

Estimation of Geothermal Energy Potential Using Monte Carlo Simulation at Jaboi Geothermal Field, Indonesia

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ABSTRACT

Geothermal energy is an alternative solution for countries looking for renewable energy. However, energy potential estimation must be estimated before a drilling step to avoid drilling failure or financial loss. Monte Carlo simulation can be performed coupled with a volumetric method to calculate geothermal energy potential. This study aims to estimate the geothermal energy potential of the Jaboi geothermal field. The parameters used in this study were derived from previous studies and various references. Two scenarios are designed to extract the geothermal energy over 25 and 30 years. For the first scenario, 25 years, we obtained 34,51 MWe (P10), 48.28 MWe (P50), and 67.45 MWe (P90). For the second scenario, 30 years, we obtained 28.84 MWe (P10), 40.19 MWe (P50), and 56.20 MWe (P90). The sensitivity analysis was then performed to determine which parameters significantly affect geothermal energy estimation. The results indicate that reservoir thickness is the most sensitive parameter. Therefore, determining this parameter must be done carefully.

1. Introduction

Energy consumption has shifted toward renewable energy sources, as fossil fuels emit significant amounts of CO₂, which can damage the ozone layer [1]. Geothermal energy is a renewable source primarily found in plate boundary areas, providing Indonesia with abundant geothermal energy resources. One of the Indonesian geothermal areas currently being explored is the Jaboi geothermal field. It is located in western Indonesia.

The Jaboi geothermal field is marked by several geothermal surface manifestations (Fig. 1), including hydrothermal features such as solfataras, fumaroles, mud pools, hot ground, and hot springs [2]. These characteristics indicate the presence of an active geothermal system in the area. Geologically, the Jaboi geothermal area is dominated by volcanic andesitic to basaltic rocks associated with the Quaternary Jaboi volcano, whose hydrothermal alteration and fault zones control the surface manifestations [3].

Previous studies have conducted geological, geochemical, and geophysical investigations to delineate the subsurface system in the Jaboi region. For instance, the 3D geological model assigns related features, such as geological structures, which will serve as the basis for developing the new reservoir model [4]. The VES and VLF surveys indicated shallow hydrothermal systems as groundwater resources [5]. The geochemical analyses of hot springs revealed a high-temperature geothermal system range of 196.9-362.8 °C [6]. Despite these findings, uncertainties remain regarding the subsurface structure, reservoir

geometry, and heat source characteristics, which limit the accurate estimation of geothermal potential.

Therefore, the use of geology, geochemistry, and geophysics (3G) survey data in volumetric calculations and Monte Carlo simulations for further interpretation is essential better to estimate the geothermal potential of the Jaboi field.

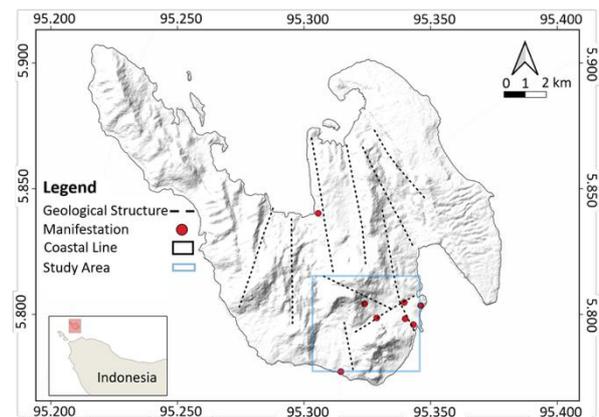


Fig 1: Map of the study area showing surface manifestation and known fault

A volumetric method is widely used to estimate geothermal energy potential [7;8]. The volumetric method calculates the thermal energy reserves in reservoir fluids and rocks, which are then converted into the equivalent amount of electrical energy that could be generated. Reservoir parameter values are divided into initial and final conditions for a certain period. The initial geothermal energy potential can be

estimated using data obtained from 3G (geological, geophysical, and geochemical) surveys, which represent the pre-exploitation conditions [9]. Meanwhile, the final conditions represent the post-exploitation state after a certain production period [10]. The volumetric method is often applied in conjunction with Monte Carlo simulations in various studies. [10-13].

