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Probabilistic Estimation of Geothermal Reserves in Dieng Field with JIWA Power Density and JIWA Volumetric

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ABSTRACT

Geothermal energy is a renewable energy source that is environmentally friendly and can be utilized for power generation. This study aims to estimate geothermal reserves in Dieng Field using Monte Carlo simulation to overcome uncertainty in the calculation of geothermal resources. The methods used include the Power Density and Volumetric Stored Heat approaches by considering geophysical, geological, and well logging data. Monte Carlo simulation produces probabilistic estimates categorized into P10, P50, and P90 scenarios. The results show that the potential geothermal reserves in Dieng Field range from 56.91 MW (P10) to 113.41 MW (P90) based on the Volumetric method and between 64.22 MW (P10) to 111.22 MW (P90) based on the Power Density method. These results provide estimation of the geothermal potential that can be utilized, and support decision-making in the sustainable development of geothermal energy.
Keywords: geothermal, monte carlo, power density, volumetric stored heat

I. INTRODUCTION

Geothermal energy is one of the renewable energy sources that can be utilized for power generation. Before being developed on a large scale, technical and economic analysis is required to assess the feasibility of geothermal power plants. One of the crucial steps in this process is the estimation of geothermal energy potential, which serves as a reference in determining the electricity production capacity that can be generated. An accurate resource assessment is essential to determine the capacity of a geothermal field as well as the basis for making investment decisions in this sector.

The Dieng Geothermal Field, located in Central Java, Indonesia, is a high-temperature geothermal system within the Dieng Volcanic Complex. The field is characterized by extensive geological activity and significant geothermal manifestations. Based on exploration reports, the Dieng geothermal reservoir has a temperature ranging from 300 to 330°C and contains two-phase fluids that can be utilized for electricity generation (Alamsyah et al., 2024; Kencana et al., 2024; Ramadhan et al., 2013). With these characteristics, the Dieng field is one of the strategic areas for geothermal energy development in Indonesia.

Estimation of geothermal resource potential can be done by various methods, including Power Density and Volumetric. The Power Density method estimates production capacity based on the power distribution per unit area of the geothermal field, while the Volumetric method calculates energy reserves by considering reservoir volume, rock heat capacity, and energy extraction efficiency (Rosiani et al., 2024; Wilmarth et al., 2021). The Monte Carlo method is a method that utilizes statistical parameter data in the reservoir. Parameter data is compiled to be used as input data for Monte Carlo simulations which will then calculate the probability of various parameter data (Widi & Wijaya Isma, 2011). With the combination of these two methods calculated using Monte Carlo simulation, a more accurate estimate of the potential energy that can be developed in the Dieng Field is obtained.

This research aims to estimate geothermal energy reserves in Dieng Field using the Volumetric and Power Density methods, and apply Monte Carlo simulation to improve the estimation results. The probabilistic approach used in this simulation allows for a more in-depth evaluation of the uncertainty in the calculation of geothermal resources. In this study, the estimation calculations were carried out using JIWA Power Density and JIWA Volumetric software developed by PT Anugerah Indonesia Lima. This software was chosen for its ability to perform Monte Carlo simulations, enabling probabilistic evaluation of reserve estimates by considering the uncertainty of input parameters. The advantage of JIWA software over manual methods is its ability to process probabilistic distributions, as well as provide estimates based on P10, P50, and P90 probability scenarios more quickly. The results of this research are expected to be a reference for stakeholders in the development of geothermal energy, as well as contribute to the development of science in the field of exploration and utilization of renewable energy.

II. METHODS

The estimation of geothermal reserves in Dieng Field was carried out with a probabilistic approach using Monte Carlo simulation. This simulation is used to consider the uncertainty factor in the input parameters, thus providing a probabilistic distribution of the reserve estimates obtained. In this study, the two main methods used are the Power Density and Volumetric Stored Heat approaches. Both methods have been widely used in the geothermal industry and can be strengthened with probabilistic approaches to improve the accuracy of the estimation.

The input data used in the analysis and estimation focuses on various high temperature reservoir parameters, including reservoir area, reservoir thickness, rock density, porosity, rock heat capacity, initial temperature, final temperature, water saturation, recovery factor, project life, and conversion efficiency. Data was obtained through several surveys such as Magnetotelluric, Well Logging, as well as references from conceptual model.

