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Geothermal Resource Evaluation employing Surface Geoscience Data: A Detailed Study of Kiejo-Mbaka Geothermal Area, South-Western Tanzania.

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ABSTRACT

The assessment of geothermal prospects is increasingly drawing attention within the geothermal energy sector, primarily to instill confidence in stakeholders and guide investment decisions during exploration and development. However, significant uncertainties persist across all stages of exploration ranging from surface assessments to deep drilling creating challenges in accurately estimating a site's geothermal power potential. These uncertainties often hinder effective resource allocation and strategic planning. To mitigate these challenges, stochastic approaches, particularly Monte Carlo Simulation, have emerged as valuable tools. Monte Carlo Simulation enables probabilistic evaluation of geothermal power potential by considering a range of variable input parameters, providing a systematic framework for decision-making despite limited data availability. This method is especially critical during early-stages of exploration, where uncertainties are most pronounced.

This study introduces the Monte Carlo Simulation approach, and volumetric analysis and showcases their application to the Kiejo-Mbaka geothermal field, based on surface exploration data. The results demonstrate the utility of stochastic techniques in overcoming initial data constraints and generating actionable insights into geothermal potential. The findings aim to enhance stakeholder confidence, optimize decision-making processes, and promote informed investment in geothermal energy resources.

1 INTRODUCTION

In geothermal exploration, the discovery of a viable geothermal prospect presents a pivotal milestone, fostering a sense of optimism among stakeholders regarding the untapped potential of the resource(Biswas, Kundu, and Poddar 2024). Upon achieving this critical milestone, there is often an immediate drive to evaluate the power-generating potential of the identified resource. This inquiry typically arises following the conclusion of surface geo-scientific investigations or and successful exploratory drilling activities. Early-stage power potential assessments are not merely a procedural step but an essential aspect of fostering confidence among project developers, investors, and other key stakeholders. Such assessments play a crucial role in securing the financial and technical resources needed for advancing subsequent phases of geothermal development (Ciriaco, Zarrouk, and Zakeri 2020; Witter, Trainor-Guitton, and Siler 2019; Izadi and Freitag 2025).

However, the early stages of geothermal exploration are inherently marked by significant uncertainties, largely due to the limited availability and quality of subsurface data(Witter, Trainor-Guitton, and Siler 2019). These uncertainties present considerable challenges, as they complicate the accurate estimation of geothermal resource potential and, by extension, the feasibility of commercial energy generation. In this context, conventional methods often fall short of providing the nuanced insights required for informed decision-making, thus necessitating the adoption of advanced analytical frameworks(Witter, Trainor-Guitton, and Siler 2014).

To address these inherent uncertainties, different methods are applied in potential assessment of geothermal power potential at a place. Some of the techniques reported by researchers are presented in Table 1. Monte Carlo (Athens and Caers 2019), a probabilistic risk analysis methods have emerged as indispensable tools and applied in different fields such as Dholera Geothermal Field, India(Shah, Vaidya, and Sircar 2018); Olkaria I Geothermal Field, Kenya (Axelsson et al. 2013) etc. These methodologies facilitate a more robust evaluation of geothermal reservoirs by accounting for the variability and range of input parameters. Specifically, the Monte Carlo approach enable researchers to estimate not only the magnitude of stored heat reserves but also the probable distribution of these reserves, offering a comprehensive probabilistic perspective. Such insights are critical for understanding the exploitable energy base, particularly in the context of newly identified geothermal fields where empirical data may be sparse or incomplete. The integration of Monte Carlo modeling into geothermal resource assessments offers multiple advantages. It not only mitigates the limitations imposed by data scarcity but also provides a systematic basis for evaluating resource uncertainty. This approach equips

stakeholders with actionable intelligence, enabling them to make strategic decisions regarding resource allocation, infrastructure development, and long-term project viability. Additionally, the probabilistic nature of these methods aligns well with the strategic goals of investors and policymakers, as it allows for a transparent and quantifiable assessment of both opportunities and risks(Athens and Caers 2019). Advances in computational technologies have further expanded the scope and precision of geothermal resource assessments. Numerical simulations have become an integral component of the evaluation process, enabling the development of more detailed and dynamic models of geothermal fields(Quinao and Zarrouk 2018). Additionally, methodologies such as Design of Experiments (DE) and Response Surface Methodology (RSM) have been applied in probabilistic assessments to streamline the evaluation process. These techniques allow for more efficient exploration of parameter space and faster convergence to optimal solutions(Pratama and Supijo 2020).

