Application of Numerical Simulation Method with Experimental Design in the Sibayak Geothermal Field, Indonesia

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ABSTRACT

This paper presents a comprehensive method for estimating geothermal field resources through numerical simulation, demonstrated through a case study of the Sibayak field. However, due to limited available data and the need to reduce subjectivity, significant uncertainties remain that must be addressed. To manage these uncertainties, an experimental design approach is employed.

The primary objective of applying experimental design in geothermal simulation is to systematically assess the impact of uncertain reservoir parameters such as liquid saturation, permeability, porosity, and fracture properties on model outputs that influence pressure, enthalpy, and production sustainability. By generating a structured set of simulation scenarios, this approach helps identify the key parameters that have the greatest effect on field performance and quantifies the probability of achieving long-term production targets.

The simulation process begins with data preparation, model construction, and the conversion of the static Sibayak model. This is followed by natural state simulation and calibration using available production history data from wells such as SBY-3, SBY-5, SBY-6, and SBY-8. Once a satisfactory history match is achieved, the model is used to forecast future production. The experimental design method is then applied to evaluate the probability of the Sibayak field sustaining production throughout the contract period.

The integration of numerical simulation and experimental design offers a structured and quantitative framework for addressing subsurface uncertainties. This combined approach improves confidence in decision making by providing a more realistic estimate of the field's long-term production potential.

1. INTRODUCTION

The Sibayak Geothermal Field is located in Berastagi, Karo Regency, North Sumatra, Indonesia. The field lies on Mount Sibayak, a relatively young volcano situated within the Singkut Caldera, at an average elevation of 1,400 meters above sea level (Figure 1). Initial studies were conducted from 1989 to 1991, which concluded that Mount Sibayak represents a promising area for geothermal development. Three exploration wells were subsequently drilled in 1991, followed by the drilling of seven production wells up to 1997. All wells encountered partial to total loss of circulation due to penetration of pre-Tertiary sedimentary rocks.

The Sibayak Geothermal Field began operation in 2008 with a production capacity of 10 MW. The initial numerical model was developed in 2001 based on limited drilling and exploration data. More recent geological field surveys, as well as magnetotelluric and gravity surveys, have been conducted to support the refinement of the conceptual model. This model was subsequently updated using more detailed and comprehensive data. Nevertheless, uncertainties remain in light of the available data, particularly regarding reservoir parameters and system responses under various operational scenarios. Therefore, an approach that minimizes subjectivity in the analysis and decision-making processes is required, one of which is the application of experimental design in reservoir simulation.

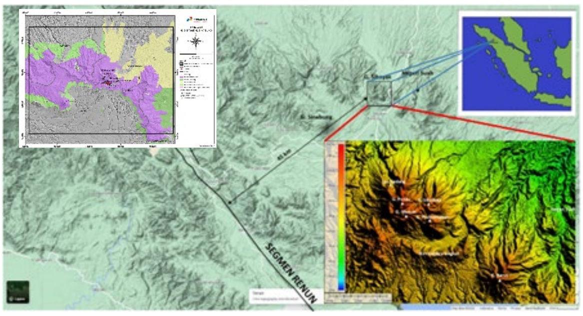

Figure 1: Location of the Sibayak Field.

2. METHODOLOGY

This methodology aims to reduce uncertainty in geothermal reservoir simulation through the application of experimental design. By using this approach, various simulation scenarios are systematically designed to identify the influence of key reservoir parameters on model outputs, such as saturation, porosity, and permeability. Each variable is set at two levels: a low level coded as -1 and a high level coded as +1. The coded variable for the i-th factor is represented as:

$$x_i = \frac{X_i - X_{01}}{\Delta X_i} \quad (1)$$

Where:

X_i = actual value of the i-th factor

X_{0i} = center point (mean) of the factor

ΔX_i = half-range of the factor, defined as $(X_{high} - X_{low})/2$

The mathematical model in the experimental design is expressed by the following equation:

$$Y = \beta_0 + \sum_{i=1}^{k} \beta_i x_i + \sum_{i<j} \beta_{ij} x_i x_j + \epsilon \quad (2)$$

Where:
β_0 = constant (intercept)
β_i = main effect of the i-th factor

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βij= interaction effect between factors i and j
ϵ = error

To provide a clearer and more structured understanding of the method, Figure 2 presents a general flowchart of the experimental design process, starting from the development of the simulation model to the generation of probabilistic data on megawatt potential.

