Towards a New Framework for the Systematic Assessment of Indonesia's Undeveloped Geothermal Resources

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ABSTRACT

The National Energy General Plan (RUEN) of Indonesia targets the production of 10 GWe from geothermal by 2030 and further increases to 17.5 GWe by 2050. Robust assessments of Indonesia's undeveloped geothermal resources are required to help prioritize systems for development.

A new method for resource assessment has been developed by the Geothermal Institute at the University of Auckland, which leverages modern geothermal modelling tools and cloud computing. The method uses the same data that are available for traditional stored heat calculation but also includes reservoir physics, wellbore physics and realistic energy extraction scenarios to provide more accurate forecasts. This framework has been used on commercial and research projects and can be applied in less than a month using widely available computational resources.

This paper discusses the application of the method to five undeveloped geothermal systems in Indonesia. The study was undertaken in collaboration with the Geological Agency (GA) of Indonesia and the Directorate-General of New Renewable Energy and Energy Conservation (EBTKE) as a step towards establishing a new framework for the systematic assessment of Indonesia's undeveloped geothermal resources. The resource assessment framework was applied to each of the five systems; Ciremai, Kotamobagu, Maritaing, Massepe, and Papandayan. This included the development of new digital conceptual models and numerical reservoir models for each system using geoscientific data from the Geological Agency. The resource assessment results for each field are presented in a standard format, and it is envisioned that the results and the models could be made publicly available in a database of Indonesia's geothermal resources in the future.

1. INTRODUCTION

Indonesia is positioned along the boundaries of active plates and boasts an impressive geothermal potential estimated at 23.36 GW distributed across 356 locations. Recognizing this vast potential, the Indonesian government has set targets to increase geothermal energy production to 10 GWe by 2030, with further expansion to 17.5 GWe by 2050 (Rencana Umum Energi Nasional, 2017). However, despite these promising prospects, the current exploitation of geothermal resources in Indonesia remains limited. Currently, 16 geothermal fields are operational, collectively generating 2,342 MW, representing less than 15% of the targeted capacity for 2050 (Alhusni et al., 2023).

The exploration and development of new geothermal resources face many challenges. The early stage of exploration is particularly risky due to the limited availability of data and the substantial investment required. However, stakeholders must ensure that the potential of a geothermal resource is sufficient to justify the investment. This is typically assessed by estimating the potential electrical power output of the geothermal field.

Traditional methodologies for estimating the potential of a geothermal resource are plagued by high levels of uncertainty, primarily due to reliance on numerous assumptions and a lack of consideration for the physical processes within the reservoir and wellbore. A new framework has been developed that incorporates a more realistic energy extraction scenario using numerical modelling and cloud computing to address these limitations (Croucher et al., 2020; Dekkers et al., 2022; O'Sullivan & O'Sullivan, 2016). This innovative approach reduces the uncertainty in power output calculations and thus reduces risk and enhances investor confidence by providing a more reliable assessment of geothermal potential.

This paper presents the application of this novel approach to five undeveloped geothermal systems in Indonesia. Conducted in collaboration with the Geological Agency (GA) of Indonesia and the Directorate-General of New Renewable Energy and Energy Conservation (EBTKE), this study marks a significant step toward establishing a systematic framework for assessing Indonesia's untapped geothermal resources.

2. METHODOLOGY

Numerical modelling for geothermal reservoirs has been carried out since the 1970s (Stanford Geothermal Program, 1980; O'Sullivan, 1985; O'Sullivan et al., 2001; O'Sullivan and O'Sullivan, 2016). In this paper, we propose a new method for assessing the potential of geothermal power output using numerical modelling, available data and innovative algorithms. This method requires simulations of a large number of different reservoir models, making it very dependent on computational speed. Fortunately, highly parallelized geothermal simulators like Waiwera, developed by the University of Auckland and GNS Science (Croucher et al., 2020), can leverage high-performance computing resources to make this new method feasible.

The advantage of the resource assessment method presented in this work is that the geothermal power estimations are based on numerical reservoir simulations. These simulations include reservoir physics, wellbore physics and realistic energy extraction scenarios. The method of resource assessment also produces robust estimates of the uncertainty using well-established uncertainty quantification techniques (Dekkers et al., 2022).

2.1 Steady state models

The first step for our resource assessment is to use the 3D digital conceptual model to set up a numerical model where representation of the geology, alteration zone, structural settings and potential deep upflow locations define a large set of model parameters. We then generate an ensemble of possible models by randomly sampling model parameters from statistical distributions based on realistic ranges. These sample models are simulated to a steady state before any production simulations are carried out. Over 2000 sample models were generated for each of the systems discussed in this paper.

2.1.1 Uncertain parameters

Generally, when we develop a new numerical model, we start with an initial guess of model parameters based on expert knowledge of rock permeabilities and upflow rates. These parameters are then manually calibrated using the available data. During the exploration stage of a geothermal field, the calibration process is rapid because few data are available. However, the lack of data means there is significant uncertainty in the model parameters. To represent this uncertainty, an ensemble of reservoir models is created by randomly sampling model parameters from realistic probability distributions. The distribution of each parameter is centred around the calibrated model parameters. Collaboration by geothermal stakeholders to specify a standardized list of required exploration data could help reduce uncertainty in the future by providing more data with which to condition the sample models.