The aim of this study is to apply monte Carlo simulation and volumetric methods to estimate the power potential at Kiejo-Mbaka. The application of stochastic modeling and probabilistic analysis represents a paradigm shift in geothermal exploration, bridging the gap between limited data availability and the need for precise resource assessments. By leveraging these methodologies, stakeholders can confidently navigate the complexities of early-stage geothermal projects, paving the way for sustainable energy solutions and informed investment strategies.

TABLE 1. Summarizing the geothermal resource assessment methods, their focus, details, examples and recommended stage.

SNO	Type of Method	Focus	Details	Recommended stage	Examples
1	Surface Thermal Flux	Heat flow measurement	Estimates geothermal potential by analyzing heat transfer through conduction and convection at the Earth's surface.	Preliminary exploration stage.	Olkaria Geothermal Field, Kenya(Nyakundi 2022).
2	Magmatic Heat Budget	Heat stored in magmatic reservoirs	Evaluates the size and age of magmatic reservoirs and calculates heat transfer to surrounding rocks.	Early exploration stage.	Taupo Volcanic Zone, New Zealand(Rowland and Simmons 2012).
3	Volumetric Method	Stored heat capacity	Calculates the heat stored in the reservoir using temperature and rock properties.	Exploration and resource estimation stage.	Krafla Geothermal Field, Iceland(Halldórsdóttir et al. 2010).
4	Numerical Modeling	Reservoir behavior simulation	Simulates reservoir dynamics to predict energy extraction scenarios, incorporating uncertainty quantification.	Development and production stage.	Waiwera Geothermal System, New Zealand(Kühn and Stöfen 2005).

SNO	Type of Method	Focus	Details	Recommended stage	Examples
5	Decline Curve Analysis	Production potential forecasting	Uses historical production data to forecast future output trends.	Production and operational stage.	Cerro Prieto Geothermal Field, Mexico(González-García et al. 2021).
6	Total Well Flow Assessment	Resource size estimation	Analyses the output of drilled wells to estimate the size of the geothermal resource.	Post-drilling and production stage.	Olkaria Geothermal Field, Kenya(Waweru 2019).
7	Lumped Parameter Modeling	Simplified reservoir dynamics	Models reservoir behavior using simplified equations for resource estimation.	Resource estimation and development stage.	Hengill Geothermal Area, Iceland(Axelsson et al. 2015).
8	Power Density/Areal Estimates	Geothermal capacity approximation	Estimates geothermal capacity based on surface area and power density.	Exploration and resource estimation stage.	The Geysers Geothermal Field, USA(Yadav, Sircar, and Shah 2024).
9	Planar Fracture Method	Heat transfer through fractures	Assesses heat transfer efficiency through subsurface fractures.	Exploration and development stage.	Soultz-sous-Forêts Geothermal Field, France(Tenzer et al. 2010).
10	AI and Machine Learning	Enhanced resource assessment accuracy	Applies advanced computational techniques to improve the precision of geothermal resource evaluations.	Exploration and development stage.	Indonesian Geothermal Exploration Projects(AlGaiar et al. 2024).

2 GEOLOGICAL SETTING OF KIEJO-MBAKA GEOTHERMAL PROSPECT

Kiejo-Mbaka geothermal prospect is situated within tectonic framework and located in southwestern Tanzania between Lake Nyasa and Mbeya town(Kajugus 2021). This area forms part of the northernmost sub-basin of the Nyasa Rift, uniquely positioned at the triple junction of the East African Rift System(Rizzello et al. 2022). The geological setting at Kiejo-Mbaka is influenced by major fault structures, notably the Mbaka intra-basin fault and the Livingstone border fault (Pasqua 2019). These faults exhibit significant permeability, facilitating the ascent of deep-seated hot water along the Mbaka fault. Both structures are seismically active and deeply rooted, with the Mbaka fault being particularly permeable, allowing hot water to migrate from the floor of the approximately 5-kilometer-deep rift basin. This phenomenon is evidenced by the presence of several hot springs emanating along the Mbaka fault such as Kilambo and Kajala(Pasqua, Chiozzi, and Verdoya 2023).

