Prioritisation of Geothermal Field Development in Indonesia for Energy Transition: A Multi-Criteria Decision Analysis Approach

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ABSTRACT

Indonesia is committed to complying with the Paris Agreement on Climate Change and has outlined its energy transition strategies through the LTS-LCCR 2050. One of the renewable energies that can replace fossil fuel plants is geothermal energy. Although promising, geothermal energy is known for its high investment cost and risk, so careful prioritisation and decision-making are required. This paper aims to develop a comprehensive decision-making framework to give insights to decision-makers and stakeholders.

This paper's proposed framework uses a combination of techno-economic multi-criteria decision analysis. GEOPHIRES v2.0 is used for techno-economic analysis. Analytical Hierarchy Process (AHP) is suggested for the multi-criteria decision analysis to evaluate the geothermal fields using various sustainable development criteria. Three scenarios of the LTS-LCCR 2050 (CPOS, TRNS, and LCCP) are used as the basis for weighting to determine the field prioritisation, which is reflected through the final AHP scoring. The above framework is applied to ten different geothermal greenfield projects across Indonesia. The results are ranked and compared using the above developed framework. Comparison with other rankings (e.g. RUPTL 2021-2030) leads to insights into the decision-making process and method.

This work suggests that fields located on Sumatra Island and Java Island should be prioritised more highly in the context of energy transition. A more comprehensive result can be achieved by including new variables in the indicator level of the AHP structure.

1. OVERVIEW

Indonesia is committed to complying with the Paris Agreement on Climate Change. It has outlined the energy transition strategies through the LTS-LCCR (Long-Term Strategy for Low Carbon and Climate Resilience) 2050 President of the Republic of Indonesia (2021). The LTSLCCR 2050 covers various mitigation pathways, including using more renewable energy for the energy sector, contributing 43% of the total CO_2 emission in 2021. The transition in the energy sector is facing serious challenges as renewable energy only accounts for about 18-19% of the total energy mix in 2021, while the tally is led by coal, natural gas, and diesel by 62%, 18%, and 1-2%, respectively (Climate Transparency, 2022). To combat this challenge, one of the renewable energies that can replace fossil fuel plants is geothermal energy. The nature of geothermal energy, which is non-intermittent and has a high-capacity factor, is the primary advantage compared to other renewable energies. Moreover, geothermal energy shares many similarities with fossil fuels regarding power plant technologies since they are all thermal power plants.

Studies show that 40% of the world's geothermal reserve lies in Indonesia which is about 24GW (Aziziah et al., 2023). As of 2021, the installed capacity is 2356 MW, placing Indonesia just behind the USA on this tally (Richter, 2023). However, this high installed capacity is only a tiny fraction of the potentially remaining geothermal reserve capacity.

Multiple aspects must be noted in developing geothermal fields for electric power generation, particularly in Indonesia, where backlash from various societies is still very common due to their concern regarding developments that may affect their livelihood (Purba et al., 2021a). Furthermore, sacrificing the environment for renewable energy power plants is not an option in the sustainable energy development concept towards energy transition, as it can cause a loss of biodiversity and conservation forest for any megawatt produced. A framework that encompasses all the development aspects is required to assist the decision-makers to assess and prioritise the geothermal fields. This study explores and proposes a techno-economic multi-criteria decision framework to support geothermal field prioritisation in the energy transition context.

GEOPHIRES v2.0 is employed to support the Techno-Economic Analysis (TEA), and the Analytical Hierarchy Process (AHP) is used for evaluating the fields through parameters that represent various aspects of the sustainable development concept in the Multi-Criteria Decision Analysis (MCDA).

Three development scenarios are used from Indonesia's LTSLCCR 2050 to weigh the different aspects and indicators used to represent the sustainable development concept. The framework is applied to ten different geothermal greenfield projects across Indonesia.

2. TECHNO-ECONOMIC ANALYSIS: GEOPHIRES V2.0 SOFTWARE

GEOPHIRES v2.0 is a Python code architecture to simulate the techno-economic analysis of geothermal energy. The code will simulate the reservoir, wellbore, and plant-based on the user's input, with heat extraction through temperature as the baseline of the architecture. The final product of GEOPHIRES v2.0 includes production temperature, electricity production, and financial costs. The feature also allows users to create serial and parallel CHP (Combined Heat and Power) scenarios that simulate electricity production and direct use based on the geothermal mass flow rate and temperature. GEOPHIRES v2.0 is under MIT license and distributed as an open source through GitHub, allowing

users to develop models based on their applications. Another major upgrade includes converting codes from FORTRAN to Python, updating the cost correlation, and enabling them to perform simulations, coupled with TOUGH2 for the reservoir simulator (Beckers & McCabe, 2018).

The v2.0 version had been designed to be a flexible, user-friendly, and robust tool for a technical and economic performance assessment of the geothermal system for broad purposes. This version provides 92 input parameters, which consist of subsurface technical parameters (47), surface technical parameters (9), financial parameters (13), capital and O&M cost parameters (21), and a simulation parameter (2) (Beckers & McCabe, 2019).

2.1 Selected Models of GEOPHIRES v2.0

GEOPHIRES v2.0 offers various models that users can select. Table 1 displays the options used in this study.

