2023) "EnergySource Minerals (ESM) Announces Contract With Ford for Geothermal Lithium", news provided by EnergySource Minerals, PR Newswire. Available at: https://www.prnewswire.com/news-releases/energysource-minerals-esm-announces-contract-with-ford-for-geothermal-lithium-301830259.html [accessed July 2023]

Financial Times (2019) "Buffett's lithium venture promises secure supply for US carmakers", 20 January 2019. Available at: https://www.ft.com/content/c9760a4e-1a76-11e9-9e64-d150b3105d21 [accessed July 2023]

Financial Times (2023) "UK's first deep geothermal energy project for 37 years switched on" 19 June 2023. Available at: https://www.ft.com/content/774c05ac-373d-45dc-bcaa-8377ddacb58f, [accessed July 2023]

Financial Times (2023) "Can Cornwall get a slice of the lithium revolution?", 14 July 2023. Available at: https://www.ft.com/content/547eec99-f4f4-4907-ace2-3a8385a87b95 [accessed July 2023]

General Motors (2021) "GM to Source U.S.-Based Lithium for Next-Generation EV Batteries Through Closed-Loop Process with Low Carbon Emissions", company news release. Available at: https://investor.gm.com/news-releases/news-release-details/gm-source-us-based-lithium-next-generation-ev-batteries-through/ [accessed July 2023]

Geo40 (2023) "Geothermal Lithium: Feedback on Our Process". Available at: https://geo40.com/geothermallithium/ [accessed 2023]

Neupane, G., and Wendt, D.D. (2017) "Assessment of Mineral Resources in Geothermal Brines in the US", 42nd Workshop on Geothermal Reservoir Engineering 2017. Stanford California, USA, 13-15 February 2017.

Goldman Sachs (2022) "Battery Metals Watch: The end of the beginning". Available at: https://www.goldmansachs.com/insights/pages/gs-research/battery-metals-watch-the-end-of-the-beginning/report.pdf [accessed February 2023]

IEA (2023) "Critical Minerals Market Review 2023" International Energy Agency, Paris. Available at: https://www.iea.org/reports/critical-minerals-market-review-2023 [accessed July 2023]

Ihgalo, et al, (2022) "Utilisation of adsorption as a resource recovery technique for lithium in geothermal water" , Journal of Molecular Liquids, 365 (2022), 120107, https://doi.org/10.1016/j.molliq.2022.120107

International Mining (2022) "GeoCubed commissions Direct Lithium Extraction Pilot Plant in Cornwall". Available at: https://im-mining.com/2022/04/14/geocubed-commissions-direct-lithium-extraction-pilot-plant-in-cornwall/, [accessed July 2023]

IRENA (2023) "Geopolitics of the Energy Transition: Critical Materials", International Renewable Energy Agency, Abu Dhabi

Jerez, B., Garces, I., Torres, B., (2021), "Lithium extractivism and water injustices in the Salar de Atacama, Chile: The colonial shadow of green electromobility", Political Geography, Volume 87, https://doi.org/10.1016/j.polgeo.2021.102382

Kelly, J., M. Wang, Q. Dai and O. Winjobi (2021) "Energy, greenhouse gas, and water life cycle analysis of lithium carbonate and lithium hydroxide monohydrate from brine and ore resources and their use in lithium ion battery cathodes and lithium ion batteries", Resources, Conservation and Recycling, Vol. 174, https://doi.org/10.1016/j.resconrec.2021.105762

Le Figaro (2023) "Lithium de France lève 44 millions d'euros pour des projets de production en Alsace", published 14 March 2023, available at: https://www.lefigaro.fr/flash-eco/lithium-de-france-leve-44-millions-d-euros-pour-des-projets-de-production-en-alsace-20230314 [accessed July 2023]

Lithium de France (2022), "Les Sources: Découvrez le projet de Lithium de France dans le nord de l'Alsace", Available at: https://www.lithiumdefrance.earth/nos-projets [accessed July 2023]

Macquarie (2022), "Lithium outlook: Strong EV demand and softer supply", Macquarie Research

Mustika, P.C.B.W., Astuti, W., Sumardi, S., Petrus, H.TB.M., and Sutijan, (2022) "Separation Characteristic and Selectivity of Lithium from Geothermal Brine Using Forward Osmosis", Journal of Sustainable Metallurgy, 8, 1769-1784 (2022)

Murphy, O., and Haji, M.N. (2022), "A review of technologies for direct lithium extraction from low Li+ concentration aqueous solutions". Front. Chem. Eng. 4:1008680. doi: 10.3389/fceng.2022.1008680