The Kiejo-Mbaka area also lies within the Rungwe Volcanic Province (RVP), a region of substantial geothermal and magmatic activity. Kiejo is the third-largest volcano in the RVP, following Ngozi and Rungwe, and is predominantly composed of lava flows with diverse compositions ranging from alkali basalt, basanite, and tephrite to phonolitic trachyte and trachyandesite(Pasqua, Chiozzi, and Verdoya 2023). Volcanism in the RVP

began during the Miocene epoch and has persisted into contemporary times, with the most recent eruption at Kiejo occurring approximately 190 years ago(Crabtree and Chesworth 1992). This sustained magmatic activity underscores the region's geothermal energy potential and its relevance for exploration.

Given the significant geothermal energy potential within the Kiejo-Mbaka area, there is a pressing need for comprehensive resource assessment. Such evaluations are vital for informed decision-making and strategic planning prior to extensive investments in geothermal development. Accurate resource assessment is particularly critical in regions where geological complexities and data limitations pose challenges to reliable predictions. By addressing these uncertainties through robust methodologies, stakeholders can better understand the potential of geothermal systems, thereby fostering sustainable resource utilization and advancing Tanzania's energy landscape.

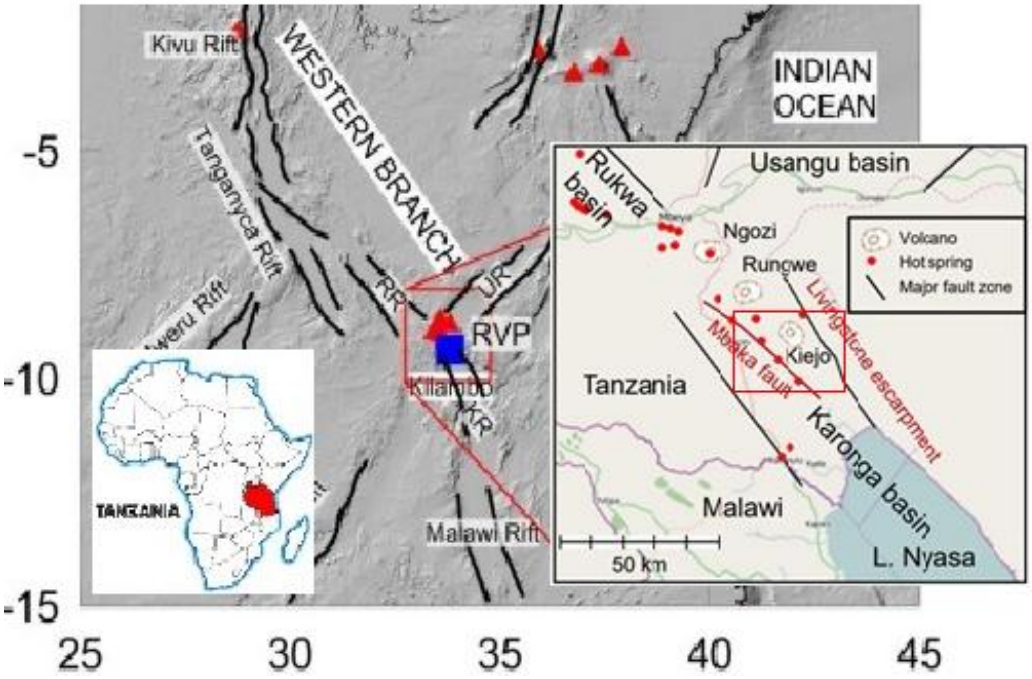


Figure 1: Map showing Kiejo-Mbaka geothermal prospect, area, Tanzania. Modified from Fact sheet for geothermal development to promote Public Private Partnerships in East Africa

3 METHODOLOGY

The evaluation of geothermal resources constitutes a foundational step in geothermal energy projects, serving as a critical determinant of resource viability. This step lays the groundwork for all subsequent project phases, including strategic decision-making, financial planning, development activities, and eventual operational management. A robust and systematic methodology is therefore essential to ensure accurate assessments that can guide both technical and economic feasibility studies.

In this study, the geothermal potential of the Kiejo-Mbaka prospect is assessed through an integrated approach combining the volumetric method and Monte Carlo simulation. These methodologies were selected for their complementary strengths in handling data limitations and uncertainties typically encountered during the early stages of geothermal exploration.