The volumetric method provides a fundamental approach for estimating geothermal potential. However, its accuracy is limited due to uncertainties in subsurface parameters derived from limited data. These data are not definitive values, as they are derived from averaged estimations obtained from previous survey results. To address this limitation, Monte Carlo simulations are applied to incorporate parameter variability and quantify uncertainty. Monte Carlo simulation is a statistical approach for determining the probability function of random events [14]. The Monte Carlo simulation enables the interpretation of calculation results under different input conditions by generating random input values and applying mathematical formulas [13]. An input distribution that closely matches the available data is crucial for accurately estimating geothermal energy potential [15]. The Monte Carlo simulation minimizes the risk associated with insufficient data by providing a reliable estimate of static potential with a confidence level that may be used as a reference for further exploration and development.

This study aims to calculate the geothermal energy potential of the Jaboi geothermal field using a Monte Carlo Simulation. The Monte Carlo Simulation has been used to evaluate the geothermal energy potential in numerous areas, including the Bohai Bay Basin [13], Mexico [12], Gujarat, India [15], and Kamojang, Indonesia [16]. Estimating the geothermal potential is required for the development planning of the Jaboi geothermal power plant.

2. Methods

The workflow of this research is illustrated in Fig. 2. Reservoir and simulation parameters are collected based on literature studies to evaluate the geothermal energy potential of the Jaboi geothermal field, utilizing geological, geophysical, and geochemical data. The data collected include reservoir parameter values and parameter assumption data from previous studies [2;17;18;19], which are presented in Table 1 or other geothermal systems with similar features [3; 20;21;22;23].

The geothermal energy takes 25-30 years, and the final temperature reaches 180°C [19]. The electrical convection factor of 10% is based on Bodvarsson (1974). The recovery factor is derived from SNI 13-6482-2000 [3;20]. Other parameters were gathered from the 3G survey. Rock density is assumed based on lithology, which comprises sediment and volcanic rock [2]. The prospect area was determined based on rock distribution analysis with low resistivity values [12]. The assumed thickness of the Jaboi geothermal reservoir system is 350 m, 500 m, and 700 m [2;17] for the minimum, most likely, and maximum estimates, respectively. The initial

temperature assumption was based on a geochemical survey employing a Cl-SO₄-HCO₃ analysis [2], which estimated the reservoir temperature of 255°C.

Geothermal energy (electric) potential was estimated using the volumetric method [4]:

$$H_e = Ah [(1 - \phi)\rho_r C_r T + \phi(\rho_L U_L S_L + \rho_v U_v S_v)] \quad (1)$$

Where H_e (kJ) represents heat energy content, U_L , U_v are specific energy of water and vapor (kJ/kg), and ρ_L, ρ_v are water and vapor density (kg/m³). The parameter mentioned except H_e is estimated to be correlated with temperature data and estimated using the Steam Table. In this study, we treated the input parameters as independent of each other.

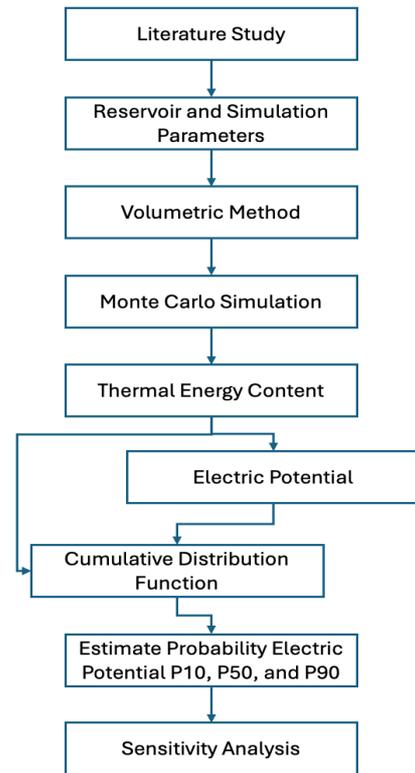


Fig 2: Workflow of this study estimating geothermal energy potential using Monte Carlo simulation

The thermal energy that can be utilized (He_m) between the initial i and final f state is determined using the following equation:

$$He_m = He_i - He_f \quad (2)$$

The potential electric generation ($H_{electricity}$) over a period of t years, expressed in megawatts electric (MWe), can be calculated using

$$H_{electricity} = \frac{He_m \eta R_f}{1000t} \quad (3)$$

Where R_f is the recovery factor, and η is the electric conversion factor. Monte Carlo simulation is performed using Microsoft Excel with Steam Table macros.