NZ Herald (2018), "Silica extraction starts at Ohaaki", Available at: https://www.nzherald.co.nz/the-country/news/silica-extraction-starts-at-ohaaki/WQFAPLNW7R2LEJGMT2A677DAMM/?c_id=16&objectid=12103986 [accessed July 2023]

Paz, S., et al., (2022), "Report of the Blue Ribbon Commission on Lithium Extraction in California", California Energy Commission, Publication Number: CEC-300-2022-009-F

Sanjuan, et al, (2022),"Lithium-rich geothermal brines in Europe: An up-date about geochemical characteristics and implications for potential Li resources", Geothermics 101 (2022), 102385, https://doi.org/10.1016/j.geothermics.2022.102385

Slunitschek, K., Kolb, J., Eiche, E. (2021) "Lithium extraction from geothermal brines: Modern adsorption method for raw material extraction", Wiley Analytical Science, 23 June 2021

Stellantis (2022), "Stellantis Secures Low Emissions Lithium Supply for North American Electric Vehicle Production from Controlled Thermal Resources", press release, 22 June 2022, Available at: https://www.stellantis.com/en/news/press-releases/2022/june/stellantis-secures-low-emissions-lithium-supply-for-north-american-electric-vehicle-production-from-controlled-thermal-resources, [accessed July 2023]

Stringfellow, W.T., Dobson, P.F., (2021), "Technology for the Recovery of Lithium from Geothermal Brines", Energies 2021, 14, 6805, https://doi.org/10.3390/en14206805

Snydacker, D.H., Grant, A.J., and Zarkesh, R.A. (2019) "Ion Exchange System for Lithium Extraction", US Patent, Patent no: US 10,439,200 B2, 8 October 2019

Suud, E.M., Suryantini, and Mubarok, M.Z. (2022) "Lithium Extraction Method from Geothermal Brine to Find Suitable Method for Geothermal Fields in Indonesia: A Review" IOP Conference Series: Earth and Environmental Science, Volume 1159, 11th ITB International Geothermal Workshop 01/08/2022 - 04/08/2022 Bandung, Indonesia

USGS, 2023, "Mineral commodity summaries 2023" U.S. Geological Survey, https://doi.org/10.3133/mcs2023.

Ventura, S., Bhamidi, S., Hornbostel,M., Nagar, A. (2020) "Selective Recovery of Lithium from Geothermal Brines", California Energy Commission, Publication Number: CEC 500-2020-020

Vulcan Energy Resources (2023) "Phase One DFS Presentation 2023", https://v-er.eu/wp-content/uploads/2023/03/Vulcan-Energy-DFS-presentation-2023-FINAL.pdf [accessed July 2023]

Warren, I. (2021), "Techno-Economic Analysis of Lithium Extraction from Geothermal Brines". Golden, CO: National Renewable Energy Laboratory." NREL/TP-5700-79178, https://www.nrel.gov/docs/fy21osti/799178.pdf.

Training for Geothermal Technician, Indonesia

Kris Pudyastuti[1], Yudistian Yunis[1], Chris Stuart[2], and Tengku Alia[3]

[1]PT GEO DIPA ENERGI
[2]WINTEC
[3]JACOBS

kris.pudyastuti12@gmail.com, yudistian@geodipa.co.id,
Chris.Stuart@wintec.ac.nz, Tengku.Alia@jacobs.com

Keywords: geothermal power plant, efficiently, technician, curricula, development

ABSTRACT

Geothermal technicians perform technical duties at geothermal power plants or at individual installations. They monitor and adjust operating equipment and power production systems and identify and correct equipment malfunctions. They play a role in the Balance of Plant (BOP) system that provides the supports needed to keep the plant running stably and efficiently.

The need for geothermal technicians with reference to the *Energy Employment Report* from the National Association of State Energy Officials, 2019, can be estimated at 2-3 technicians per MW.

The NZ Government's assistance program, through NZSTIGS is to support the geothermal sector by preparing curricula, modules and trainers to train the technicians that will be needed. For this reason, capacity building has been carried out several times since 2019 for trainers, one of which was recently conducted from 19 to 22 June 2023 in the Patuha Geothermal Working Area (WKP).

This paper describes the role of geothermal technicians, as well as the curricula and modules that have been provided by NZSTIGS, and thoughts on managing or developing them, especially after taking over from NZSTIGS.

1. INTRODUCTION

NZSTIGS, New Zealand Support for Training in Indonesia Geothermal Sector. This Activity's objectives will increase workforce skills and capability in geothermal energy through targeted support to cover all aspects of on-job and off-job training for geothermal trades, technicians and plant operators in Indonesia. The intended purpose is to increase workforce skills and capability in geothermal energy.