3.1 Volumetric Method

The volumetric method, a widely used approach in geothermal resource assessment, serves as the foundation for estimating the stored heat within a geothermal reservoir. This method relies on a conceptual model of the reservoir, incorporating key geological, geophysical, and geochemical parameters. These parameters include reservoir volume, temperature distribution, rock properties, and recovery factors, all of which are used to estimate the total thermal energy stored in the subsurface. While the volumetric method provides a structured framework for initial assessments, it is inherently deterministic, meaning that its outputs are sensitive to uncertainties in the input data. This limitation necessitates the integration of probabilistic techniques to capture the full range of possible outcomes. The volumetric method is given in equation 1.

$$Q_h = \rho_r C_r (1-\varphi) V (T_r - T_s) + \rho_w C_w (T_r - T_s) \quad \text{.....eqn (1)}$$

In this formula;

Q_h (J) represents the total geothermal energy stored in the reservoir, encompassing both rock and fluid.

ρ_r and ρ_w denote the densities of rock and geothermal fluid, respectively.

C_r and C_w ($J \cdot m^{-3} \cdot °C^{-1}$) signify the specific heat capacities of rock and fluid.

ϕ (%) is the porosity of the reservoir rock.

V (m^3) represents the reservoir volume.

T_r(°C) and T_s (°C) correspond to the reservoir temperature and the average surface temperature, respectively.

This equation provides a quantitative framework for estimating the stored geothermal energy, serving as a baseline for subsequent probabilistic evaluations. The integration of Monte Carlo simulation and this technique ensures that resource estimates are both robust and representative of the inherent uncertainties in geothermal systems

3.2 Monte Carlo Simulation

To address the uncertainties inherent in the volumetric method, Monte Carlo simulation is employed as a probabilistic modeling tool. This stochastic approach allows for the incorporation of variability and uncertainty in the input parameters, enabling the generation of a probability distribution for the estimated geothermal potential. By iteratively sampling input parameters within predefined ranges, the Monte Carlo simulation produces a range of possible outcomes, providing a probabilistic evaluation of the geothermal resource. This approach not only enhances the reliability of the assessment but also offers stakeholders a transparent understanding of the associated risks and potential returns.

The reservoir volume approach, augmented by advanced probabilistic and numerical methods, can be mathematically represented as follows;

Key Steps in Monte Carlo Simulation;

Develop a deterministic parametric model, expressed as $Y = f(x1, x2, \ldots . xq)$.....eqn (2)

Generate a set of random variables $\left(x_{i1}, x_{i2}, \ldots . x_{iq}\right)$

Evaluate the model for each set of inputs and record the outputs as y_i

Repeat steps 2 and 3 for i, iterating from 1 to n

Analyze the output dataset using tools such as histograms, summary statistics, and confidence intervals to interpret the results.

The integration of the volumetric method with Monte Carlo simulation is particularly advantageous for geothermal prospects such as Kiejo-Mbaka, where data availability is constrained during the early exploration phases. This combined methodology ensures that the assessment accounts for both the deterministic estimates of stored heat and the probabilistic uncertainties associated with input parameters, resulting in a more comprehensive evaluation of the geothermal potential. The assumed input parameters are indicated in Table 2.

3.3 Application to Kiejo-Mbaka Prospect

The methodology was applied to the Kiejo-Mbaka geothermal prospect, a site characterized by its complex geological and structural setting within the East African Rift System. Input parameters for the volumetric method were derived from available surface geological studies, geophysical surveys, and geochemical analyses conducted in the region. These parameters were then integrated into the Monte Carlo simulation framework to model the probabilistic distribution of geothermal potential. The combined approach enabled a detailed evaluation of the resource, accounting for both known data and inherent uncertainties. The combined data are presented in Table 2. Through this integrated methodology, the study aims to provide a robust assessment of the geothermal potential at Kiejo-Mbaka. The results are intended to support informed decision-making by stakeholders, including project developers, investors, and policymakers, thereby facilitating the advancement of geothermal energy development in the region.