2.1.2 Conditioning on the clay cap

The second step of our approach is to filter the steady state models based on the location and temperature of the base of the clay cap. This process is called “conditioning” and involves discarding sample models that do not fit the available reservoir engineering data. We do this using approximate Bayesian computation (ABC) (Beaumont, 2019; Marin et al., 2012) as described in Dekkers et al. (2022). Thus, to apply our methodology, some data giving the location of the clay cap is required, e.g., MT survey data, clay mineralogy from drilling cuttings or downhole temperatures. A clay cap is formed by alteration of the rock structure due to heating. Temperatures of approximately 200 °C are needed to form a clay cap. After the clay cap is formed, the hot fluids do not flow easily through the clay cap due to its low permeability. Thus, the location of the clay cap can be used as a proxy for the temperature distribution at the top of the geothermal system (i.e., top of the reservoir). The resistivity boundary and estimates of the location of the top of the reservoir are used in a similar way as in a traditional stored heat calculation. However, a stored heat calculation neglects the physics of subsurface fluid flow and does not make use of the full three-dimensional shape of the interpreted clay cap. Expert interpretation of resistivity is still required in both a traditional stored heat calculation and our new approach to account for phenomena such as relict alteration and clay sediments. The temperature threshold for conditioning can also be modified where mineralogy indicates it is appropriate.

2.2 Production models

After filtering the steady state models to an ensemble containing only those that match the geophysical data, we apply an innovative method to run production scenarios that maximize the power output of each sample model. We use the steady state model as an initial state for the production model and then simulate 25 years of future production extracting energy using a typical binary power plant configuration. This method can be easily modified to accommodate different power plant designs and operating conditions depending on the geothermal system that is being analysed.

One of the challenges with using uncertainty quantification of geothermal models for resource assessment is that the optimal production strategy is different for each sample model. Typically, the design of future scenarios for a geothermal model is done manually by geothermal reservoir modelers and then optimized to achieve maximum energy extraction. However, this manual approach is clearly not viable with thousands of sample models.

The innovative method we have developed is an iterative algorithm that can select the best targets for production and reinjection for any given sample model. The iterative algorithm continues selecting targets until the additional energy produced is less than 5% of the previous iterative step, indicating diminishing returns on adding new wells.

Wellbore modelling is used to represent the behaviour of each of the production wells. Before running the iterative algorithm, wellbore models are run for all possible target depths under all the likely range of thermodynamic conditions. This process can be completed on a standard desktop computer within 2-3 days. Vertical, single-feed wells with typical completion designs are assumed in this work to demonstrate the approach. However, the parameters of production wells, including the completion design and number of feeds, could easily be modified. Additionally, areas where wells can (or cannot) be sited (e.g., due to factors such as topographical constraints or consent boundaries) can be easily specified.

It is important to remember that the objective of this method is to calculate the production potential for each sample model efficiently using a realistic extraction scenario. It does not aim to design the optimal extraction scenario for each sample model or the system in general. Designing an optimal extraction scenario for the system is expected to take place during the development of the production stage once exploration drilling and early production testing have taken place. The details of the iterative algorithm of our innovative method are provided in Dekkers et al. (2022).

3. UNDEVELOPED GEOTHERMAL FIELDS

Indonesia has an abundant amount of geothermal potential mainly due to its location at the junction of several tectonic plates. Its location produces volcanic arcs and tectonically active zones along many of the islands across the country. Sunda Arc, which is the subduction product between Indo-Australian plate and Eurasian plate, hosts geothermal systems from Sumatra to Java and then through to Nusa Tenggara (MacPherson & Hall, 2002; Varekamp et al., 1989). Modern volcanoes in the area were formed during the Quaternary period and have mainly generated basaltic andesite to andesite effusive and explosive products (Pacey et al., 2013). In contrast to the islands in the Sunda Arc, the regional area of Sulawesi Island was formed by interactions of three different plates, namely Eurasian, Indo-Australian, and Pacific plates (Hall, 2002; Hamilton, 1979; Katili, 1975; Nugraha et al., 2022). A unique K-shape feature in Sulawesi is the evidence of robust tectonics and volcanics activity since the Miocene to Late Pliocene (Katili, 1978).

This study applied the new resource assessment framework to five undeveloped geothermal fields namely Ciremai and Papandayan (Java); Maritaing (Nusa Tenggara); and Massepe and Kotamobagu (Sulawesi) (Figure 1~~Figure 1~~). The sections below discuss the newly developed numerical and 3D geological model for each geothermal field. Data from Geological Agency of Indonesia, the Directorate-General of New Renewable Energy and Energy Conservation (EBTKE) and previous publicly available research were used to support this paper.