2.2 GEOPHIRES v2.0 Modification

GEOPHIRES v2.0 is built based on data and trends in the United States. Some of the codes have been changed to comply with the location of this study, Indonesia. Table 2 presents the modifications done in this study.

2.3 GEOPHIRES v2.0 Input Assumptions

Some assumptions are required to make GEOPHIRES v2.0 fit with the case conditions and to compare different models with each other. Input assumptions for GEOPHIRES v2.0 are shown in Table 3 and Table 4.

Part	Model
Reservoir	Linear Thermal Drawdown
Wellbore Model	Default Temperature Drop (5°C)
Surface Plant Model	1. Subcritical ORC 2. Supercritical ORC 3. Single-Flash 4. Double-Flash

Table 1. GEOPHIRES v2.0 used options

Part	Modification Detail
Total Well Costs (Cwells)	GEOPHIRES v2.0 assumes the drilling success rate is 100%, which clearly overestimates the actual condition of the geothermal drilling. To overcome this limitation, modifications were made to the code to include success rate. The calculation for the success rate used the round-up function to obtain an integer, not a fraction number. The success rate is 71%, adapted from the work by Sanyal & Morrow (2012).
Operation and Maintenance (O&M) Cost	To align with the study's case in Indonesia, the total O&M refers to the study by Winofa et al. (2021). Make-up water cost will not be included as it is assumed that there is no loss of water in the reservoir. The total well costs are: $C_{O\&M}(\$) = 80000 \cdot (Plant\ Capacity)$
All Costs	The financial outputs in GEOPHIRES v2.0 are built in the 2017 constant dollar price, hence the value will be converted to the 2022 USD price using an inflation calculator. 1 USD in 2017 is equal to 1.19 USD in 2022 (U.S Inflation Calculator, n.d).

Table 2. Modified parameters in GEOPHIRES v2.0

Reservoir and Wellbore	Inputs
Production Well Diameter	9.625 inch
Injection Well Diameter	9.625 inch
Production Well Temperature Drop	5°C (default of GEOPHIRES v2.0)
Surface Temperature	25°C
Drilling Method	Directional
Mass Flow Rate	Regional average based on report by JICA (2007)
Productivity and Injectivity Index	10 kg/s/bar (default of GEOPHIRES v2.0)
Injection Temperature	45°C
Decline Rate	0.5% (default of GEOPHIRES v2.0)

Table 3. Reservoir & Wellbore Assumptions

Financial	Inputs
Plant Lifetime	30 years
Loan: Equity	70% : 30%
Inflation rate	2%
Interest	4%
Interest during Construction	4%
Tax Rate	25%

Table 4. Financial assumptions by Winofa et al. (2021)

3. MULTI-CRITERIA DECISION ANALYSIS: ANALYTICAL HIERARCHY PROCESS (AHP)

The utilisation of MCDA in the energy sector is not new, as Wang et al. (2009) have documented various MCDA frameworks for different cases. Wang et al. (2009) described this method as favourable due to its effectiveness in supporting options that involve trade-offs between objectives, multiple interests, and perspectives and account for complex and evolving biophysical as well as socio-economic facets.

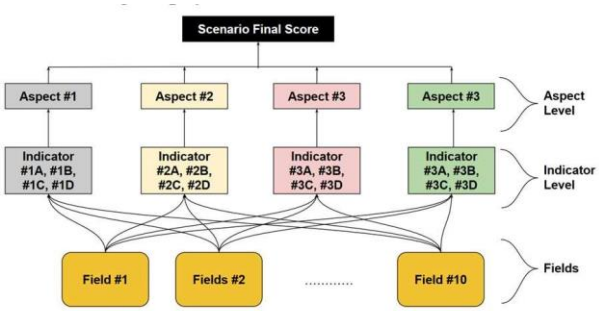

Figure 1. AHP hierarchy structure in this study

A sustainable energy approach is chosen here as developing geothermal fields must be evolved considering multiple aspects. Sustainable energy is related to the recontextualisation of energy systems as an integral part of sustainable development. The National Science Board of the United States (2009) described sustainable energy as "affordable, safe, and available in sufficient quantity to enable continued economic and social development while promoting environmental stewardship". This study utilised four aspects, in line with Prionggo (2021) selected from numerous papers: technical, economic, social, and environmental. Each aspect is elaborated into four indicators. Therefore, 16 indicators were used for this study in total.

3.1 Technical Aspects

3.1.1 Efficiency

Efficiency is the most technical indicator used to evaluate energy systems (Wang et al., 2009). For instance, efficiency is also one of the power plant performance indicators. In this study, the efficiency of the power plant will be generated from GEOPHIRES v2.0. The value is dimensionless, expressed in percentage (%), ranging from 0% to 100% with a positive orientation.

3.1.2 Technology Familiarity

Technology familiarity measures the degree of technology and refers to how widespread the technology can be at both a national and international level (Wang et al., 2009). In this study, the technology means that power plant technology is well-known in Indonesia. The geothermal power plant is divided into two categories: Flashing and binary plant. Flashing power plants have similar designs and working principles to any steam power plant, with gas and coal as primary energy, in the case of Indonesia, in which knowledge has been spread widely. Some spare parts are also easier to find locally, which can improve the reliability of the power plant. With this consideration, binary plants will score less than flashing plants.