TABLE 2: Probability distribution and the best estimates

Input	Units	Best guess	Probability distribution		
			Type	Min	Max
Surface Area	km2	10	Rectangular	7	13
Thickness	m	400	Triangular	300	500
Rock Density	kg/m3	2,500	Constant	N/A	N/A
Rock Spec. Heat	kJ/kg °C	1	Constant	N/A	N/A
Porosity	%	0.1	Triangular	0.1	0.1
Temperature	°C	135	Triangular	130	139
Base Temp.	°C	64	Constant	N/A	N/A
Fluid Density	kg/m3	985	Steam Table	N/A	N/A
Fluid Spec. Heat	kJ/kg °C	4.27	Steam Table	N/A	N/A
Recovery Factor	%	0.1	Triangular	0.1	0.2
Conversion Efficiency	%	0.1	Triangular	N/A	N/A
Plant Life	years	25	Triangular	20	30
Load Factor	%	95	Constant	N/A	N/A

3.4 Geothermal features data and other input variables

3.4.1 The features of geothermal fields

The geothermal activity along the Mbaka fault is exemplified by the Kilambo and Kajala hot springs, situated at elevations ranging from 646 to 1420 meters above sea level. These two spring systems, separated by a distance of just 600 meters, exhibit water flow rates of approximately 10 L/s and 5 L/s, respectively. The maximum outlet temperature recorded is 64 °C. Notably, significant travertine deposits can be observed, especially at the Kilambo site, alongside the presence of Fe (III) oxyhydroxides. Both locations are also characterized by notable emissions of gases.

Comprehensive geochemical analyses of spring water and gas were performed in tandem with geophysical and geological investigations. The undiluted reservoir liquid at the Kilambo-Kajala site in Kiejo-Mbaka was found to have a maximum discharge temperature of 64 °C. However, reservoir temperatures, inferred through silica-based and other geothermometric methods, are estimated to range between 135 and 150°C. Furthermore, the subsurface geothermal reservoir in the Kiejo-Mbaka area is believed to lie at an approximate depth of 1 km below sea level.

3.4.2 The features of geothermal fields

The findings presented at the 13th ITB International Geothermal Workshop (IIGW) 2024 by Kobare at al. (Kobare, Kashiwaya, and Koike 2025). showed that Kiejo-Mbaka geothermal prospect features with low to medium-temperature thermal waters. These waters were classified as Na-Ca-Mg-HCO_3 type due to mixing with shallow, cooler waters, with observed spring temperatures ranging from 18 to 64 °C. Classical geothermometers applied to the thermal waters indicated equilibrium with mineral phases such as chalcedony, quartz, chrysotile, and CO_2 gas, while anhydrite remained undersaturated. Minerals like aragonite, calcite, and dolomite showed oversaturation, which introduced uncertainties affecting geothermometric modeling, specifically the Na-K-Ca-Mg geothermometer. Despite these challenges, geothermometric modeling incorporating mineral equilibria yielded reliable reservoir temperature estimates for the Kiejo-Mbaka geothermal system at 135 ±20 °C. These

results align with previous geochemical studies of the area, providing a strong foundation for understanding the geothermal reservoir. Other properties are mentioned in Table 2.

4 RESULTS AND DISCUSSION

Results indicates that the power potential for Kiejo-Mbaka using the volumetric method is approximately 9.01 Mwe. On the other hand, Monte Carlo gives the estimate of 11.2MWe at a probability of 90% and 14.6MWe at a probability of 50% (Figure 2) indicating that the actual power output will fall within this range. The highest and lowest values obtained from the simulation are 30.1 MWe and 7.9MWe, respectively (Figure 3). The mean and median values are 15.1 MWe and 14.3 MWe, indicating a slightly skewed distribution. The standard deviation is 3.8 MWe, which gives us an idea of the spread of the data.