3.1 Ciremai

The Ciremai geothermal field, located in West Java, Indonesia, is a volcanic-type geothermal system with promising potential for energy development. Situated around the prominent stratovolcano Mount Ciremai, the field covers an area of approximately 38,560 hectares, making it a possible target for Indonesia's geothermal development strategy. The geological setting of Ciremai is characterized by a complex stratigraphy that includes the Cinambo Formation, Halang Formation, Ciherang Formation, and various volcanic deposits dating from the Tertiary to Quaternary periods (Djuri, 2011; Silitonga et al., 1996). The area is dominated by the northwest-southeast trending fault system, which serves as the primary conduit for geothermal fluids (Sukaesih et al., 2021) (see Figure 2~~Figure 2~~). Notable geothermal manifestations include the Cilengkrang, Sangkanhurip, and Ciniru hot springs, which provide surface evidence of the geothermal activity beneath the surface.

The hydrogeology of the Ciremai geothermal field involves a complex interaction between volcanic aquifers, fracture zones, and recharge areas. The system is influenced by two primary flow mechanisms: a porous media system and a fracture-driven volcanic aquifer system resulting in a relatively low water table. Recharge occurs in the highlands, discharging at lower elevations (250-650 meters above sea level) through numerous springs (Irawan & Puradimaja, 2006). This hydrogeological framework is vital for understanding the geothermal system and is integral to developing accurate conceptual and numerical models (Irawan et al., 2009).

3.2 Kotamobagu

The Kotamobagu geothermal field is located in North Sulawesi, Indonesia, approximately 200 km southwest of Manado City. This geothermal site, situated within the Minahasa region, is known for its significant potential as a geothermal energy resource. The field is characterized by a complex geological setting, with stratigraphy including sedimentary rocks of the Tinombo Formation, Bilungala Volcanics, Tapadaka Formation, and Pinogu Volcanic deposits. Recent volcanic deposits from the Ambang Volcanics also play a crucial role in the geothermal system (Apandi & Bachri, 1997) (see Figure 3~~Figure 3~~). The field features geological formations from the Eocene to the Holocene, reflecting a dynamic volcanic and tectonic history shaped by regional geological processes.

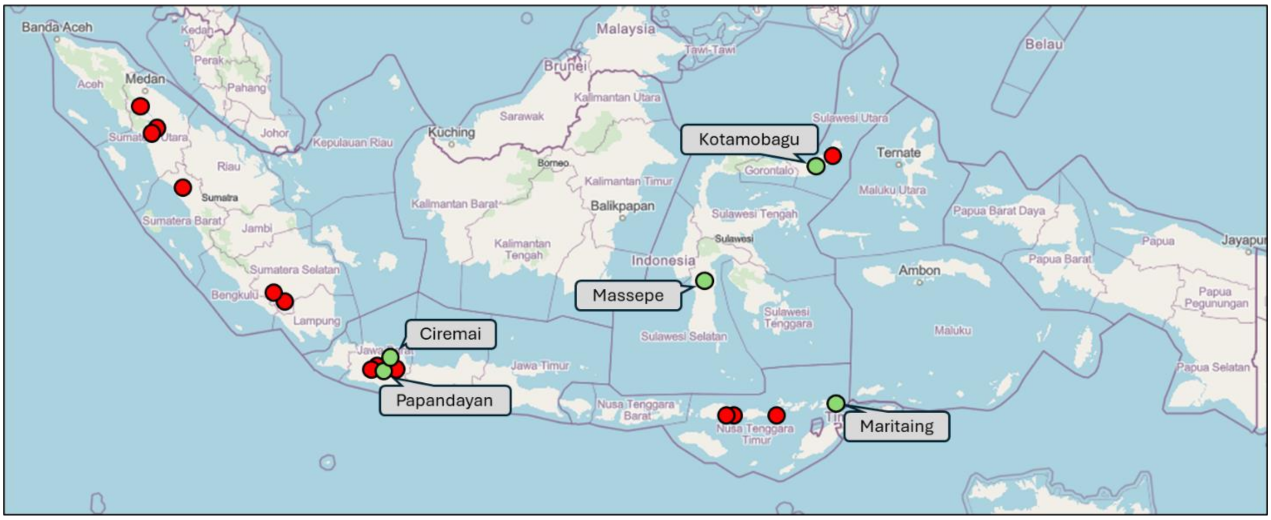

Figure 1: Exploitation stage geothermal fields (red) and five undeveloped geothermal fields (green).