Calculating geothermal energy potential is challenging due to the limited availability of data and the need to use assumed reservoir or field parameters from other geothermal fields with similar characteristics. With limited data, Monte Carlo simulation and the volumetric method could minimize uncertainty in geothermal energy estimation. Monte Carlo simulation is a probabilistic method that utilizes a random number-generating process to estimate the potential of electrical energy with a certain degree of accuracy. Monte Carlo simulation results can be classified into three probability categories using the cumulative distribution function P10, P50, and P90. These percentile values represent different confidence levels in the estimated geothermal power potential. The P10, P50, and P90 percentiles were selected as they represent the standard confidence levels used in probabilistic assessments of geothermal and petroleum resources, as established by organizations such as USGS, IGA, and SPE-PRMS. Utilizing these percentiles allows for a consistent approach to quantifying uncertainty and risk, which is crucial for informed decision-making in resource management.

Monte Carlo simulation employs random numbers from triangular, uniform, or fixed values. We listed the probability distribution assigned to each Monte Carlo input in Table 1. We used triangular distributions for variables such as reservoir thickness, recovery factor, and reservoir lifetime, which had minimum, most likely, and maximum values. This method captures the most probable value and the range of uncertainty. For Parameters like rock density that only had lower and upper bounds, we used uniform distributions. We treated parameters such as area, porosity, rock heat capacity, and initial

and final temperature and water saturation as fixed values since their expected variability is low compared to other uncertainties. We represented the electrical convection factor, which has a narrow range (0.10 to 0.11) with no preferred mode, using a uniform distribution.

Furthermore, we validated our model in two ways. First, we reproduced geothermal resource calculations from previous studies, achieving estimates for stored heat and electric power that matched reference values. Second, we verified input parameters by comparing them to data from similar geothermal reservoirs, ensuring they fell within typical ranges for high-enthalpy systems. Internal consistency checks also confirmed that thermodynamic relationships remained within expected limits. Although we lack long-term production data for calibration, these validation steps reinforce the reliability of our methodology, aligning with standard geothermal assessment practices.

We performed a sensitivity analysis to calculate results for 25- and 30-year scenarios. A one-factor-at-a-time (OAT) sensitivity analysis was conducted to evaluate the impact of key reservoir parameters on the calculated electric power output. Each parameter was individually varied to its minimum and maximum values, as detailed in Table 1. The parameters tested included porosity, rock density, rock heat capacity, reservoir thickness, temperature, water saturation, recovery factor, and electrical convection factor. For each variation, the minimum and maximum power outputs were calculated. This methodology allows for a direct assessment of the relative significance of each parameter in determining the geothermal power potential.

Table 1: Reservoir Parameters Used in Volumetric Method and Monte Carlo Simulation

Parameter	Symbol	Distribution Type	Min	Most	Max	Unit
Area	A	Fixed	-	6	-	km ²
Reservoir Thickness	h	Triangular	350	500	700	m
Porosity	ϕ	Fixed	-	0.1	-	kJ/kg
Rock Heat Capacity	C_r	Fixed	-	1	-	kJ/kg°C
Rock Density	ρ_r	Uniform	2,500	-	2,700	kg/m ³
Initial Temperature	T_i	Fixed	-	255	-	°C
Final Temperature	T_f	Fixed	-	180	-	°C
Initial Water Saturation	S_L	Fixed	-	1	-	
Final Water Saturation	S_v	Fixed	-	0.50	-	
Electrical Convection Factor	η	Uniform	0.10	-	0.11	
Recovery Factor	R_f	Triangular	0.45	0.50	0.60	
Lifetime	t	Uniform	25	-	30	year

3. Result and Discussion

The Monte Carlo simulation in the Jaboi geothermal area provides a different probability value for each estimated period of use, which is 25 years and 30 years. The difference in values in the two periods is because the longer the geothermal energy utilization, the smaller the estimate generated to ensure that the potential energy produced can last for the desired period. When determining the amount of geothermal energy using the Monte Carlo simulation, each parameter will be paired with a random number to test the function of each parameter. In this study, 30,000 random numbers are employed to calculate the energy potential in each lifetime period. Random numbers are used to simulate as many random numbers as possible for each reservoir parameter, utilizing complex algorithms and calculations to enhance accuracy.