The Power Density method is used to estimate production capacity based on simple parameters, such as power density (MW/km²), reservoir area (km²), and estimated reservoir temperature. Power density values were obtained from scientific literature, including the study by Wilmarth et al. (2020), so they can be used as a reference in determining the potential electrical power per unit area of the reservoir. The formula that can be used for the Power Density approach is (Saptaji, 2001):

$$H = A \times Q \qquad (1)$$

Where:

H: Estimated Reserves (MWe)

A: Reservoir Area (km^2)

Q: Electrical Power per Unit Area of Reservoir (MWe/km^2)

In contrast, the Volumetric Stored Heat method is used to estimate the potential energy stored in a reservoir based on the volume of hot rock, the heat capacity of the rock, and the energy conversion efficiency. The formula that can be used for the Volumetric approach is (Saptaji, 2001):

$$H = \frac{A \times h\{(1-\phi)\rho_r c_r + \phi\rho_l c_l\}(T_i - T_f)R_f \times \eta}{t \times 365 \times 24 \times 3600 \times 1000} \qquad (2)$$

Where:

H: Estimated reserves (MWe)

A: Reservoir area (km2)

h: Reservoir thickness (m)

ϕ : Porosity

ρ_r: Rock density (kg/m^3)

c_r: Rock heat capacity (kJ/kg˚C)

ρ_l: Fluid density (kg/m^3)

c_l: Fluid heat capacity (kJ/kg˚C)

T_i: Initial temperature (˚C)

T_f: Final temperature (˚C)

R_f: Recovery factor

η: Electrical conversion factor

t: Project time (Year)

In the probabilistic approach, the input parameters are not assumptions but fixed values that are modeled as probability distributions based on industry references and national standards such as SNI 6482:2018. The parameters used in this calculation include rock porosity, rock heat capacity, rock density, project life, electricity conversion factor, and recovery factor as summarized in **Table 1**.

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Vol. 6 No. 1 2025

Table 1. Assumption of Resource Potential Determination Parameters According to SNI 6482: 2018 Guidelines

Parameters	High Temperature >225°C
Porositas Batuan Reservoir (%)	7
Kapasitas Panas Batuan (kJ/kg°C)	1
Rock density (kg/m^3)	2650
Project time (tahun)	30
Electrical conversion factor	10
Recovery factor	30

To overcome the uncertainty that arises when estimating reserves, a Monte Carlo simulation will be used that allows variations in input values according to the appropriate probability distribution. The simulation is conducted using JIWA Power Density and JIWA Volumetric software that allows probabilistic analysis with estimation results in the form of scenarios at various confidence levels, ranging from P10 (Proven) to P90 (Possible). By considering the uncertainty of input parameters, a more realistic evaluation of reserve estimates will provide deeper insights that support appropriate decision making.

As can be seen in the flowchart of geothermal reserve estimation in **Figure 1**, the process begins with the collection, processing, and validation of reservoir, fluid, and rock data. The validated data is then used in the Power Density and Volumetric Stored Heat approaches using JIWA software. The results of the simulation will also be evaluated to obtain a final estimate that can be used in decision-making related to the management of existing resources in the Dieng Geothermal Field. Through this approach, reserve estimation is not only based on assumptions and available input data, but also considers the uncertainty of the available data so as to provide more accurate and reliable estimation results.