3.1.3 Regional Electrification Ratio

The electrification ratio is the ratio of household customers with access to electricity over the total household in a particular region. Although the ratio is considerably higher than it was ten years ago, it is still lower than the target of a 100% electrification rate for 2022 (PLN, 2021). From a technical perspective, a higher electrification ratio of the region is interpreted as the geothermal power plant being needed less in the grid than the region with a lower electrification rate. This Indicator has a negative orientation.

3.1.4 Remoteness of Geothermal Point

The exploration of geothermal resources is challenging as multiple articles of equipment for drilling and well testing must be brought to the site. Indonesia is blessed with rich geothermal potential, but sadly, that comes with unequal development among islands. This disparity causes a logistics problem in delivering the technology. Other potential problems caused by a lack of equipment are security issues, local people's low understanding of geothermal energy, and a lack of geothermal experts (Purba et al., 2021b).

Well-testing and scaling removal require trucks to deliver the equipment; therefore, a geothermal point in an area that lacks supporting infrastructures will bring challenges throughout the plant's lifetime. To rectify this issue, the fields that are in the area mentioned in Presidential Regulation No.63 of 2020 concerning the Determination of Underdeveloped Regions will be given a high score (Presidential Decree No. 63/2020 on Determination of Underdeveloped Regions in 2020-2024, 2020). This indicator has a negative orientation

3.2 Economic Aspects

3.2.1 Estimated LCOE

LCOE, or Levelised Cost of Electricity, is an indicator to measure a unit of price to generate a unit of electricity for the power generation sector. Lazard (2018) describes LCOE as the average minimum revenue needed to recover the cost of construction and O&M of a power plant in a designated lifetime. LCOE has a negative orientation, with the value generated by GEOPHIRES v2.0.

3.2.2 Estimated LCOE to Regulated Price

The President of the Republic of Indonesia released Presidential Regulation No.112/2022 for the acceleration of renewable energy that also regulated the ceiling price for each type of renewable energy that may vary for each region (Presidential Regulation 112/2022 on Acceleration of Renewable Energy Development for Electricity Supply, 2022). The estimated LCOE from the output of GEOPHIRES v2.0 will be divided by the regulated price for geothermal plants, referring to Presidential Regulation No.112/2022 to determine the ratio. A lower value means the price is competitive for commercial operation. The value is in percentage ranging from 0% to 100% and has a negative orientation.

3.2.3 Estimated Capital Cost / GWh

The total capital cost consists of all costs related to the project's upfront cost, such as mechanical-electrical equipment, installation, and construction. For this study, the value of the estimated capital cost is generated by the GEOPHIRES v2.0. The value of the estimated capital cost will be divided by GWh, which GEOPHIRES V2.0 also generated. A higher value can be seen as the project will cost more to give 1 GWh. This indicator has a negative orientation.

3.2.4 Impact to GDP

Enriko (2023) stated that investment in renewable energy would create a new value chain, resulting in value-added on a local to global scale. IRENA found that GDP in the construction year of renewable energy power plants may increase by 0.2-4% (IRENA, 2016). Specifically for the case of Indonesia, Hartono et al. (2020) described the impact of investment in various renewable energy plants on GDP, which estimated that Indonesia would gain 0.669% per GW installed for geothermal power plants. This indicator has a positive orientation.

3.3 Social Aspects

3.3.1 Possible Direct-Use

The direct use of geothermal is the utilisation of geothermal energy in a more conventional way, such as heating, greenhouse, bathing, and food processing. This utilisation can benefit the local people by creating participation from multiple communities, not only through power plant employment. In the sustainable development framework, the direct use of geothermal energy must be included to make a more socially-centred project (Cataldi, 2001). Bagaskara et al. (2023) found that coffee drying, rice drying, and fish drying are the most beneficial for the most suitable direct use applications in Indonesia with consideration of product durability, existing related industry, and required temperature. This indicator has a positive orientation.

3.3.2 Job Creation

Investing in a geothermal power plant, without a doubt, will bring new job opportunities. The plant needs people to build during construction and operate and maintain when it is already generating electricity, opening employment along the life cycle. With a sustainable system, more jobs can be created for people to bring improvements to their quality of life (Wang et al., 2009). In this study, the number of jobs created is 0.89 per GWh during their lifecycle, based on work by Anderson and Rezaie (2019). This indicator has a positive orientation.

3.3.3 Social Risk Level

Indonesia is widely known for cultural diversity. Nevertheless, the development of geothermal projects was considered to potentially increase negative social impacts in areas where indigenous people lived and increase the reputational risk faced by developers, the regional government, and even the central government (PROFOR, 2019). Some of Indonesia's geothermal fields intersect with Indigenous people's living places and customary land, which may cause social friction over the project's lifetime. Reports by PROFOR (2019) are used with modifications to account for the existence of indigenous people, social forest, and customary land in each field. This indicator has a negative orientation, considering a higher value means higher risks.

3.3.4 Regional Electrification Ratio and Grid Type

The electrification ratio has been added in the technical aspect. However, in this indicator, the normalised score of the electrification ratio in technical aspects will be added with a grid-type score to account for the importance of the geothermal plant as a base load for the people inside the grid. The grid electrification as a technical aspect gives the score of how a project is beneficial technically in the attempt to reach the 100% electrification rate. On the other hand, the social aspect of grid electrification and grid type provide a perspective of how a project can benefit the people. This indicator has a positive orientation.