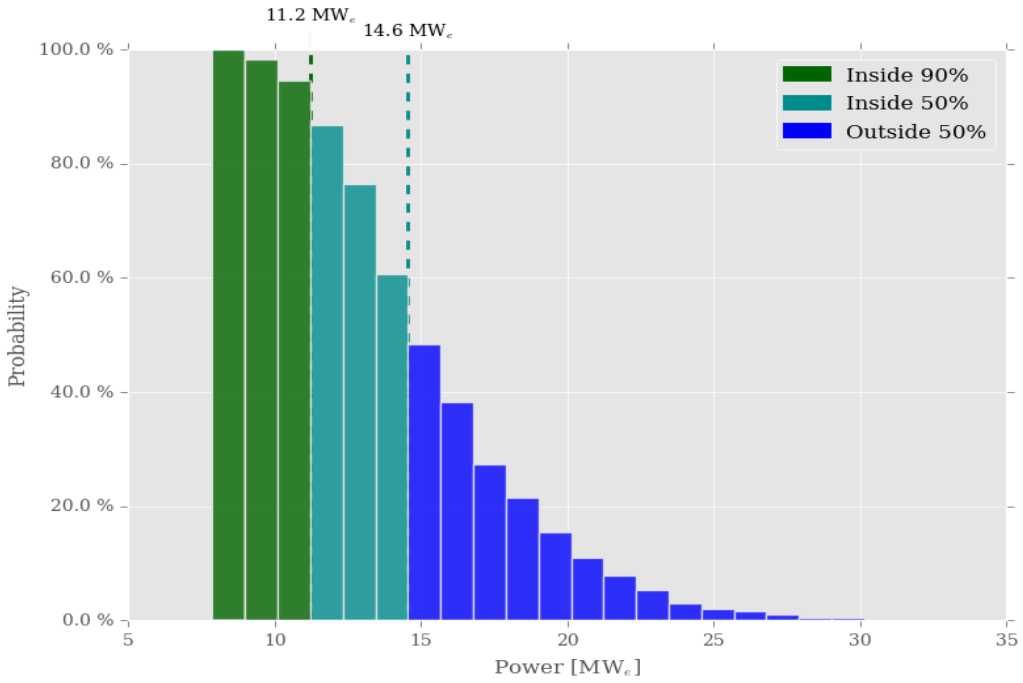


Figure 2: The estimation of the power potential in Kiejo-Mbaka with a probability of 90%, 50% and outside of 50%

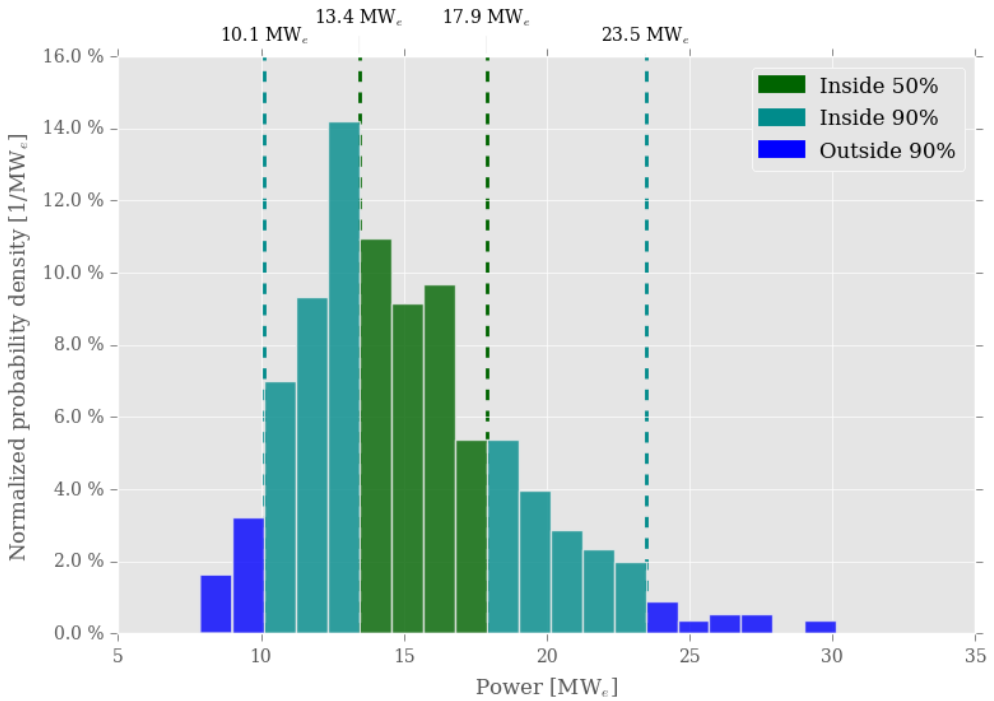


Figure 3: Estimations of the probability density of the power at Kiejo-Mbaka.