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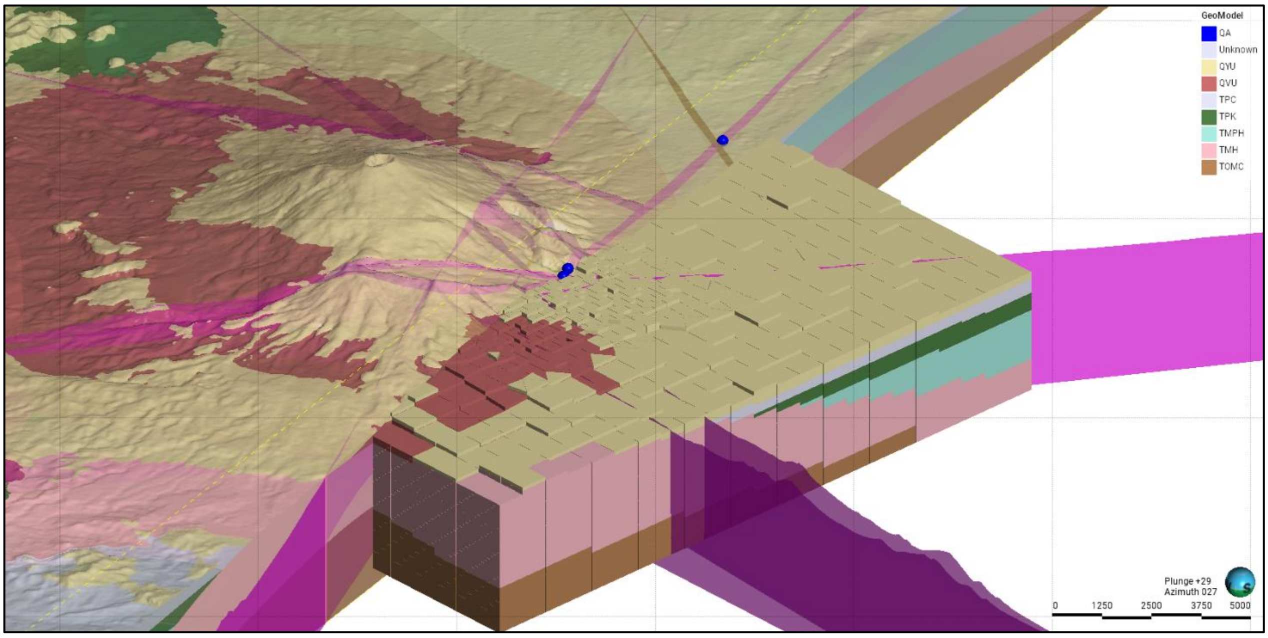

Figure 2: Ciremai geological model alongside the numerical model. Magenta planes represent NE-SW and NW-SE faults. Blue dots represent alkali chloride surface manifestations.

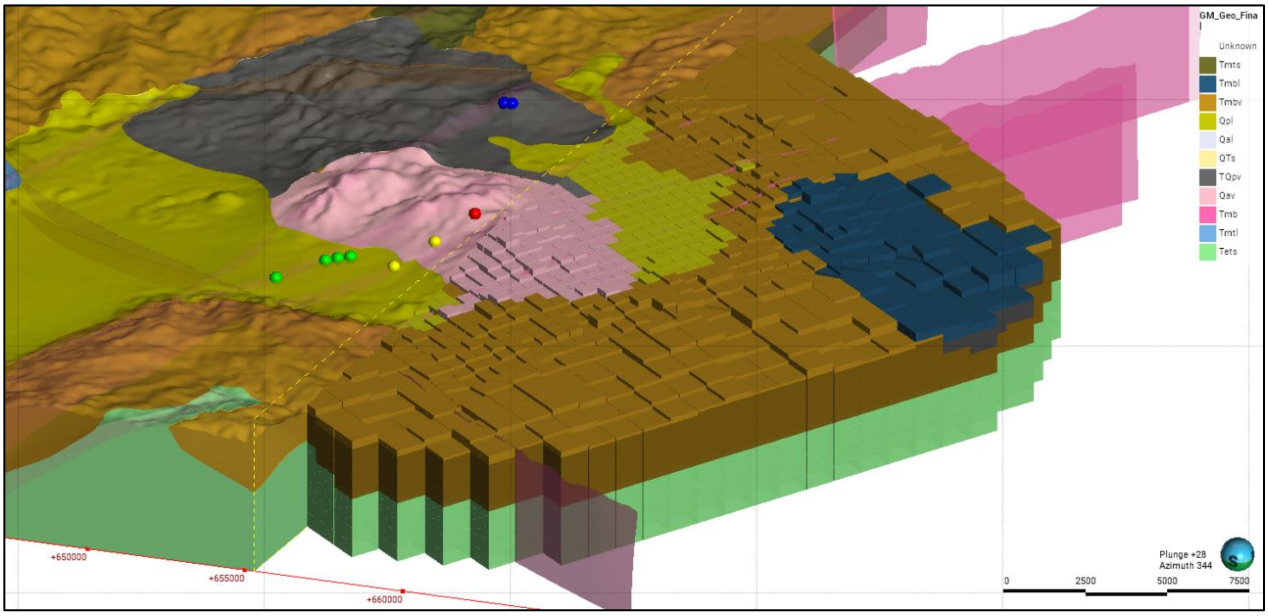

Figure 3: Kotamobagu geological model alongside the numerical model. Magenta planes represent NE-SW and NW-SE faults. Coloured dots represent survey manifestations such as acid sulphate (red), sulphate-chloride (yellow), and bicarbonate (green), and alkali chloride (blue).

A previous conceptual model has been made and geochemical surveys have identified key features of the Kotamobagu geothermal system (Riogilang et al., 2011b, 2011a; Riogilang, Itoi, & Taguchi, 2012; Riogilang, Itoi, Tanaka, et al., 2012). The presence of fumaroles and hot springs around the Mt. Muayat area indicates an active, liquid-dominated reservoir with temperatures ranging from 230°C to 320°C (Riogilang et al., 2013). The system is influenced by NE-SW and NW-SE trending fault lines, which serve as pathways for geothermal fluids and control the distribution of manifestations across the field. These fault structures are critical for understanding the geothermal fluid flows and potential resource area within the Kotamobagu site.