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3.4 Environmental Aspects

3.4.1 Technology's Lifecycle GHG Emission

It is widely believed that various greenhouse gas (GHG) emissions caused the rapid rise in global temperature. CO_2 is the most prevalent among those gasses, accounting for 81% of the global GHG emissions in 2018 (U.S Environmental Protection Agency, 2019). Parisi et al. (2019) explained that the life cycle of emissions is very common in evaluating a power plant's environmental performance, of which the emission is calculated by assessing material and energy flow during a plant's lifetime. In contrast to other renewable energy sources, geothermal power plants still generate GHG emissions during the operation phase from the NCG, which is brought along with extracted geothermal fluid (Kaya & Zarrouk, 2017). Comparing the technology of flash plants and binary plants, research by Sullivan et al. (2010) found that flash power plants generate more emissions than binary power plants. However, both numbers are significantly lower than coal-fired power plants. Scoring is used in this indicator, and the orientation is negative.

3.4.2 Regional GHG Emission from Power Generation

As Indonesia's power generation mix is still heavily reliant on fossil fuels, the high contribution from the power sector is understood. Coal-Fired Power Plants are used as base load providers, which tend to operate at maximum capacity and only shut down during maintenance or grid constraints. Among renewable energies, geothermal is the wisest option to replace coal because geothermal is known for being a nonintermittent resource, and the technology is relatively the same as in coal-fired power plants, which also employ a thermal plant principle. Although geothermal power plants still emit GHG, compared to coal the emissions are less than 10% (Sullivan et al., 2010), which means geothermal power plants will generate significantly fewer emissions than coal with the same capacity. This indicator has a positive orientation, with the higher regional emissions meaning a higher urgency to construct geothermal plants.

3.4.3 GHG Reduction by Geothermal

As mentioned, geothermal power plants still emit GHG, yet the emission is very low compared to any fossil fuel power plant. This indicator is implemented to account for the impact of one field on GHG emission reduction. The reduction of GHG is a result of the work by Bloomfield and Moore (1999). The reduction value of 1.3933 lbs.CO_2/GWh is retrieved by calculating the average emission of fossil fuels subtracted by geothermal emission. This is because the power plant base load in the grids in Indonesia is not always coal; in some cases, the plant is fired by diesel and gas. This indicator has a positive orientation.

3.4.4 Environmental Risk Level

Darma et al. (2021) stated that the geothermal reserves are in 312 different locations and have a potential of 29GWe, which comprises speculative resources, hypothetical resources, possible reserves, probable reserves, and proven reserves. Nevertheless, all the locations have unique characteristics, which can cause different challenges for development. Some fields lie beneath conservation and protection areas, while others are in production forests as classified by the Ministry of Environment and Forestry (MoEF) of Indonesia. Although located in a production forest, the geothermal point of some fields might intersect with UNESCO World Heritage sites or IBA (Important Bird Area) and KBA (Key Biodiversity Area). Although developing geothermal power plants aims to increase the renewable energy mix and reduce emissions, exploring higher-risk fields could cause collateral impacts such as a loss of biodiversity and the deforestation of protected land. PROFOR (2019) released a macro-assessment of potential and risk from all geothermal field locations in Indonesia, and the data is used in this indicator. This indicator has a negative orientation.

4. ENERGY TRANSITION FRAMEWORK: LTS-LCCR 2050

Along with Indonesia's Enhanced National Determined Contribution (NDC), Indonesia also submitted the Low-Term Strategy for Low Carbon and Climate Resilience (LTSLCCR) 2050 to UNFCC (United Nations Framework Convention on Climate Change) as a commitment to comply with the goal of the Paris Agreement. The three scenarios that are presented in this study are based on the LTS-LCCR 2050, which are the Current Policy Scenario (CPOS), the Transition Scenario (TRNS), and the Low Carbon Scenario Compatible with the Paris Agreement target (LCCP).

Each scenario has its priorities. CPOS refers to a commitment to continuing current policies or business as usual, which shows that emissions will continuously increase after 2030. Emissions in TRNS are decreasing but not adequately enough to reach the 2050 goal. LCCP is committed to reducing carbon emissions and reach the 2050 goal of which a significant reduction will take place after 2030 (Enriko, 2023).

Scenario	Aspect	Relative Weight	CR
CPOS	Technical	0.26335	0.04437
	Economic	0.55789	
	Social	0.12187	
	Environmental	0.05689	
	SUM	1.00000	
TRNS	Technical	0.15751	0.00544
	Economic	0.48241	
	Social	0.08829	
	Environmental	0.27180	
	SUM	1.00000	
LCCP	Technical	0.07684	0.07540
	Economic	0.26299	
	Social	0.15909	
	Environmental	0.50108	
	SUM	1.00000	

Table 5. Weighting of aspects in each scenario

4.1 Weighting of the Indicators

Geothermal energy is utilised to achieve an electrification ratio of 100%, which makes the regional electrification ratio the top priority for technical aspects. On the other hand, developing geothermal power plants is not as easy as constructing fossil fuel plants, as geothermal energy has geographical constraints that are only available in specific locations. The first steps in developing geothermal power plants are during the exploration stage, which requires mobilising drilling equipment using trucks. For this reason, the remoteness of the geothermal point emerges as the second priority. Efficiency is the third priority, as higher efficiency can lead to more sustainable resource usage to prevent geothermal depletion (O'Sullivan et al., 2015). Technology familiarity is the least important. Although binary is new in Indonesia, knowledge can be learned in various ways, and within several years, its expertise will no longer be a problem.