The assistance then cascaded by three contracts, among other is the contract titled Implementation of NZSTIGS, was extended until September 2023 because of Covid19.

The implementation of NZTIGS has started in October 2018, starting with capacity building for trainers up to 7 times since then, each for 4-5 days, the second is done online. Training for geothermal technicians has been carried out approximately 88 workshops in total generally carried out offline and on line.

This assistance will end in September 2023. Against this background, the author will explain several things related to the object of assistance, namely geothermal technicians, and their curriculum, and conclusions suggesting the necessary preparations.

2. GEOTHERMAL POWER PLANT OPERATION

Electricity generation from geothermal natural sources can be divided into two main operation areas namely steam field operation which is sometimes called upstream and power plant operation (downstream).

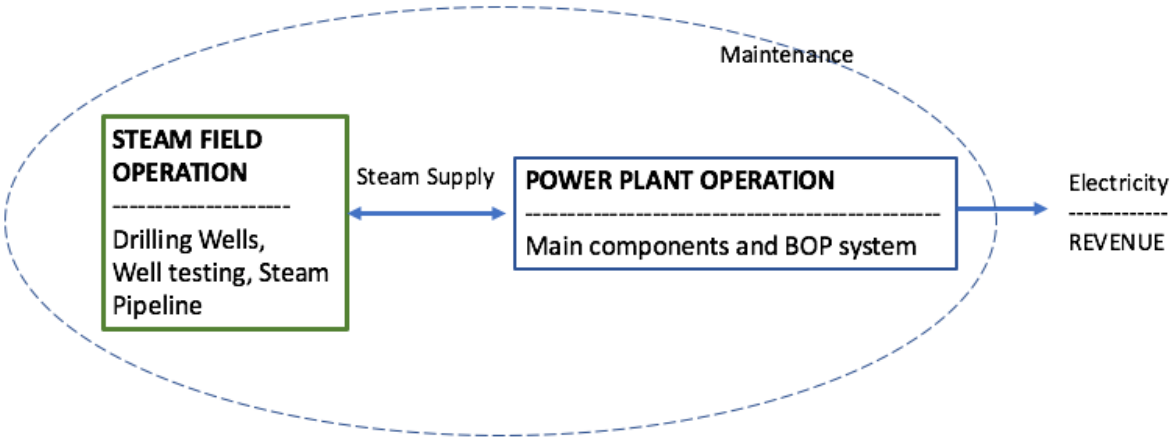


Figure 1: The two main operation areas of geothermal electricity generation, and the activities that affect their sustainability, stability and efficiency.

The drilling of wells, starting from exploration, then development, make-up, injection, including testing, is intended to maintain sufficient steam production and prolong the life time of the source (reservoir) in a stable and efficient manner.

In geothermal power generation area, there are the main components, and the BOP) system. The main components of conventional geothermal power plant are the steam turbine, generator, cooling system (that mainly consists of two components: condenser and cooling tower), gas removal system and hydrogen sulfide abatement system.

Moreover, there are various supporting and auxiliary components of a power plant system required to produce energy, called BOP system. The hot-well-pump units are part of the cooling system in a geothermal power plant, most influential to the efficiency of electricity generation which needs to be maintained from trip threats due to excessive loads (Figure 2).

BOP (balance of plant) systems provide the supports needed to keep the plant running stably and efficiently.

More than that, there is a part of a geothermal operation, namely maintenance which covers these two areas.

Figure 2: a) The two hot well pump units of cooling system in geothermal power plant. b) the waste (hot brine) that came from cooling tower, will be reinjected to the reservoir.

2.1 Monitoring and control system

Geothermal power plants are generally located in secluded and scattered mountainous areas where it is inconvenient for operation and maintenance personnel to reside. As there is less concern about safety in geothermal power plants due to their lower steam pressures and temperatures, and simpler plant systems and operation compared to fossil fuel thermal power plants, remote monitoring and control systems can be utilized.

A monitoring room is commonly situated nearby the power station, but sometimes located 23 kilometers from the power station, for example the Tohoku Electric Power Co., Inc.'s Kakkonda Unit-2 project [1]and [2].

Operation and maintenance personnel are usually in the (remote) monitoring room. Normal load operation and emergency shutdown can be carried out from the (remote) monitoring room. Start up and normal shut down operations must be carried out from the central control room of the power station. Maintenance personnel go to the power station for daily patrols and periodic testing. In case of abnormal plant conditions, the maintenance personnel immediately go to the power station for trouble shooting.