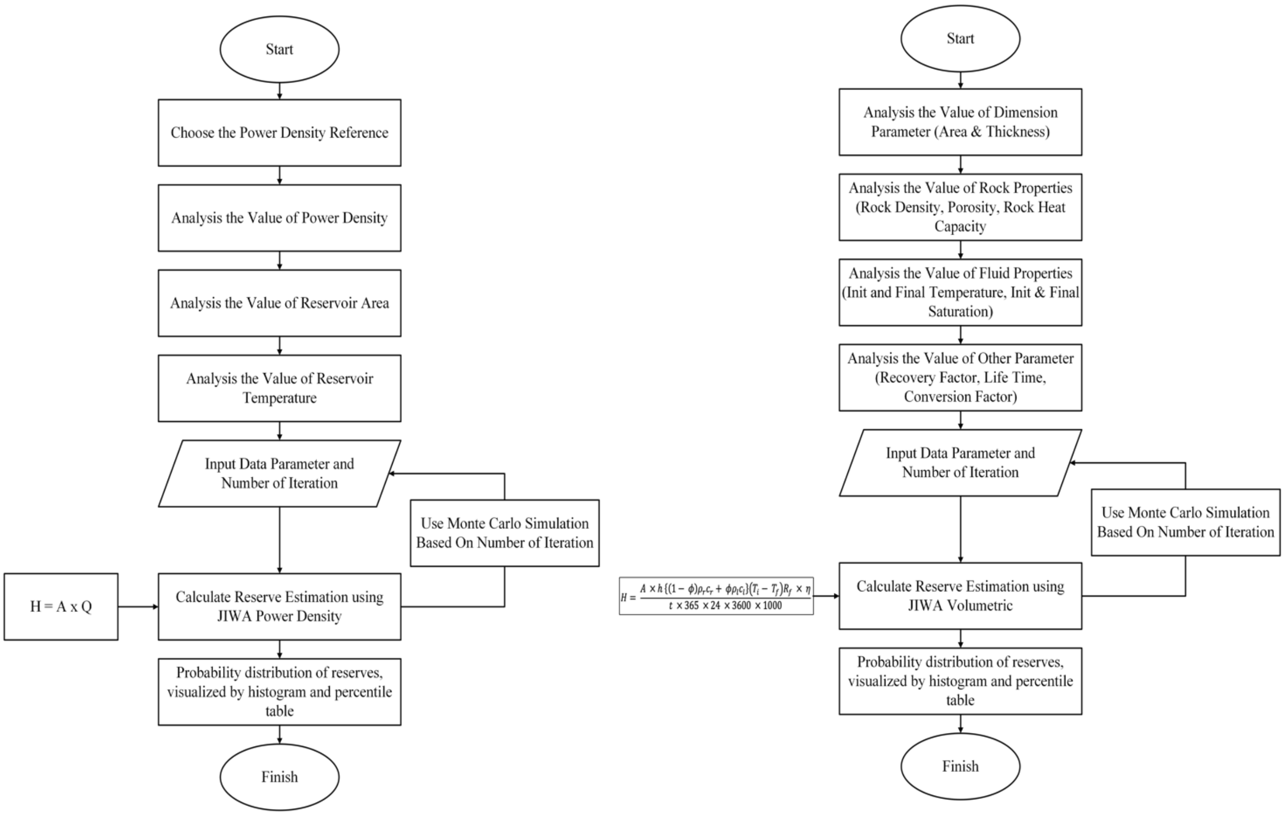

Figure 1. Flowchart for Determining Geothermal Reserve Potential Using JIWA Power Density (Left) and JIWA Volumetric (Right)

III. RESULTS AND DISCUSSION

This section presents the results of the analysis and calculation of potential geothermal reserves in the Dieng Geothermal Field based on available geoscience, geophysical and geochemical data. Key parameters such as area, reservoir thickness, reservoir temperature, rock porosity, and fluid saturation are used to calculate geothermal energy potential using the volumetric method. In addition, to account for uncertainties, a probabilistic analysis is performed with Monte Carlo simulation. These results aim to provide an initial estimate of the potential electricity that can be generated and become a basis for consideration in further field development.

3.1. Input Parameters

In the calculation of geothermal reserve potential, various key parameters are required that reflect the reservoir characteristics. These parameters are obtained from available geoscience, geophysical, and geochemical data, here are the main parameters used in the estimation of geothermal reserves in Dieng Field.

3.1.1. Area

Based on the geoscience interpretation and drilling campaign for the development of Unit-2 in the Dieng Geothermal Field, the proven reservoir area increased from the initial estimate of 6.2 km² to 11.7 km² after the drilling campaign was completed (Alamsyah et al., 2024; Sirait et al., 2015).