3.3 Maritaing

The Maritaing Geothermal Field, situated on Alor Island in East Nusa Tenggara province, Indonesia, has a modest geothermal potential. The field is located approximately 800 km from the Ulumbu field and about 700 km from Maritaing. The area encompasses 3 km² and is characterized by a reservoir temperature estimated at 170-200°C as indicated by Na-K geothermometer analyses of water from a partial-equilibrium Kura hot spring (Setiawan et al., 2015). Preliminary studies have focused on its geological, geophysical, and geochemical properties. The geological composition mainly includes volcanic and sedimentary rocks such as andesite lava, pyroclastic flows, conglomerates, and limestone. These formations are part of the Alor formation, which consists of various lava layers and breccia layers interspersed with tuff.

The geological structure of the Maritaing field features prominent NW-SE and NE-SW trending faults, forming the Maritaing depression and acting as fluid controls for the Kura hot springs (Supriyadi et al., 2015). Faults in this region are crucial for controlling the geothermal system's dynamics, as they facilitate the movement of fluids and recharge in the reservoir. A recent gravity survey shows high amplitude values in the complete Bouguer anomaly signal, suggesting the presence of andesitic lava rocks (Boling et al., 2024). The magnetotelluric (AMT and TDEM) surveys have revealed low-resistance zones (<10 Ohm.m) indicative of altered rock formations acting as a caprock (Rahadinata et al., 2017).

A previous conceptual model (Setiawan et al., 2015) proposed that the geothermal system is linked to young magmatic activity, with meteoric water infiltrating the Maritaing Depression and heating up due to residual magmatic heat. This results in a convective hydrothermal system, with hot fluids emerging at the surface as hot springs. In this study a new 3D geological model was developed to give a better understanding of the system (Aloanis, 2024) (see Figure 4~~Figure 4~~).

3.4 Massepe

The Massepe Geothermal Field, located in South Sulawesi, Indonesia, presents a promising potential for the development of geothermal energy. Geographically situated within the Sidenreng Rappang Regency and approximately 194 km from Makassar City, the Massepe field is characterized by diverse geological formations and notable geothermal activity. The region consists of volcanic, intrusive, and sedimentary rocks dating from the Tertiary to Quaternary periods (Sukamto, 2012). Key stratigraphic units include the Soppeng, Camba, Walanae, Parepare formations, and more recent alluvial deposits (Risdianto et al., 2008). Notably, the geological structure is dominated by the north-south trending Massepe fault, which acts as the primary conduit for geothermal fluids and plays a crucial role in the hydrothermal system. The hydrogeology of the area includes recharge zones in the hilly regions where meteoric water infiltrates and interacts with deep-seated geothermal fluids, leading to surface manifestations such as the Pajalele and Alakuang hot springs (Risdianto & Soetoyo, 2008) (see Figure 5~~Figure 5~~).

The geophysical surveys provide detailed subsurface features. The Bouguer anomaly resulted from the gravity survey show low-mid-high values, which are associated with altered and less dense volcanic rock, sedimentary rocks, and shallow andesitic intrusions rocks, respectively (Risdianto & Soetoyo, 2008). The resistivity anomalies confirm the geological structures, particularly at the north-south Massepe Fault, which contribute to the emergence of hot springs at Pajalele and Alakuang. The low resistivity anomaly (<20 Ωm) appears to be the upflow zone of the system, while the values between 20-60 Ωm, thought to be the reservoir zone, are clustered around the Pajelele hot spring, and extend towards the Alakuang and Warede hot springs (Joni et al., 2019).

3.5 Papandayan

The Papandayan geothermal field, located in West Java, Indonesia, offers potential for the development of geothermal energy. Mount Papandayan, a prominent stratovolcano, rises from 1,100 to 2,665 meters above sea level and is situated between Bandung and Garut District. The site has been studied since the early 2000s, with investigations focusing on lithology mapping, geological structures, ground deformation, alteration, and fluid analysis from thermal features, which include solfataras, fumaroles, mud pools, and hot springs (Alzwar et al., 1992; Byrdina et al., 2018; Mazot et al., 2008; Nasution et al., 2008; Z. Abidin et al., 2003). The field's geological framework comprises several rock formations, ranging from Quaternary Holocene volcanic deposits to Tertiary Miocene formations such as the Bentang and Jampang formations. These formations are linked to ongoing volcanic activity, which provides a heat source that elevates the temperature of permeable rocks, creating geothermal reservoirs (see Figure 6~~Figure 6~~).

A key feature of the Papandayan geothermal system is its complex fault structure, which significantly influences fluid flow and geothermal activity. The fault system in the area includes NE-SW and NW-SE trending faults that create pathways for geothermal fluids, impacting the distribution and intensity of thermal features (Sulastri et al., 2014). The presence of a clay cap dome below the area with many acidic thermal features, particularly in the Mas Crater, presents a challenge, as it is not feasible for drilling.