Calculating the heat energy potential in the Jaboi geothermal system with limited data can lead to significant uncertainty. Monte Carlo simulation helps produce probable results with improved confidence levels. The Results are shown in Table 4. The thermal energy simulation results are shown in Fig. 3. The red solid line shows the cumulative percentage of thermal energy. Blue, purple, and red dash lines show the P10, P50, and P90, respectively.

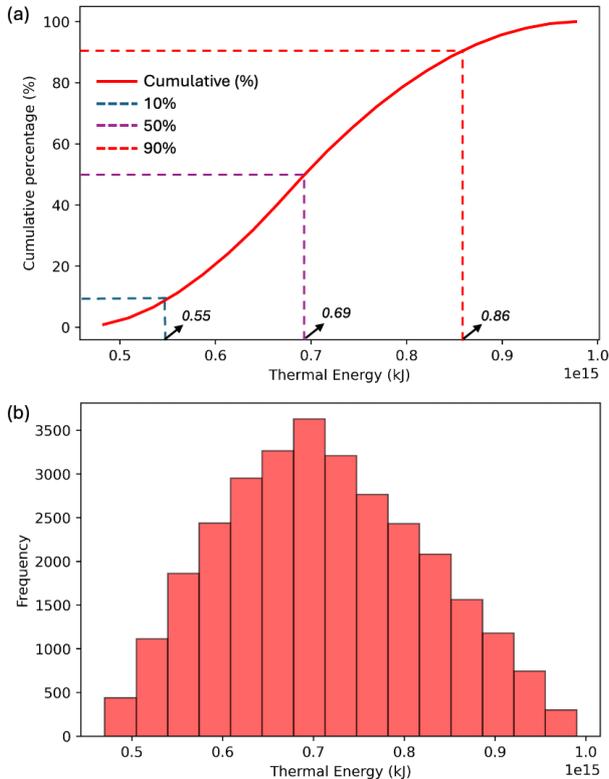


Fig 3: (a) Cumulative percentage of thermal energy, and (b) Histogram chart of thermal energy by Monte Carlo simulation.

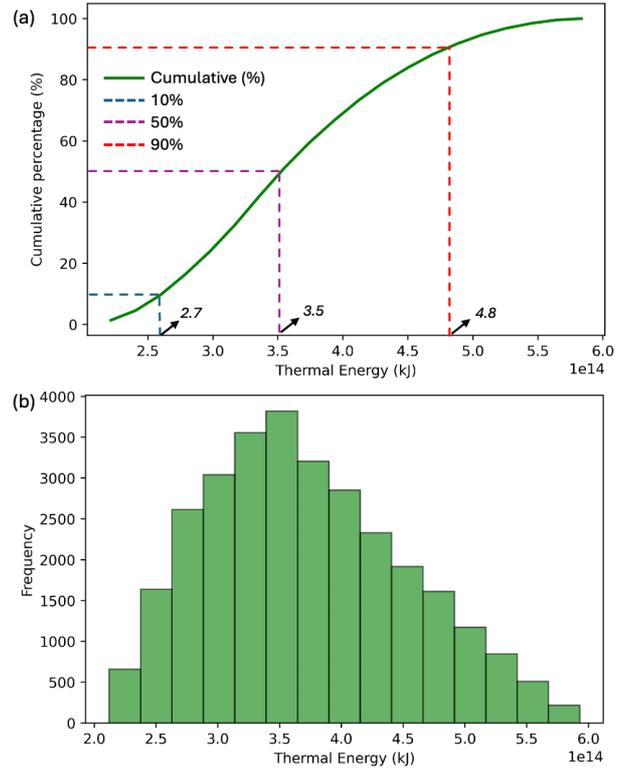


Fig 4: (a) Cumulative percentage of thermal energy, and (b) Histogram chart of possible extracted thermal energy by Monte Carlo simulation.