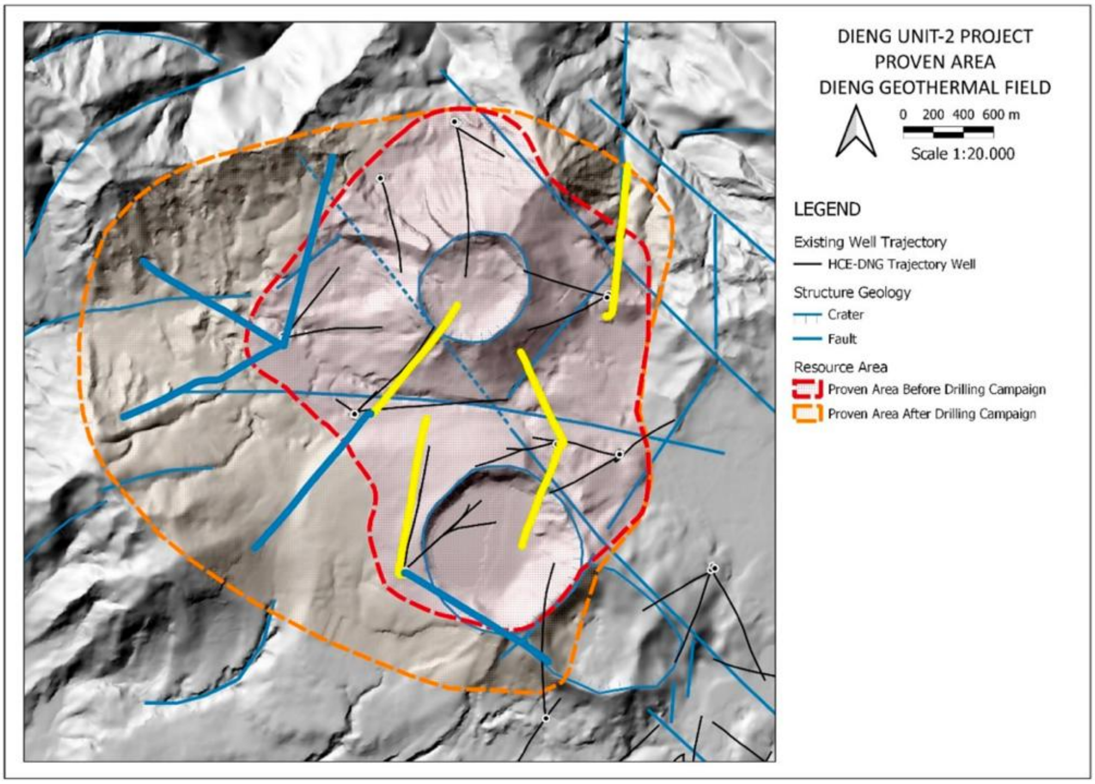

Figure 2. The Enlargement Of Proven Area After The Newest Data Successfully Obtained From Dieng Unit-2 Drilling Campaig (Alamsyah et al., 2024)

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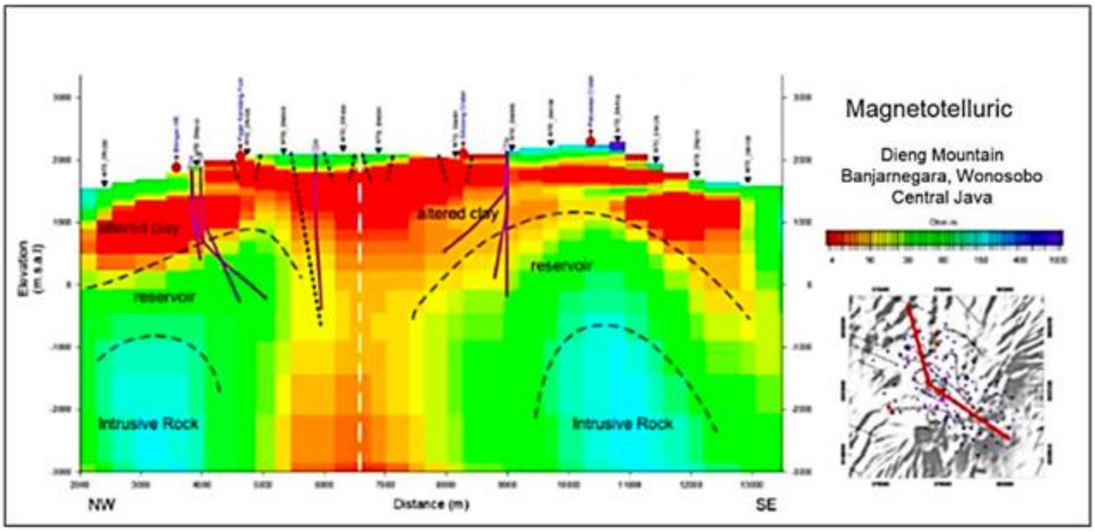