Affordability is one of the essential keys to sustainable energy development and emerges as a facet that must be highly prioritised. LCOE has a close relationship with affordability, which accounts for price per kWh, making it the most crucial economic indicator. LCOE to regulated price ratio measures how economical the plant is if compared to the regulated price. The estimated total cost per GWh ratio is the third priority to account for how expensive the project is per electric power generated. Renewable energy development will impact GDP, yet it is not the companies' objective to increase GDP; hence, it is set as the lowest priority.

The attempt to achieve an electrification ratio is seen as the government's commitment to provide equal electricity to the people of Indonesia, regardless of the location. The

"electrification ratio and grid characteristics" can create an image of how important electricity is for the local people. The existence of geothermal power plants in an isolated grid will have a higher impact on the people, as it will serve the primary base load plants, compared with an interconnected grid with more power supplied from anywhere. Job creation by renewable energy is one of the issues addressed in LTS-LCCR 2050, which is the project expected to accommodate manpower from the mining and fossil fuel sectors. The project is expected to provide opportunities for the younger generation and local people, which may catalyse regional economic growth. Social risk levels include the presence of indigenous people, social forestry, and customary land, which are vital components in the development of geothermal power plants. Disrupting them may potentially increase the negative social impact in areas and the reputational risk faced by stakeholders despite effective and comprehensive mitigation reducing the impact. One of the mitigations involves the direct use of geothermal energy, which would be based on the region's potential local resources. With all respect and consideration, social risk level and direct use are the third and fourth priorities.

The environmental aspect is the most anticipated key in sustainable development, as it justifies that any activities will not negatively affect the environment. The environmental risk level is at the top of the chart, accounting for the conservation area, forest land status, heritage value, and land cover. The included points are crucial in the preservation of conservation areas and biodiversity. Geothermal power plants are seen as one of the solutions to reduce GHG emissions, specifically from the power generation sector; hence, regional GHG emissions from the power generation sector are set as the second priority in the environmental aspect. Although the emission is lower than that of any fossil fuel, geothermal power plant technology still produces emissions that accumulate from the production stage.

Aspect	Indicator	Relative Weight	CR
Technical	Electrification Ratio	0.46061	0.0153
	Remoteness	0.32838	
	Plant Efficiency	0.13636	
	Technology Familiarity	0.07464	
	SUM	1.00000	
Economic	Estimated LCOE	0.36967	0.02294
	Estimated LCOE to Regulated Price Ratio	0.36967	
	Estimated CAPEX/GWh	0.22501	
	Impact to GDP	0.03564	
	SUM	1.00000	
Social	Electrification Ratio & Grid Type	0.45983	0.06002
	Job Creation	0.25366	
	Social Risk Level	0.20092	
	Potential Direct-use	0.08559	
	SUM	1.00000	
Environmental	Environmental Risk Level	0.39719	0.04479
	Grid GHG from Power Generation	0.35650	
	GHG Reduction	0.20119	
	Plant's LC GHG Emission	0.04511	
	SUM	1.00000	

Table 6. Weighting of indicators

4.2 Indicator Global Weight in Each Scenario

The final, global weighting of each indicator is the aspect score multiplied by the indicator score. The normalised score of each indicator will be multiplied by the indicator's global weight to give a value of how an indicator contributes to the final scoring. Table 8 shows the indicator global weight after calculations.

Aspect	Indicator	Indicator Global Weight		
		CPOS	TRNS	LCCP
Technical	Electrification Ratio	12.130%	7.255%	3.539%
	Remoteness	8.648%	5.172%	2.523%
	Plant Efficiency	3.591%	2.148%	1.048%
	Technology Familiarity	1.966%	1.176%	0.574%
Economic	Estimated LCOE	20.624%	17.833%	9.722%
	Estimated LCOE to Regulated Price Ratio	20.624%	17.833%	9.722%
	Estimated CAPEX/GWh	12.553%	10.855%	5.918%
	Impact to GDP	1.988%	1.719%	0.937%
Social	Electrification Ratio & Grid Type	5.604%	4.060%	7.316%
	Job Creation	3.091%	2.239%	4.035%
	Social Risk Level	2.449%	1.774%	3.196%
	Potential Direct-use	1.043%	0.756%	1.362%
Environmental	Environmental Risk Level	2.260%	10.796%	19.903%
	Grid GHG from Power Generation	2.028%	9.690%	17.863%
	GHG Reduction	1.145%	5.468%	10.081%
	Plant's LC GHG Emission	0.257%	1.226%	2.261%
	SUM	100.000%	100.000%	100.000%

Table 7. Indicator global weight

5. STUDY CASE

In this study, ten different geothermal greenfields across Indonesia are used. The fields used in this study are Jaboi, Sungai Penuh, Danau Ranau, Rajabasa, Cisolok-Cisukarame, Ungaran, Bedugul, Songa-Wayaua, Atadei, and Gunung Sirung. The fields are chosen based on the data availability found in released studies, up to resource assessment, using the numerical modelling method. These fields are already mentioned in the RUPTL 2021-2030 (PLN, 2021) as the comparative strategy that existed in Indonesia. The main data used for the prioritisation process is outlined in Table 8.