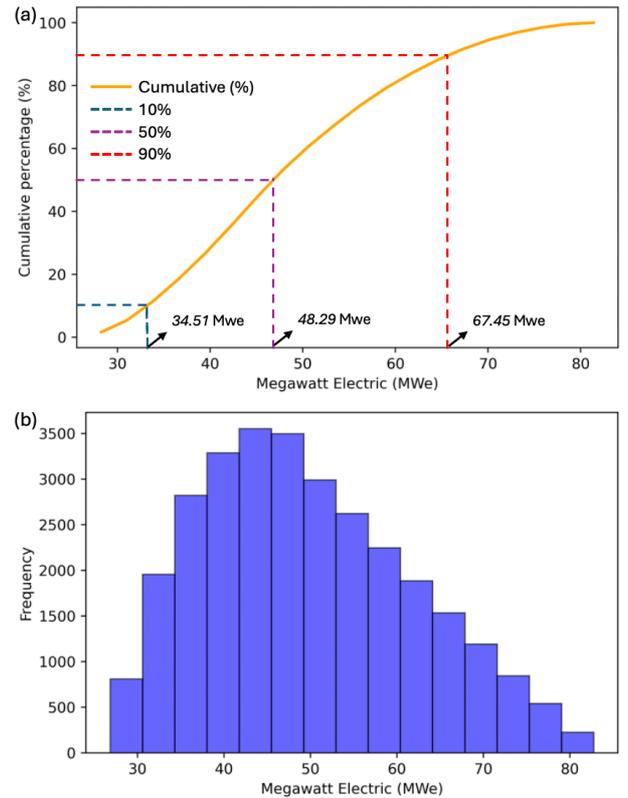


Fig 5: (a) Cumulative percentage of electricity potential for 25 years, and (b) Histogram chart of geothermal energy potential for 25 years.

As we focus on three possible results, we obtain 5.5×10^{14} kJ, 6.9×10^{14} kJ, and 8.6×10^{14} kJ for P10, P50, and P90, respectively. However, not all thermal energy can be extracted and utilized to generate electricity because it depends on the recovery factor. Fig 4 shows the results of possible extracted thermal energy. For the 45-60% recovery factor used in this study, we obtain the thermal energy that can be extracted as 2.7×10^{14} kJ, 3.5×10^{14} kJ, and 4.8×10^{14} kJ for P10, P50, and P90, respectively.

Next, the geothermal energy potential was calculated based on the thermal energy that can be extracted. For 25 years, the quantity of electricity that can be generated is 34.51 MWe for P10, 48.29 MWe for P50, and 67.45 MWe for P90 (Fig. 5). For 30 years, the quantity of electricity that can be generated is 28.84 MWe for P10, 40.19 MWe for P50, and 56.20 MWe for P90 (Fig. 6).