Figure 3. Results of Magnetotelluric Inversion Resistivity Cross Section (Rosid & Sibarani, 2021)

Meanwhile, the magnetotelluric (MT) survey results presented in **Figure** 3 provide an overview of the subsurface conductivity distribution in the Dieng Field. MT surveys are used to map reservoir boundaries based on the resistivity properties of rocks and fluids, thus enabling more accurate identification of prospect zones. Resistivity analysis from this survey shows that the proven reservoir area is not only larger than initially estimated, but also confirms the presence of upflow and outflow zones in the Sileri, Sikidang and Merdada sectors (Rosid & Sibarani, 2021). This increase in area has an impact on the calculation of the estimated electrical power that can be generated. To understand this impact, the following section will discuss the Power Meeting values used as estimation parameters.

3.1.2. Power Density

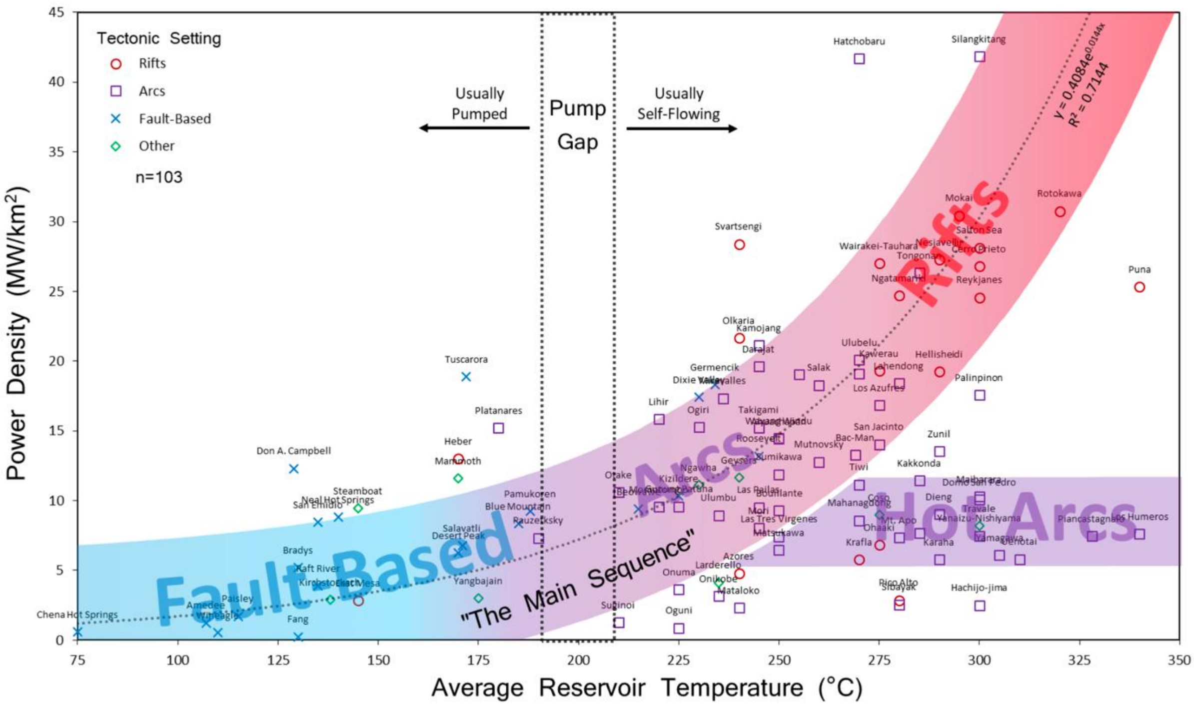

Figure 4. Value Power Density of the Geothermal Field (Wilmarth et al., 2021)

Dieng field is in a hot arc type tectonic setting, as identified by (Wilmarth et al., 2021). The power density range for this type is 5-10 MW/km². This value reflects a realistic and relevant energy production capacity for the reservoir conditions in the Dieng Field, which is characterized by high temperatures (>225°C). This parameter becomes one of the important references in estimating the potential electricity that can be generated by geothermal fields with similar configurations.