6. RESULTS & DISCUSSION

6.1 GEOPHIRES v2.0 Simulation Results

The GEOPHIRES v2.0 simulation results are presented in Table 9. The cost parameters will be converted to the 2022 price described in section 2.2 before entering the AHP structure. GEOPHIRES v2.0 can only perform and analysis of a maximum of 20 wells for production and reinjection, which caused Rajabasa to be only simulated for Plants #1 and #2.

6.2 AHP Normalisation Matrix

The values used for the normalisation stage are based on both GEOPHIRES v2.0 results and individual performances. Table 10 displays the normalisation matrix of each indicator.

Aspect	Indicator	Orientation	Min	Max
Technical	Electrification Ratio	Negative	0.85	1
	Remoteness	Negative	1	5
	Efficiency	Positive	0	0.25
	Technology Maturity	Positive	0	1
Economic	LCOE cUSD/kWh	Negative	3.927	11.305
	LCOE/BPP $/$ 1-10	Negative	0.34988	0.92664
	Estimated M$/GWh	Negative	0.49708	1.19184
	Impact to GDP (0.669%*GW)	Positive	3.3E-05	0.00074
Social	Electrification Ratio & Grid Type	Positive	2	15
	Job Creation (0.89*GWh)	Positive	34.9948	770.802
	Social Risk Level	Negative	1	13
	Potential Direct-use	Positive	0	12
Environmental	Environmental Risk Level	Negative	1	23
	Grid GHG from Power Generation	Positive	1	9
	GHG Reduction	Positive	54784.6	1206695
	Plant's LC GHG Emission	Negative	1	3

Table 10. Normalisation matrix

Parameter	Fields									
	Jaboi	Sungai Penuh	Danau Ranau	Rajabasa	Cisolok-Cisukarame	Ungaran	Bedugul	Songa-Wayaua	Atadei	Gunung Sirung
Location	Sabang, Aceh	Sungai Penuh, Jambi	OKU Selatan, South Sumatera	South Lampung, Lampung	Sukabumi, West Java	Semarang Regency, Central Java	Tabanan, Bali	South Halmahera, North Maluku	Lembata, East Nusa Tenggara	Alor, East Nusa Tenggara
Island	Sabang	Sumatera	Sumatera	Sumatera	Java	Java	Bali	Bacan	Lembata	Alor
1st Planned Capacity, MWe	5	55	20	2 x 110	20	55	10	2 x 5	2 x 5	5
1st Commercial Operation Date/COD (PLN, 2021)	2023	2028	2028	2025	2030	2026	2025	2025	2024	2029
Mass Flow Rate in kg/s (JICA, 2007)	50	52.778	56.111	50	52.778	52.778	61.111	44.444	44.444	50.39
Estimated Reservoir Temperature, °C	250 - 300 (Nugraha & O'Sullivan, 2018)	210 (Hidayat et al., 2016)	250 (Afiat et al., 2021)	250 - 380 (Darmawan et al., 2023)	212 (Sumartha et al., 2020)	250 (Jatmiko et al., 2022)	278 (Keitjem et al., 2023)	240 (Hasbi et al., 2018)	221 (Supijo et al., 2018)	260 (Taufan et al., 2018)
Estimated Well Depth, m	600 (Nugraha & O'Sullivan, 2018)	910 (Hidayat et al., 2016)	1200 (Afiat et al., 2021)	800-1200 (Darmawan et al., 2023)	1000 (Sumartha et al., 2020)	2500 (Jatmiko et al., 2022)	1800 (Keitjem et al., 2023)	800 (Hasbi et al., 2018)	1200 - 1400 (Supijo et al., 2018)	1000 - 2000 (Taufan et al., 2018)
Electrification Ratio 2021 (PLN, 2021)	99.99%	99.72%	98.71%	99.99%	86.15%	99.99%	100%	99.99%	86.15%	< 90.00%
Grid Type (PLN, 2021)	Isolated, no integration plan	Interconnected	Interconnected	Interconnected	Interconnected	Interconnected	Interconnected	Isolated, no integration plan	Isolated, no integration plan	Isolated, no integration plan
Listed as Underdeveloped	No	No	No	No	No	No	No	No	Yes	Yes
Potential Direct-Use from City/Regency BPS Data	Fish	Coffee, Rice	Coffee	Rice, Fish	Rice	Coffee, Rice	-	Fish	Coffee, Fish	Rice, Fish
Social Risk Level (PROFOR, 2019)	0	0	2	2	2	0	0	0	2	0
Environmental Risk Level (PROFOR, 2019)	5	1	5	5	0	1	15	2	1	3
Regional GHG from Power Gen. in MtCO2 (PLN, 2021)	43.8	43.8	43.8	43.8	185.6	185.6	185.6	7.2	7.2	7.2