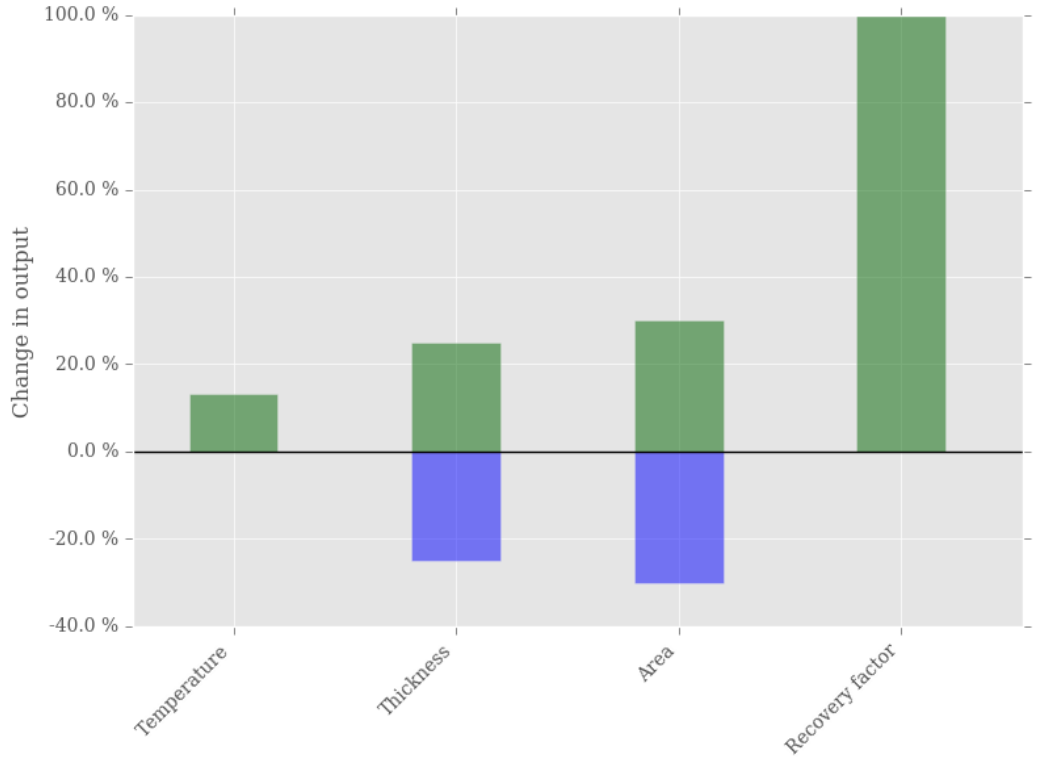


Figure 4: Sensitivity of the data during the analysis

The power potential using the volumetric method is approximately 9.01 MWe. On the other way the monte Carlo gives the following analysis. From the figure 2, it explains that the most likely value of the power with a 90% acceptance range of 11.2 MWe to 21.2 MWe. This range indicates that there is a 90% probability that the actual power output will fall within this range. The highest and lowest values obtained from the simulation are 30.1 MWe and 7.9 MWe, respectively. Figure 4, the mean and median values are 15.1 MWe and 14.3 MWe, indicating a slightly skewed distribution. The standard deviation is 3.8 MWe, which gives us an idea of the spread of the data.

To decide on investment, we need to consider the potential risks and rewards. The results of the simulation provide us with a range of possible outcomes, which can be used to assess the uncertainty of the project. The 90% acceptance range gives us a good idea of the likely power output, and the standard deviation provides a measure of the spread of the data. Based on these results, we can decide on investment, but it should be based on a thorough analysis of the potential risks and rewards, including the likelihood of achieving the expected power output.

4.1 Implications of Key Metrics

I. Most Likely Value (12.9 MWe): This value serves as a central estimate for stakeholders, indicating that under typical conditions, the project can be expected to generate around this amount of electricity. Investors often look for reliable estimates when making funding decisions, and this figure provides a solid baseline.

II. 90% Acceptance Range (11.2 to 21.2 MWe): This range indicates that there is a high level of confidence (90%) that the actual generation capacity will fall within these bounds. For investors, this range helps in assessing risk; a narrower range suggests more certainty about potential returns, while a wider range may indicate higher risk.

III. Highest and Lowest Values (30.1 and 7.9 MWe): These extremes highlight the potential variability in resource output due to geological factors or operational challenges. Investors may view the highest value as an optimistic scenario that could yield significant returns if realized, while the lowest value represents a worst-case scenario that could lead to losses.