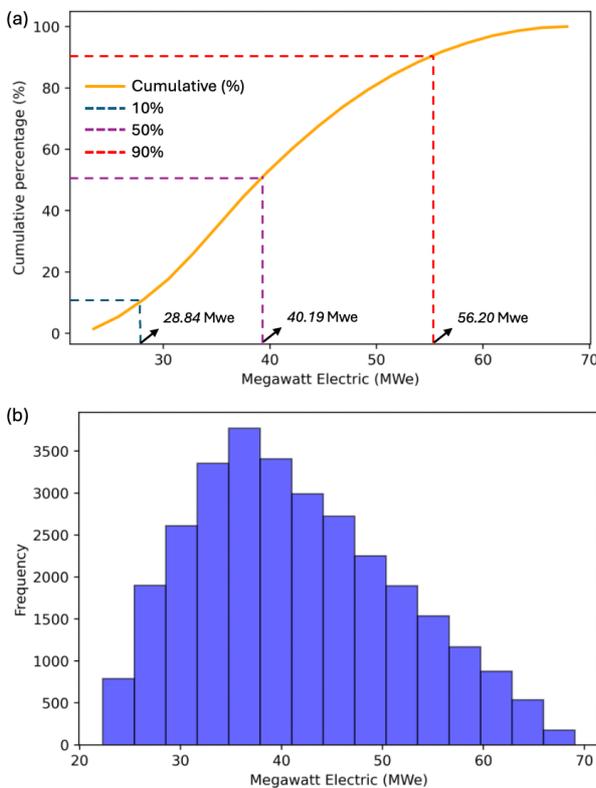


Fig 6: (a) Cumulative percentage of electricity potential for 30 years, (b) Histogram chart of geothermal energy potential for 30 years.

P10 indicates a 10% probability that the actual resource potential exceeds this value, representing an optimistic scenario with favorable reservoir parameters, which helps understand the best-case development potential. P50, the median estimate, suggests a 50% probability that the resource is higher or lower, serving as the expected estimate for project feasibility and design assumptions. P90 reflects a conservative estimate with a 90% probability that the resource potential exceeds this value. A low P90 indicates that even under pessimistic conditions, the reservoir can still provide energy, while a significant difference between P90 and P50 suggests considerable geological uncertainty. The spread

between P10, P50, and P90 offers a quantitative assessment of uncertainty. A narrow spread indicates that the system's thermal potential is well-defined by the available data, suggesting high reliability in the results. Conversely, a wider spread implies that specific parameters have a significant impact on the outcomes, highlighting areas of uncertainty that may require further investigation.

Estimating geothermal energy potential using a Monte Carlo simulation yields a probabilistic value, with specific parameters significantly influencing the calculation. In this study, we performed a sensitivity analysis for 25- and 30-year scenarios to determine which parameters significantly affected the energy estimation (Fig. 7 and Fig. 8). The detail of each parameter's output results is presented in Table 2 and Table 3 for the 25-year and 30-year scenarios, respectively. Both results indicate that reservoir thickness is the most sensitive parameter in determining geothermal energy potential, which varies between 33.43 and 66.86 MWe for the 25-year scenario and between 27.86 and 55.71 MWe for the 30-year scenario. The total volume of hot rock and fluid for heat extraction increases with reservoir thickness. Suppose favorable factors, such as temperature and permeability, allow for more geothermal energy to be extracted from a geothermal reservoir [10]. In geothermal energy calculations, the energy potential is proportional to reservoir thickness.

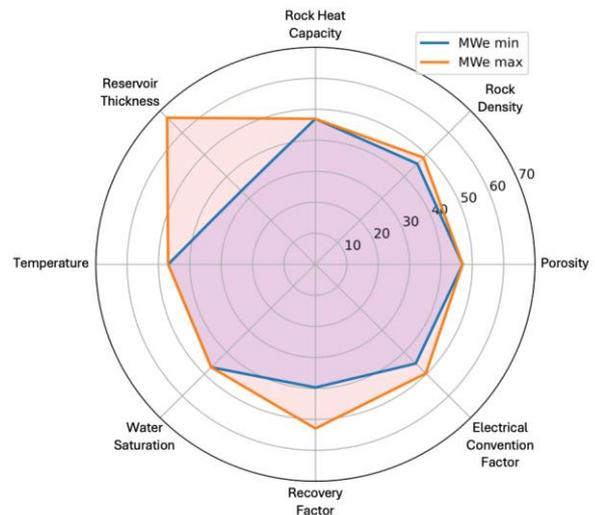


Fig 7: Sensitivity analysis for 25 years to Monte Carlo simulation parameters.

The recovery factor, which describes the amount of heat that can be recovered based on the geothermal system's efficiency, is a second factor that significantly influences the geothermal energy calculation. The recovery factor impacts the estimate, ranging from 39.71 to 52.95 MWe for the 25-year scenario and between 33.09 and 44.12 MWe for the 30-year scenario. Due to factors such as heat loss, fluid flow limitations, and technological constraints, not all the heat in the reservoir can be extracted [21]. Higher recovery factors increase the portion of the reservoir's heat that can be utilized.