3.1.3. Reservoir Thickness

Reservoir thickness in the Dieng Geothermal Field was analyzed based on Magnetotelluric (MT) and Pressure-Temperature-Spinner (PTS) survey data. The MT data identified the presence of a low resistivity zone interpreted as the main reservoir, with caprock as the overlying protective layer. This zone is located at a depth of up to 2000 meters below the surface. Meanwhile, the PTS survey shows the distribution of feed zones at depths of 1200 to -800 meters below sea level (msl) The dominant feed zone in the Dieng Field contributes up to 65% to the production of certain wells, especially in the Sileri sector, with thicknesses varying from 1 to 1.5 km (Alamsyah et al., 2023). The varying thickness of the reservoir also contributes to the temperature distribution within the field. Therefore, understanding the reservoir temperature is important to determine the efficiency of geothermal energy conversion.

3.1.4. Reservoir Temperature

Reservoir temperatures in the Dieng Geothermal Field vary between the Sileri and Sikidang sectors. Based on the Na-K-Mg geothermometer and pressure-temperature (PT) survey results, the temperature in the Sileri sector ranges from 283-338°C, while in Sikidang it is in the range of 260-324°C (Kencana et al., 2024). Sileri is dominated by intensive water-rock interaction, resulting in a neutral fluid, while Sikidang shows a more dominant magmatic fluid influence with more acidic fluid characteristics.

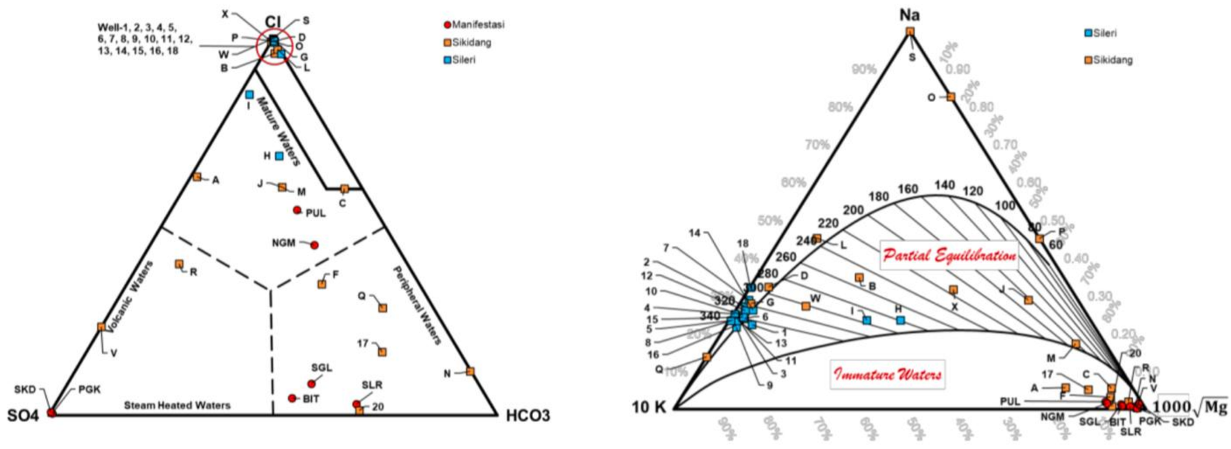

Figure 5. Cl-HCO3-SO4 (left) and Na-K-Mg (right) From Sileri And Sikidang Wells (Ashat et al., 2019)

The Na-K-Mg geothermometer was used due to its accuracy for liquid-dominated and two-phase systems, with an error rate of ±5-10°C. The final reservoir temperature was set at 180°C as the abandonment temperature, i.e. the economic limit of fluid utilization for power generation (Ashat et al., 2019). The results of this analysis provide a basis for optimal reservoir management by considering the thermal variations and geochemical characteristics in each sector.

3.1.5. Rock Porosity

The reservoir porosity in the Dieng Geothermal Field is categorized as a high enthalpy geothermal field. Based on the review (Zarrouk & Simiyu, 2013), Reservoir porosity in high-enthalpy geothermal systems ranges from 5-10%, which is in line with the characteristics of the Dieng field. This porosity reflects the limited storage capacity of hot fluids, which is typical for fracture-dominant systems. Numerical simulations conducted by (Ashat et al., 2019) for the Dieng Field further shows that the porosity of the reservoir matrix is in the range of 5%. This value reflects the dominance of the fracture pattern as the main pathway for hot fluid flow.