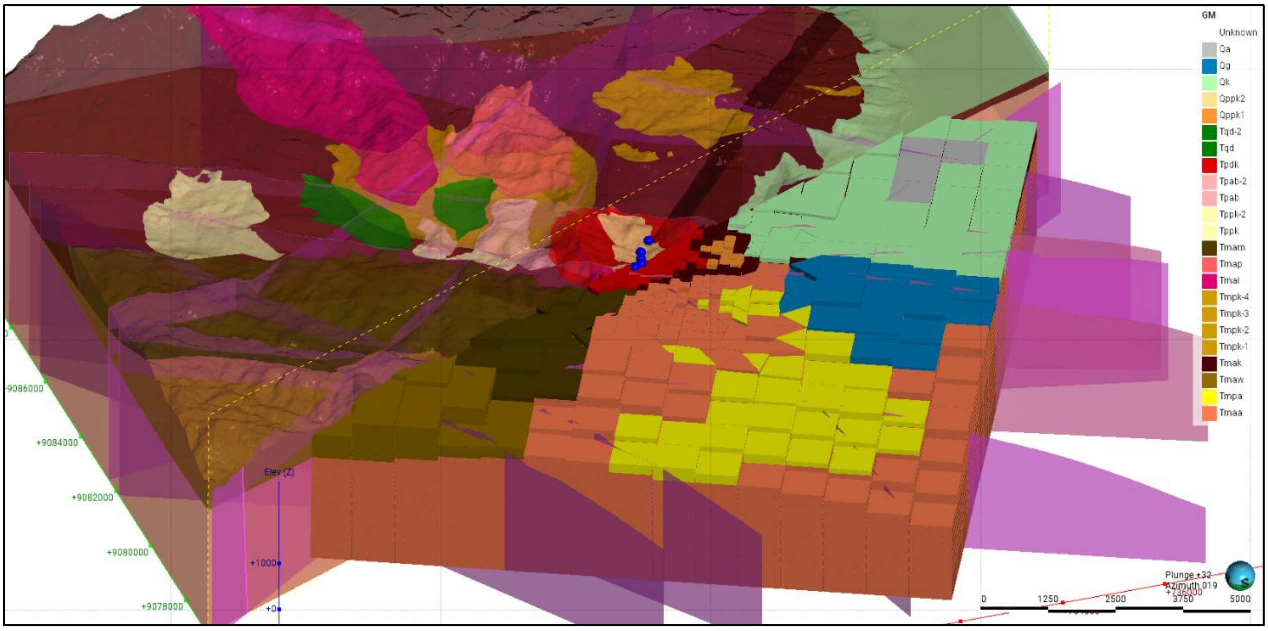

Figure 4: Maritaing geological model alongside the numerical model. Magenta planes represent NW-SE and NE-SW faults. Blue dots represent alkali chloride surface manifestations.

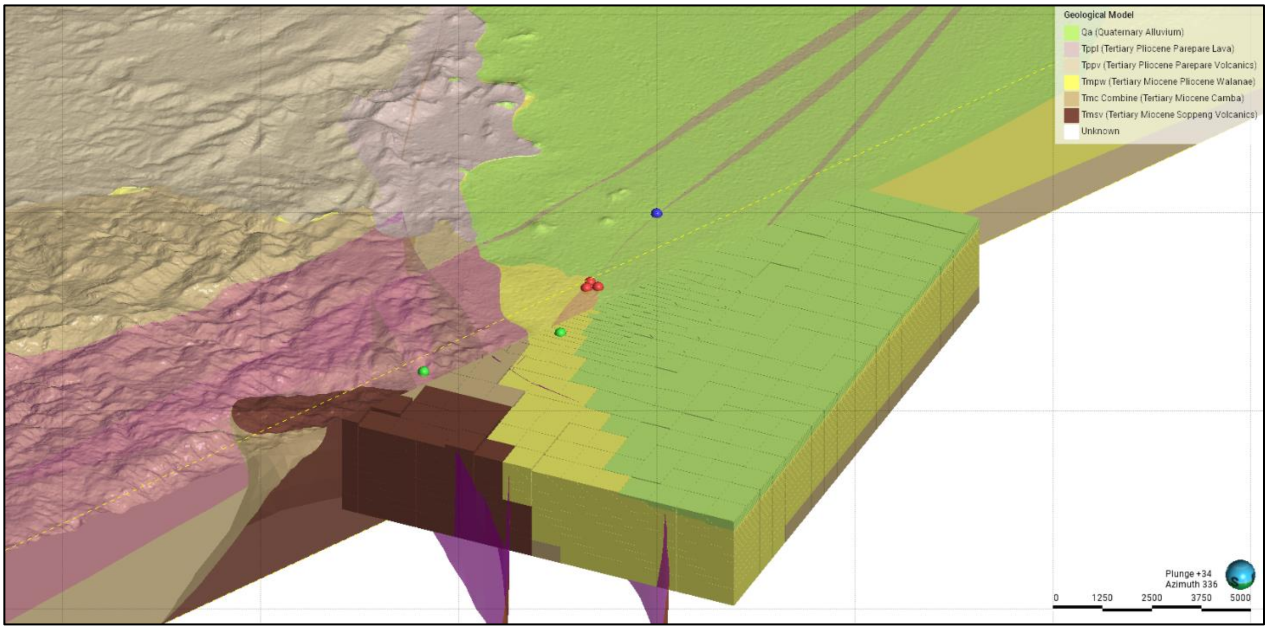

Figure 5: Massepe geological model alongside the numerical model. Magenta planes represent the N-S faults. Coloured dots represent survey manifestations such as bicarbonate sulphate (red), bicarbonate (green), and alkali chloride (blue).