Table 8. Utilised data for prioritisation process

Parameter		Fields								
		Jaboi	Sungai Penuh	Danau Ranau	Rajabasa	Cisolok-Cisukarame	Ungaran	Bedugul	Songa-Wayaua	Atadei	Gunung Sirung
Plant #1 Subcritical ORC	Number of Production Wells	1	14	1	18	6	9	1	3	3	1
	Number of Reinjection Wells	1	4	1	4	2	2	1	1	2	1
	Avg. Net Electricity (MWe)	5.00	54.93	5.99	109.56	19.86	54.97	10.00	10	9.98	5.99
	Estimated CAPEX (M$)	23.46	221.48	33.34	360.62	96.82	276.85	46.79	54.88	77.04	33.34
	Avg. Annual Net Electricity (GWh)	39.42	432.97	39.42	863.31	156.34	433.05	78.77	78.82	78.61	39.42
	Plant Efficiency Year-1	15.97%	11.71%	16.43%	15.45%	11.10%	15.4803	19.52%	15.0645	0.120893	0.164288
	Estimated CAPEX/GWh	0.593	0.512	0.846	0.418	0.619	0.639	0.594	0.696	0.980	0.846
	LCOE (¢USD/kWh)	3.3	4.3	3.5	3.5	4.3	4.7	4.1	4.8	6.7	3.5
Plant #2 Supercritical ORC	Number of Production Wells	1	13	1	19	5	9	2	2	3	1
	Number of Reinjection Wells	1	3	1	4	2	4	1	1	2	1
	Avg. Net Electricity (MWe)	5.00	54.94	5.68	109.89	19.95	54.95	10	9.99	10.56	5.68
	Estimated CAPEX (M$)	24.89	234.61	32.8	394.52	95.52	309.13	59.92	57.64	82.22	32.8
	Avg. Annual Net Electricity (GWh)	39.42	433.1	39.42	866.07	157.18	432.96	78.84	78.75	83.42	39.42
	Plant Efficiency Year-1	14.21%	12.83%	14.43%	14.32%	12.23%	14.8238	15.53%	14.3469	0.127662	0.144341
	Estimated CAPEX/GWh	0.629	0.542	0.456	0.456	0.608	0.714	0.760	0.732	0.986	0.832
	LCOE (¢USD/kWh)	3.4	3.7	3.6	3.7	4.1	5.2	3.9	6.1	4.6	3.6
Plant #3 Single-Flash	Number of Production Wells	2	20	2.0	Out of GEOPHIRES v2.0 range	8	14	2	3	4	2
	Number of Reinjection Wells	1	5	1		3	3	1	1	2	1
	Avg. Net Electricity (MWe)	5.00	54.67	7.77		19.99	54.94	10	9.99	9.78	7.77
	Estimated CAPEX (M$)	28.14	217.25	40.39		100.02	286	51.46	56.16	77.94	40.39
	Avg. Annual Net Electricity (GWh)	39.42	431.01	39.42		157.44	432.87	78.84	78.7	77.11	39.42
	Plant Efficiency Year-1	9.75%	8.25%	10.22%		7.97%	9.6789	11.57%	9.6672	0.084292	0.102248
	Estimated CAPEX/GWh	0.702	0.504	1.025		0.635	0.661	0.653	0.714	1.011	1.025
	LCOE (¢USD/kWh)	3.7	4	3.1		4.7	5.4	3.5	6.5	9.6	3.1
Plant #4 Double-Flash	Number of Production Wells	2	16	1	Out of GEOPHIRES v2.0 range	6	11	2	3	3	1
	Number of Reinjection Wells	1	4	1		3	3	1	1	2	1
	Avg. Net Electricity (MWe)	5.00	54.94	4.99		19.98	54.91	10	10	9.83	4.99
	Estimated CAPEX (M$)	31.64	221.06	31.9		101.5	271.28	56.72	62.13	78.55	31.9
	Avg. Annual Net Electricity (GWh)	39.42	432.87	39.32		157.43	432.55	78.84	78.84	77.47	39.32
	Plant Efficiency Year-1	12.25%	10.59%	12.84%		10.27%	12.4771	14.34%	12.1873	10.72%	0.128373
	Estimated CAPEX/GWh	0.679	0.511	0.811		0.645	0.627	0.719	0.788	1.014	0.659
	LCOE (¢USD/kWh)	4.0	3.8	5		4.5	5	3.7	4	9	5

Table 9. GEOPHIRES v2.0 simulation results

6.3 Comparing AHP Final Score to RUPTL 2021-2030

RUPTL 2021-2030 is the most recent energy provision plan by PLN. This plan also mentions the COD (Commercial Operation Date) of the plant from PLN's geothermal field. The COD year is arranged to construct a prioritisation of geothermal field developments by PLN. The prioritisation is presented in Figure 2, compared to the discussed scenarios.

In comparing the field prioritisation in RUPTL 2021-2030 with the simulation results in this study, it appears that RUPTL 2021-2030 hasn't followed any of the LTS-LCCR 2050 scenarios. The prioritisation method is not mentioned in RUPTL 2021-2030. Both RUPTL 2021-2030 and LTSLCCR 2050 were released in the same year and both were formulated independently, not correlated with each other.