3.1.6. Water Saturation

Initial water saturation (Swi) in the Dieng Geothermal Field reflects the proportion of fluids in the reservoir prior to exploitation. Based on geochemical analysis and Pressure-Temperature-Spinner (PTS) surveys, Swi in the Sileri sector is expected to be high, between 0.90-0.95. This is due to the dominance of neutral fluids with high chloride content (9,600-19,000 mg/kg) and the result of intensive water-rock interaction, as described by (Kencana et al., 2024). Meanwhile, in the Sikidang sector, which is influenced by the steam cap zone and magmatic fluids, Swi is lower, around 0.85-0.90, indicating a mixture of liquid and vapor fluids (Ashat et al., 2019; Supijo et al., 2024). The combination of these two sectors results in an average Swi value for the entire field in the range of 0.88-0.93.

Final water saturation (Swf) indicates the change in the proportion of liquid in the reservoir after production. Swf in the Sileri sector remains relatively high, at 0.50-0.70, despite fluid depletion due to boiling during production. In contrast, the Sikidang sector shows a lower Swf of about 0.30-0.50, due to the dominance of steam in the steam cap zone. This difference reflects the heterogeneity of reservoir characteristics in both sectors. For the entire Dieng Geothermal Field, the Swf is estimated to be in the range of 0.30-0.60, reflecting the combination of a liquid dominated system in Sileri and a two-phase system in Sikidang.

Geochemical analysis, including chloride concentration data and non-condensable gas (NCG) content, supports this difference. The Sikidang sector, which has a high NCG content (2-21 wt%) and more acidic fluid characteristics, demonstrates the important role of the steam cap zone in determining changes in fluid saturation over the life of production (Maratama et al., 2024).

3.2. Calculation Result of Geothermal Reserve Potential of Dieng Field

The calculation of potential geothermal resources in Dieng Field was conducted using two methods, namely Volumetric Stored Heat and Power Density, as additional validation. The selection of these two methods is based on the need to obtain a more accurate estimate, considering that the Dieng Field is in the development stage, not initial exploration. With heterogeneous reservoir characteristics, the Volumetric Stored Heat method provides a conservative estimate suitable for complex geothermal systems such as Dieng, while the Power Density method offers an empirical approach based on the tectonic characteristics of the field setting.

The input parameters used in the calculation of both methods are summarized in **Table 2** and **Table 3**. For the Power Density method, the power density reference comes from (Wilmarth et al., 2021), key parameters such as a power density range of 5-10 MW/km², reservoir initial temperature (260-338°C), and a fixed reservoir area (11.7 km²) are used as the basis for estimating electricity capacity. Meanwhile, the Volumetric Stored Heat method takes into account more reservoir parameters, including reservoir thickness, porosity, water saturation, as well as other factors such as recovery factor and electricity conversion efficiency. The probabilistic distribution of each parameter is modeled using a Monte Carlo approach to generate reserve probability estimates at P10, P50, and P90 confidence levels.

The combination of these two methods, which use input parameters from the table, ensures that the calculation results are not only realistic but also cover a wide range of possible scenarios that reflect the complexity of the Dieng Field reservoir. This approach provides a solid basis to support the sustainable development of the field.

Table 2. Input Parameters Using the Power Density Method

Variable	Unit	Min	Max	Most Likely	Distribution
Ti	°C	260	338		Rectangular
Tf	°C			180	Fix
Power Density	MW/Km^2	5	10		Rectangular
Area	Km^2			11.7	Fix

Table 3. Input Parameters Using the Volumetric Stored Heat Method

Variable	Unit	Min	Max	Most Likely	Distribution
Area	Km^2			11.7	Fix
Thickness	m	1000	1500		Rectangular
Rock Density	Kg/m^3			2650	Fix
Porosity	Fraction	0.05	0.1		Rectangular
Rock Heat Capacity	kJ/kg°C			1	Fix
Ti	°C	260	338		Rectangular
Tf	°C			180	Fix
Water Sat. Init.	Fraction	0.88	0.93		Rectangular
Water Sat. Fina.	Fraction	0.3	0.6		Rectangular
Recovery Factor	Fraction	0.1	0.17		Rectangular
Life Time	Year			30	Fix
Conversion Efficiency	Fraction			0.12	Fix