Table 2: Electricity potential of sensitivity analysis results for the 25-year scenario

Parameter	Min (MWe)	Max (MWe)	Influence Level
Porosity	46.93	46.93	Negligible
Rock density	45.87	48.66	Moderate
Rock heat capacity	46.93	46.93	Negligible
Reservoir thickness	33.43	66.86	High
Temperature	46.93	46.93	Negligible
Water saturation	46.93	46.93	Negligible
Recovery factor	39.71	52.95	High
Electrical convection factor	45.21	49.73	Moderate

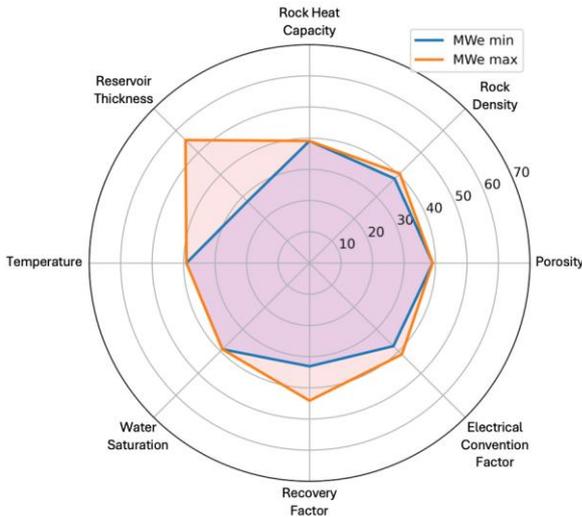


Fig 8: Sensitivity analysis for 30 years to Monte Carlo simulation parameters.

Table 3: Electricity potential of sensitivity analysis results for the 30-year scenario

Parameter	Min MWe	Max MWe	Influence Level
Porosity	39.11	39.11	Negligible
Rock density	38.23	40.55	Moderate
Rock heat capacity	39.11	39.11	Negligible
Reservoir thickness	27.86	55.71	High
Temperature	39.11	39.11	Negligible
Water saturation	39.11	39.11	Negligible
Recovery factor	33.09	44.12	High
Electrical convection factor	37.68	41.44	Moderate

The electrical conversion factor is the third factor that significantly influences the calculation of geothermal energy, which is shown in Table 2 and Table 3 for both scenarios. The type of power plant (e.g., binary cycle and flash steam) and operational efficiency affect the electrical conversion factor. The conversion factor directly scales down the potential thermal energy to electrical energy, impacting the final estimation of the geothermal potential. To avoid overestimating geothermal potential, sensitive factors, particularly reservoir thickness, must be carefully determined. While rock density, electrical convection factor, rock heat capacity, temperature,

and water saturation show moderate effects, they do not influence the minimum and maximum output, which remains at 39.11 MWe. Overall, the findings highlight that the primary sources of uncertainty in geothermal power estimations are reservoir thickness and recovery factor, while the other parameters have minimal impact.

Table 4: Summary of thermal energy, possible extracted thermal energy, and geothermal energy potential

Energy Potential	P10	P50	P90
Thermal energy (kJ)	5.5×10^{14}	6.9×10^{14}	8.6×10^{14}
Possible extracted thermal energy (kJ)	2.7×10^{14}	3.5×10^{14}	4.8×10^{14}
Geothermal energy potential for 25 years (Mwe)	34.51	48.29	67.45
Geothermal energy potential for 30 years (Mwe)	28.84	40.19	56.2

4. Conclusion

Calculating geothermal energy potential using limited data is challenging. However, we successfully estimate the potential using a Monte Carlo simulation. This method produces statistical results that are often interpreted in terms of P10, P50, and P90. We also designed two scenarios for extracting geothermal energy over 25 and 30 years. For the first scenario, spanning 25 years, we obtained 34.51 MWe (P10), 48.28 MWe (P50), and 67.45 MWe (P90). For the second scenario, 30 years, we obtained 28.84 MWe (P10), 40.19 MWe (P50), and 56.20 MWe (P90). For the maximum energy (P90) that could be extracted, we obtained 67.45 MWe and 56.20 MWe for 25 years and 30 years, respectively. The sensitivity analysis suggested that three parameters influence geothermal energy estimation: reservoir thickness, recovery factor, and electrical conductivity factor.

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