Figure 3: Monitoring and control system room in power plant Patuha Unit-1 (personal file, 19 July 2023).

2.2. Geothermal Plant Technician

Geothermal technicians are also called I C and E Technicians (Instrumentation, Control, and Electrical Technicians), Operations and Maintenance Technicians (O and M Technicians); Operations Technicians, and Plant Technicians. What they do? They perform technical activities at commercial power plants or individual installations necessary for the generation of power from geothermal energy sources. They monitor and control operating activities at geothermal power generation facilities and perform maintenance and repairs as necessary. They install, test, and maintain residential and commercial geothermal heat pumps (individual installation).

They monitor and adjust operating equipment and power production systems and identify and correct equipment malfunctions. They play a role in the Balance of Plant (BOP) system that provides the supports needed to keep the plant running stably and efficiently.

They should be knowledgeable in engineering & technology (mechanical, electrical, instrumentations and control, geothermal operation), in mathematics and science (physics, chemistry), in a branch of art and humanities (English language), in education and training (teaching and course design), as well as basic skills, problem solving skills, people skills and technology system skills

3. GEOTHERMAL TECHNICIAN FOR INDONESIA

Referring to the 2021 U.S. Geothermal Power Production and District Heating Market Report: current geothermal capacity in the United States of 3,673 MW-electric from 93 power plants per Geothermal Rising's survey is only marginally higher than the 3,627 MW-electric [3] from 97 plants that the GEA reported for 2015 (GEA 2016).

Moreover, there are currently 23 GDH systems in the United States. The oldest installation dates from 1892 (Boise, ID), and the most recent installation was completed in 2017 (Alturas, CA). The total installed capacity of those GDH is 89.7 MW-thermal [4] or 31.4 MW-electric (with efficiency of energy conversion, 35%). So, the total of the US geothermal generation capacity (power plant and GDH) currently is around 3704.4 MW.

Referring to the *U.S. Energy Employment Report* from the National Association of State Energy Officials, 2019 [5], approximately 8,500 people are directly employed in the geothermal industry.

Based on those numbers, the need for geothermal technicians for Indonesia can be estimated at 2-3 technicians per MW.

4. CURRICULA AND TRAINING MODULE FOR GEOTHERMAL TECHNICIANS

A curriculum is a form of learning intended to help students or trainees make meaningful connections across disciplines with the goal of improving trainee success in critical thinking, and problem solving skills.

Curriculum clusters highlight the valuable uses of both instructional technology and media throughout students' lives to develop varying perspective of technology through media exposure learning experiences. Instructional technology and media for learning show how perfectly technology and media formats can be integrated with teaching in the classroom [6].

A module is a planned learning program package, designed to help participants achieve training objectives that are self-contained and self-instructed. It is a learning model that applies an instructional system/technology approach. In contrast to handouts, textbooks, and other written materials, modules are generally in the form of printed material. The principles of module development are goal oriented i.e. competence, self-instruction, continuous progress, self-contained (- complete modular arrangement of material), cross referencing (- between training modules), and self-evaluation. [7][8]

NZSTIGS has developed 56 training modules consisting of three levels of courses i.e. 32 basics, 10 skilled and 14 advanced [9]. During the training implementation, Covid19 hit the world, so the training has been shifted into an online training. To provide a great online learning experience, a reliable learning management system (LMS) has been put in place, alongside attractive courses and course content. The LMS can be accessed for those who has been granted an access via the link https://stigs.elearning.nz/.

In March 2023, NZSTIGS has resume their offline in-house training for geothermal technician which was held at Patuha's WKP facilitated by PT Geo Dipa Energi (Figure 4a).

Figure 4: Training for geothermal technician: a) March 2023 at Patuha Power Plant and b) May 2023 at PT Geo Dipa Energi Office Jakarta.

Curriculum development

Curriculum design is central to the development of curriculum, and it can be done in several ways. Each design has advantages and disadvantages for both learners and teachers. Ralph Tyler included four questions that guided his curriculum design model. Tyler's model influenced later curriculum designs by John Goodlad, D.K. Wheeler, John Kerr, Hilda Taba, and others.

For the development of the existing curriculum, provided by NZSTIGS, the author suggests choosing the Kerr method, as it seems simpler. John Kerr, a British Curriculum specialist in the 1960s, was particularly concerned with the following issues: objectives, knowledge, school learning experiences, and evaluation. This is reflected in the sketch (Figure 5).