JOURNAL OF PETROLEUM AND GEOTHERMAL TECHNOLOGY
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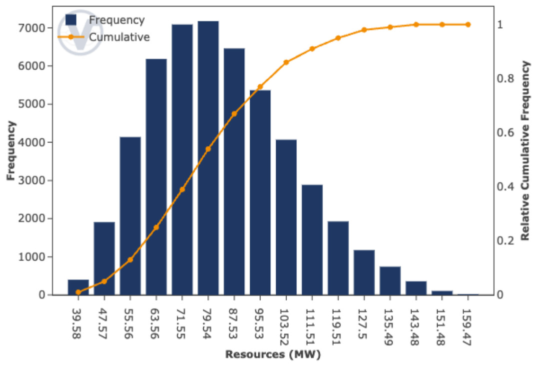
Vol. 6 No. 1 2025

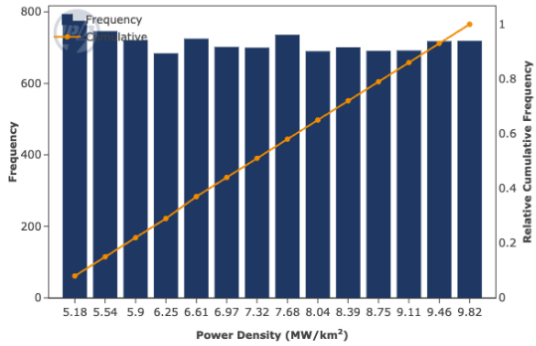
The simulation results of estimating the potential of geothermal resources in Dieng Field using two methods, namely Volumetric Stored Heat and Power Density, are summarized in **Table 4**. The Monte Carlo simulation produces reserve categories based on probability confidence levels, namely P10 (Proven), P50 (Probable), and P90 (Possible).

Table 4. Simulation Results of Reserve Determination

Metode	P10 (MWe)	P50 (MWe)	P90 (MWe)
Volumetric	56.91	81.38	113.41
Power Density	64.22	88.13	111.22



(a)



(b)

Figure 6. Frequency Graph of Potential Reserves, (a) Volumetric Method, (b) Power Density Method

The simulation results of estimating the potential of geothermal resources in Dieng Field using two methods, namely Volumetric Stored Heat and Power Density, are summarized in **Table** 3. The Monte Carlo simulation produces reserve categories based on probability confidence levels, namely P10 (Proven), P50 (Probable), and P90 (Possible).

For the Volumetric Stored Heat Method, the reserve estimate at confidence level P10 is 56.91 MW, P50 is 81.38 MW, and P90 reaches 113.41 MW. The probability distribution graph in **Figure 6** (left) shows that this method produces a skewed data distribution, reflecting the sensitivity to variability in input parameters such as reservoir thickness and water saturation. Meanwhile, the Power Density Method provides higher estimates at the P50 and P90 confidence levels than the Volumetric method. The results are 64.22 MW for P10, 88.13 MW for P50, and 111.22 MW for P90. The probability distribution graph in **Figure 6** (right) shows a more uniform distribution pattern of the data, in accordance with the empirical approach based on the power density values.

A comparison of the two methods shows that the Volumetric Stored Heat method tends to provide conservative estimates, while the Power Density method provides more optimistic estimates. The combination of these two methods provides additional validation to ensure more accurate estimates, taking into account reservoir complexity and input data variability.

IV. CONCLUSION

Based on the results of calculations using the Volumetric Stored Heat and Power Density Method supported by Monte Carlo simulations using JIWA Power Density and JIWA Volumetric software, the following conclusions were obtained:

1. The use of both calculation methods, namely Volumetric Stored Heat and Power Density, is helpful in providing a more accurate estimation of geothermal resource potential. The Volumetric method provides conservative results suitable for geothermal systems with complex characteristics such as Dieng Field, while the Power Density method provides a more optimistic empirical approach.
2. The electricity potential calculation results from the Volumetric Method show an estimated P10 of 56.91 MW, P50 of 81.38 MW, and P90 of 113.41 MW. Meanwhile, the Power Density Method resulted in an estimated P10 of 64.22 MW, P50 of 88.13 MW, and P90 of 111.22 MW.
3. Monte Carlo simulation provides a probabilistic picture of potential reserves with varying confidence levels (P10, P50, and P90), which is the basis for decision making at the Dieng Field development stage.

4. The combination of these two methods provides additional validation to ensure the accuracy of geothermal reserve potential calculations, supports sustainable reservoir management, and provides a solid basis for further field development.

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