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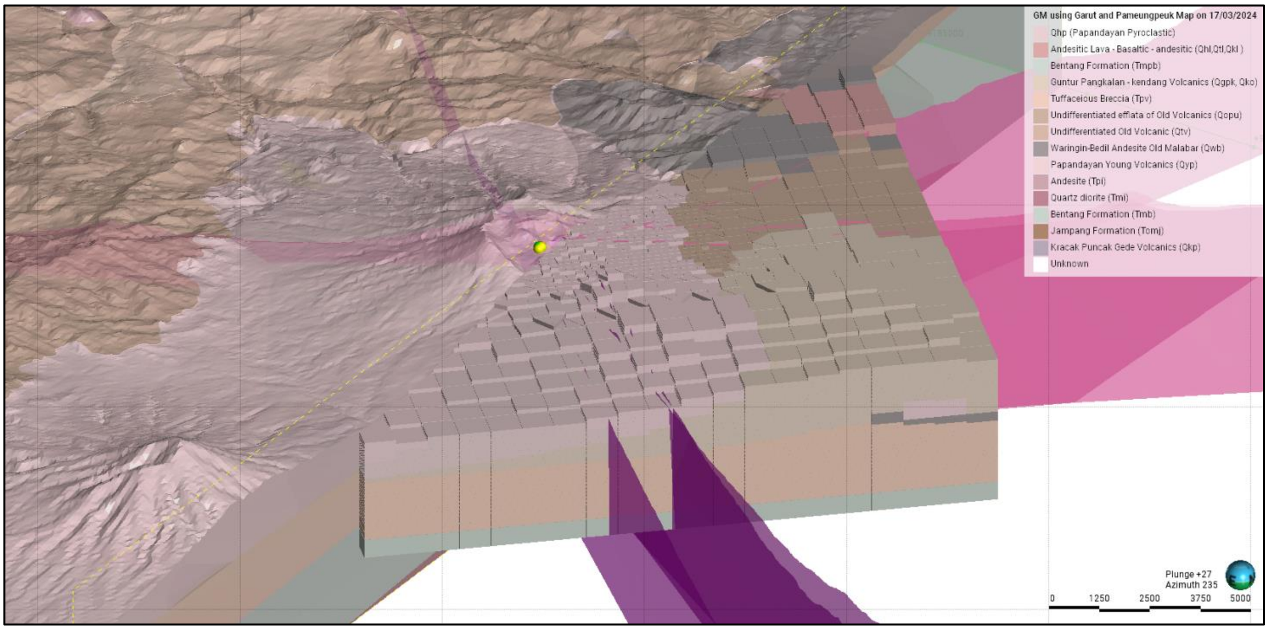

Figure 6: Papandayan geological model alongside the numerical model. Magenta planes represent NW-SE and NE-SW faults. Yellow dots represent acid sulphate manifestations.

4. RESOURCE ASSESSMENT RESULTS

The resource estimates were made using the method outlined in Section 2 with the calibrated natural state model of each geothermal field as the initial input. Key parameters such as rock permeabilities, porosities and heat upflows were sampled from distributions to establish realistic parameter ranges for developing an ensemble of sample models. Note that these distributions could also be constrained by any available laboratory analysis data. Each sample model was then run to achieve a steady state before undergoing the filtering process. The models that successfully converged to a steady state were conditioned based on their temperature distribution at the base of the clay cap. These selection criteria required models to reach temperature between 180-200℃ beneath the alteration zone, indicating an accurate representation of the geothermal conditions during the formation of the clay cap.

The accepted models were subsequently used to estimate the maximum power output using the production scenario algorithm outlined in Section 2. By combining the predictions from the thousands of sample models, the uncertainty range of the power output can be quantified and expressed probabilistically using P10, P50, and P90 estimates.

A 25-year production scenario was applied to each of the five undeveloped geothermal fields in this study (Alia, 2024; Aloanis, 2024; Fuad, 2024; Nagoro & O'Sullivan, 2023; Rahmansyah, 2024). All scenarios used a binary power plant setting and assumed a conversion efficiency of 15% from net thermal power output to electrical power output. This conversion efficiency is only used in the post-processing of the results and thus it can be easily changed when more information is available.

Stored heat calculation from published sources by EBTKE (Direktorat Panas Bumi, 2017), The Geological Agency (Badan Geologi, 2019), and Rahmansyah (2024) are also presented in this study as direct comparison with the result obtained from numerical methods. The stored heat calculation estimates the total thermal energy output and accounts for the recovery factor, conversion efficiency, and parasitic load (Zarrouk & Simiyu, 2013). Depending on the field, values in the range of 10-20% can be used for the recovery factor and conversion efficiency. Monte Carlo simulation is typically used to quantify the uncertainty for parameters including reservoir size, average reservoir temperature, and porosity. This allows P10, P50, and P90 estimates to be made using the stored heat method. Table 1Table 1 presents the resource estimation results using both approaches for each of the geothermal fields studied.