IV. Mean (15.1 MWe) and Median (14.3 MWe): Both metrics provide insights into the expected performance of the project over time, with the mean offering an average output and median indicating that half of all simulated outcomes are below this value and half above it.

V. Standard Deviation (3.8 MWe): A relatively low standard deviation compared to the mean suggests that most outcomes are clustered closely around the average output, indicating less volatility and potentially lower risk for investors.

VI. Skewness (0.9): A positive skewness indicates that there are more extreme high values than low values in the distribution of outputs, suggesting an upside potential for investors but also cautioning them about possible outlier scenarios (Figure 4).

5 CONCLUSION

The power potential estimated from the volumetric method is estimated to be 9.01 MWe, representing a significant insight into the resource capacity of the Kiejo-Mbaka geothermal project. Supplementing this, the Monte Carlo simulation further refines the evaluation by providing a probabilistic range of potential outputs. The simulation results indicate that the highest power potential value achieved through this approach is 30.1 MWe, while the lowest is 7.9 MWe, showcasing the variability inherent to the resource estimation process. Together, these methods provide a complementary perspective on the project's potential, offering both deterministic and probabilistic insights into the geothermal resource availability.

While the volumetric method remains an essential tool in geothermal energy assessment, its application is not without limitations. Factors such as assumptions in rock properties, recovery efficiency, and thermodynamic parameters can introduce uncertainties that affect the precision of the results. Despite these constraints, the volumetric analysis demonstrates its relevance when compared to the probabilistic Monte Carlo simulation outputs, aligning its estimation within the simulated range. This correlation reinforces the reliability of using both methodologies in tandem to strengthen geothermal resource evaluations.

The Monte Carlo simulation plays a pivotal role in addressing uncertainties that the volumetric method might overlook. By incorporating probabilistic distributions for key parameters such as reservoir thickness, temperature, recovery factor, and conversion efficiency, the Monte Carlo approach captures the inherent variability of the resource estimation process. This enables a more comprehensive understanding of the geothermal resource's potential, accounting for risks and uncertainties that are often present in real-world geothermal development projects.

The findings from these analyses hold substantial implications for stakeholders involved in the Kiejo Mbaka geothermal initiative. By highlighting the upper and lower limits of the resource's power potential, these results empower stakeholders to make informed decisions about the project's investment viability. Understanding the variability ranging from optimistic scenarios of high-power outputs to more conservative outcomes facilitates a balanced perspective on both the opportunities and challenges associated with geothermal resource exploitation. This, in turn, can foster confidence among investors, policymakers, and project developers by providing transparent insights into the project's potential returns and associated risks.

In addition to influencing investment decisions, the integrated use of volumetric and Monte Carlo methods exemplifies the importance of adopting a multidimensional approach to geothermal resource assessment. The combination of deterministic and probabilistic techniques ensures that evaluations are both rigorous and adaptable to the uncertainty's characteristic of resource exploration. Such a comprehensive approach not only enhances the credibility of the resource assessment but also contributes to the sustainability and long-term success of geothermal energy projects.

Ultimately, the insights gained from this analysis underscore the strategic importance of geothermal resource evaluation in advancing clean and renewable energy initiatives. By leveraging advanced methodologies like the Monte Carlo simulation alongside traditional volumetric techniques, the Kiejo-Mbaka project demonstrates a commitment to robust scientific practices that prioritize accuracy, transparency, and stakeholder confidence. This sets a solid foundation for the continued development and optimization of Tanzania's geothermal energy resources, paving the way for sustainable energy solutions in the region

6 RECOMMENDATIONS

To improve geothermal prospect assessment, it is recommended to integrate stochastic methods particularly Monte Carlo Simulation early in the exploration process. These approaches allow for probabilistic evaluation of geothermal power potential, accommodating uncertainties in surface and subsurface data. Applying such techniques, as demonstrated in the Kiejo-Mbaka field, enhances decision-making by generating reliable estimates despite limited data. Stakeholders should adopt these models to guide strategic planning, optimize resource allocation, and boost investment confidence. Volumetric analysis combined with stochastic

simulation offers a robust framework for evaluating geothermal resources, especially in data-scarce environments, and should be standard practice in early-stage geothermal exploration.

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The study has no fund provided.

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9 DECLARATION OF CONFLICTING INTERESTS

The authors declare no conflict of interest.

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