RUPTL 2021-2030 can be seen to focus on the smaller islands instead of the major ones. Four of the five are between the first and fifth priorities in smaller islands. Although Jaboi can be considered on Sumatra Island due to its location being close, the Jaboi is on Sabang Island, and there is no interconnection between Sabang and Sumatra. Bedugul is on Bali Island, and Bali is part of the JAMALI (Java-Madura-Bali) grid, which is the grid that has the highest installed power in Indonesia. Nevertheless, Bali is still outside Java Island, and generators in Java Island mainly supply the electricity in Bali. This condition might become one of the factors that make Bedugul a priority.

In prioritising smaller islands within the top five priorities, CPOS leads among other scenarios. CPOS has four fields, whereas only one field is for others. With this consideration, RUPTL 2021-2030 is closer to CPOS than TRNS and LCCP.

Conversely, Java Island and Sumatra Island fields are more prioritised in TRNS and LCCP. The underlying factors are that both islands significantly contribute to the total emissions from the power generation sector in Indonesia, and the environment is put on higher urgency. Therefore, to aim for the energy transition, the objective is to develop the fields in Java and Sumatra Island instead of the other. Ungaran and Sungai Penuh showed a fall in CPOS, but they emerged significantly in TRNS and LCCP. Gunung Sirung and Bedugul are more suitable for CPOS since they fall behind in TRNS and LCCP. Among all the tested fields, Rajabasa and Jaboi are the two most favourable

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CPOS	#1	#2	#3	#4	#5	#6	#7	#8	#9	#10
	Rajabasa	Jaboi	Gunung Sirung	Danau Ranau	Bedugul	Songa Wayaua	Atadei	Cisolok-Cisukarame	Sungai Penuh	Ungaran
	7.345 Plant-1	7.128 Plant-1	7.033 Plant-1	6.731 Plant-2	6.659 Plant-3	6.511 Plant-4	6.462 Plant-2	6.367 Plant-2	6.291 Plant-2	5.968 Plant-1

TRNS	#1	#2	#3	#4	#5	#6	#7	#8	#9	#10
	Rajabasa	Cisolok-Cisukarame	Jaboi	Sungai Penuh	Ungaran	Gunung Sirung	Danau Ranau	Bedugul	Atadei	Songa Wayaua
	7.545 Plant-1	7.005 Plant-2	6.973 Plant-1	6.765 Plant-2	6.733 Plant-1	6.651 Plant-1	6.628 Plant-2	6.408 Plant-3	6.178 Plant-2	6.153 Plant-4

LCCP	#1	#2	#3	#4	#5	#6	#7	#8	#9	#10
	Ungaran	Rajabasa	Cisolok-Cisukarame	Sungai Penuh	Jaboi	Danau Ranau	Gunung Sirung	Atadei	Bedugul	Songa Wayaua
	7.262 Plant-1	7.211 Plant-1	7.108 Plant-2	6.746 Plant-2	6.156 Plant-1	5.959 Plant-2	5.885 Plant-1	5.837 Plant-2	5.498 Plant-1	5.339 Plant-1

RUPTL 2021-30	#1	#2	#3-5			#6	#7-8		#9	#10
	Jaboi	Atadei	Bedugul	Rajabasa	Songa Wayaua	Ungaran	Danau Ranau	Sungai Penuh	Gunung Sirung	Cisolok-Cisukarame
	2023	2024	2025	2025	2025	2026	2028	2028	2029	2030

Figrue 2. Prioritisation results

fields for all the scenarios. On the contrary, Atadei and Songa Wayaua are the least favourable.

6.4 Potential Improvement for Decision-Making

In light of GEOPHIRES v2.0 being built through parameters of the U.S standards, such as the labour cost, it is highly recommended to conduct further studies to build a TEA software architecture that is based on Indonesia's labour cost and trendline of various parameters from geothermal fields. Such a software architecture can assist decision-makers, investors, and researchers in better evaluating the geothermal fields in Indonesia.

One reason why the results of the LTS-LCCR 2050 scenarios differ from the RUPTL 2021-2030, is that the latter considers some variables that could not be included in this study due to time, data, and resource limitations. For further improvement and utilisation by decision-makers, some additional variables are suggested to include at the indicator level:

- Technical: Grid power balance and reserve, distance of projected geothermal plant to the major transmission and load centre, replacement of existing fossil fuel power-plant, geothermal fluid chemistry.
- Economic: RoI (Return of Investment), additional transmission-distribution line cost, additional geotechnical work cost, and revenue from direct-use commodities.
- Social: More detailed job creation (particularly the jobs in the geothermal plant), local perceptions (acceptance or rejection) of geothermal energy through survey or study.
- Environmental: Specific GHG from replaced fossil fuel existing power-plant.

7. CONCLUSION

Conclusions that can be derived from this study are as follows:

- GEOPHIRES v2.0 can be modified to adapt to the conditions in Indonesia. Nevertheless, a similar software that is explicitly dedicated to Indonesia should be developed.
- AHP structure has been constructed to comply with the sustainable development criteria.
- The prioritisation in RUPTL 2021-2030 does not fit with any LTS-LCCR 2050 scenarios. However, considering the number of fields in smaller islands, RUPTL 20212030 is closer to CPOS than TRNS and LCCP.
- Geothermal fields in Sumatra Island and Java Island are mostly more favourable for energy transition scenarios rather than business-as-usual.
- This proposed framework is flexible and powerful, and users and decision-makers can quickly adapt. However, more accurate and comprehensive results can be improved by including more variables at the indicator level.

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