The results in Table 1 show that the stored heat method yields higher resource estimates than the numerical model approach for the fields considered in this study. However, the stored heat estimates are subject to important limitations, primarily due to their high sensitivity to key input parameters and simplifying assumptions. The stored heat method neglects the importance of the heterogeneity typical of geothermal systems by using an average temperature to represent the entire reservoir. Numerical reservoir models can capture reservoir heterogeneity. The stored heat method also assumes simplified reservoir geometries and ignores reservoir physics, which further bias thermal energy estimates. Importantly, the recovery factory parameter used in stored heat calculations is very uncertain and cannot reflect the complexities of producing from different geothermal systems.

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Table 1: Result of the resource assessment using a traditional stored heat approach and the numerical modelling framework applied to five undeveloped geothermal fields. The stored heat calculations were carried out by EBTKE (Direktorat Panas Bumi, 2017) [1], Rahmansyah (2024) [2], and The Geological Agency (Badan Geologi, 2019) [3].

Geothermal Field	Stored Heat Estimate (MWe)			Numerical Modelling Estimate (MWe)		
	P90	P50	P10	P90	P50	P10
Ciremai[1]		150		28.6	37.5	55.1
Kotamobagu[1]		225		70	160	270
Maritaing[1]		17		10.2	16.7	22.9
Massepe[2]	24.4	39.4	55.4	25.8	34.5	43.4
Papandayan[3]	16	21	26	12.3	18.5	28.4

Our numerical modelling approach presented in this work provided robust estimates of the potential power output for each geothermal field, as the methodology accounts for reservoir and wellbore physics and fluid flow dynamics. The approach also allows additional insights into the nature of the geothermal resource. For example, it was found that accurately modelling the water table level was critical for the Ciremai system. The initial numerical resource assessment yielded a very low power estimate due to the system having a very deep water table. The deep water table strongly affects the reservoir pressure in the system and the ability of geothermal wells to flow without pumping. Our research indicated that it was unlikely for conventional wells to self-discharge at the Ciremai system. Thus, a scenario involving drilling highly-deviated wells from lower elevations was considered. Development scenarios such as this can only be considered using numerical reservoir modelling techniques. The stored heat calculation for Ciremai can only account for the low reservoir pressure crudely through the recovery factor and most likely overestimated the resource potential as a result.

For Kotamobagu the results are quite similar with our numerical modelling approach estimating a lower resource potential. For this system the MT data and their interpretation are quite uncertain and as a result our interpretation of the target reservoir was slightly smaller than the resistivity boundary used in the stored heat calculation. The target reservoir zone could be expanded once more geoscientific data or exploration drilling more clearly identify its extent.

Additionally, models of Maritaing, Massepe, and Papandayan also yield slightly lower resource estimations (P50). MT data are available and are reasonably comprehensive due to recent survey by Geological Agency and EBTKE, thus giving confidence in the alteration model for each system. However, these systems are highly influenced by fault structures and the analysis of the fault network is pivotal to describing the fluid flow dynamics, which can be done by implementing the numerical modelling framework.

5. CONCLUSION

This study presents five case studies demonstrating a new framework for assessing the resource potential of geothermal systems. This framework uses early-stage exploration data to constrain numerical reservoir models and estimate the potential power output of the geothermal system. This approach can provide a more realistic estimate of geothermal resource potential than traditional methods, such as stored heat calculations, as it can represent the complex reservoir dynamics that affect how much energy can be extracted.

For each system, a new 3D geological model was constructed using publicly available data and data from the Geological Agency (GA) and the Directorate-General of New Renewable Energy and Energy Conservation (EBTKE). These 3D models provide a better conceptual understanding of each system and allow critical geological structures and features to be visualized and included in the models. Subsequently, numerical models compatible with AUTOUGH2 and Waiwera were developed representing key aspects of the geothermal system, such as temperature distribution, heat transfer, and fluid flow.

The methodology then uses the calibrated models to generate an ensemble of sample models from sets of reasonable parameters, thereby representing the uncertainties inherent at the exploration stage. Our method is also adaptable, enabling refinement of production strategies as additional data becomes available and allowing for seamless updates when geological models are revised. The production algorithm calculates realistic maximum energy extraction scenarios using wellbore modelling and takes into account all thermodynamic conditions for each of the thousands of sample models and can also be adjusted to suit specific project criteria.

The case studies presented show that our novel approach can be used to estimate the early resource potential of geothermal systems with diverse geological settings and thermodynamic conditions. They have also highlighted some typical flaws in estimates made using the stored heat method. It provides valuable insights and captures a range of potential scenarios for developing the geothermal reservoir (as demonstrated in the Ciremai case). The method can be implemented using only publicly available data (see Kotamobagu) though the availability of comprehensive exploration data, including geoscience and exploration well data, is preferable, as it enhances the accuracy of the conceptual model and provides more data to constrain the numerical reservoir models.

By working with the Geological Agency (GA) and the Directorate-General of New Renewable Energy and Energy Conservation (EBTKE) to combine high quality geoscientific surveys and exploration data with our robust numerical modelling approach we hope this framework can help to address some of the challenges in estimating the capacity of geothermal resources during early exploration, and contribute to the broader goals set by the Indonesian government for expanding geothermal energy production.

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