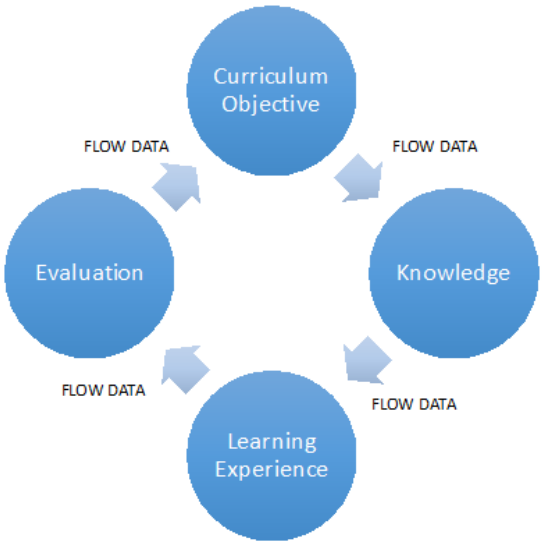


Figure 5: The sketch of curricula design/development suggested by Kerr's model.

This model is similar to that of Ralph Tyler and Wheeler, with emphasis on the interrelatedness of the various components in terms of the flow of the data between each component of curriculum development.

First step, the designer develops general objectives. These are subjected to a screening process, using the philosophy of education and psychology of learning as the major screens. Social values are also used as a screen, but sometimes these are subsumed in the philosophy of education. This yields a feasible number of objectives that are focused on education. Specific objectives are then derived from these general objectives. Then each of the specific objectives, learning experiences (including the subject matter/content) and learning activities are identified.

Prior to the Evaluation stage, Ralph Tyler's model suggests organizing learning experiences to ensure that effective learning takes place. The principles of the organization include, among others, scope, sequence, integration, and continuity.

The final step: evaluation is to determine the extent to which the objective have been met. Evaluation feedback is then uses to modify the learning experiences and the curriculum as found necessary.

5. CONCLUSION

This assistance will soon expire in September 2023. This needs to be followed up by preparing an agreement between the giver and recipient. The points of agreement include who is the recipient of the training (geothermal company technician or university or advocacy school). The need for assistance in the form of supervision for curriculum evaluation and development.

REFERENCES

2021 U.S. Geothermal Power Production and District Heating Market Report. https://www.nrel.gov/docs/fy21osti/78291.pdf

Amanda Kolker et.al., National Renewable Energy Laboratory, https://publications.mygeoenergynow.org/grc/1034393.pdf: Geothermal District Heating in the United States: 2021 Update; GRC Transaction, Vol. 45,2021

Asep Herry Hernawan; http://file.upi.edu/Direktori/FIP/JUR.KURIKULUM

Curriculum cluster; https://www.mymajors.com/career/geothermal-technicians/skills/

Geothermal Technicians; https://firsthand.co/professions/geothermal-technicians

NZSTIGS-file

PB-Pressbooks; https://oer.pressbooks.pub/curriculumessentials/chapter/curriculum-design-development-and-models-planning-for-student-learning-there-is-always-a-need-for-newly-formulated-curriculum-models-that-address-contemporary-circumstance-an/

Rodrigo Mora Salas et.al; Design of Monitoring and Control Systems for Geothermal Steam Gatherings Systems – Comparison with the Existing System For The Miravalles Geothermal Field; https://orkustofnun.is/gogn/unu-gtp-report/UNU-GTP-2009-19.pdf

Smaldino, et al; Instructional technology and media for learning Twelfth edition / Sharon E. Smaldino, Deborah L. Lowther, Clif Mims, James D. Russell, https://opac.perpusnas.go.id/DetailOpac.aspx?id=1295414

Shinji Nishikawa et.al; Remote Monitoring and Control of the Kakkonda Geothermal Power Plants; https://www.geothermal energy.org/pdf/IGA standard/WGC/2000/R0705.PDF

Supported by: Hosted by: Endorsed by:

THE 9th INDONESIA INTERNATIONAL GEOTHERMAL CONVENTION & EXHIBITION

20 - 22 SEPTEMBER 2023

JAKARTA CONVENTION CENTER

THE 9th INDONESIA INTERNATIONAL
GEOTHERMAL
CONVENTION & EXHIBITION
20 - 22 SEPTEMBER 2023
JAKARTA CONVENTION CENTER

Supported by: Hosted by: Endorsed by:

ISSN 2986-1268

Asosiasi Panasbumi Indonesia (API)
Apartemen Menteng Square, BR-9 Tower B
Jl. Matraman No 30 E, Jakarta Pusat - 10320 Indonesia
Email: api.inaga@yahoo.co.id