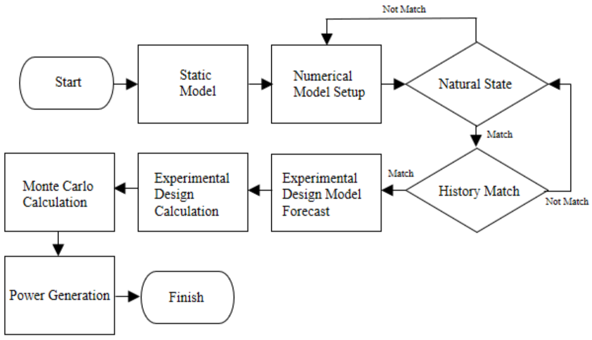


Figure 2. Methodology Flowchart

3. CONCEPTUAL MODEL UPDATE

The geothermal system developed within the Sibayak Geothermal Field is a volcanic-hosted system situated on Mount Sibayak (Figure 3). It is characterized by a high-standing, convective, high-temperature reservoir located beneath the summit region of the volcano. The reservoir is associated with the conduit zones of two small stratovolcanoes situated within a partially infilled, compact caldera (Hochstein et al., 2015).

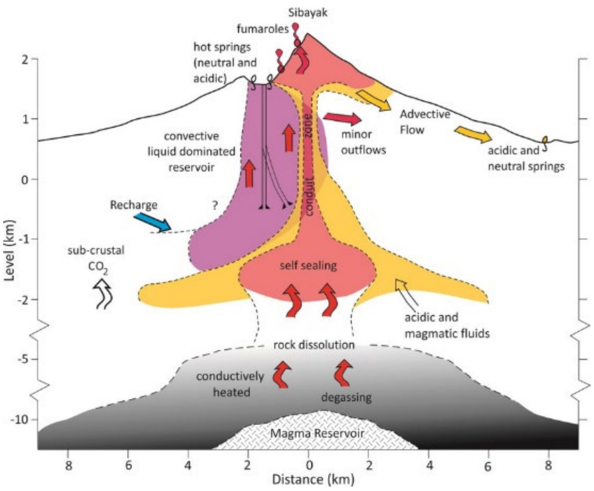


Figure 3. Conceptual model nof a volcanic-hosted geothermal system (adapted from Hochstein et al., 2015).

The presence of various complex surface manifestations within the Singkut Caldera, along with the intensively altered zone confined to Mount Sibayak, indicates that the upflow zone is located within and directly beneath the mountain (Figure 4). This interpretation is further supported by recent geochemical analyses of several manifestation samples, which reveal that the fluids are predominantly influenced by magmatic volatiles rather than meteoric water contributions.

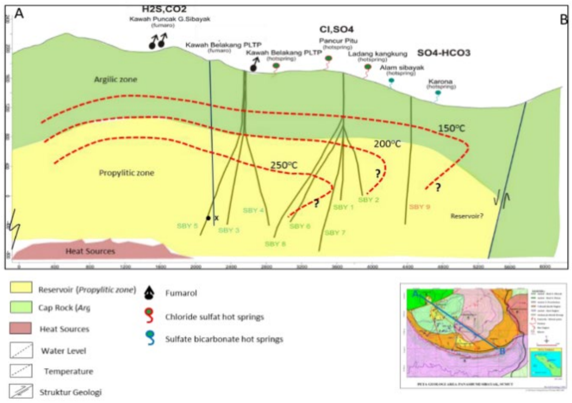


Figure 4: Conceptual model of Sibayak geothermal system (PGE, 2022).

Magnetotelluric (MT) studies reveal low resistivity values associated with an altered hydrothermal clay cap, approximately 700–1000 meters thick. These results indicate the presence of an updoming heat source beneath Mount Sibayak. Furthermore, MT data suggest that the hydrothermal outflow extends roughly 3 kilometers towards the east-southeast.

Local structures within the Sibayak Geothermal Field exhibit dominant orientations of NW–SE and NE–SW. In addition to the extensive fracturing, three major faults—namely the Tengkorak Fault, the Semangat Gunung Fault, and the Pariban Fault—play a significant role as conduits for hydrothermal activity and as sources of secondary permeability. A ring fault is also present within the Singkut Caldera, further enhancing secondary permeability and facilitating hydrothermal flow. The ring fault additionally serves as the main recharge zone for the geothermal system. Unlike the isotherms depicted in the previous conceptual model, the updated model incorporates the effects of recharge flow into the reservoir as well as the extent of the outflow zone. As a result, the revised conceptual model provides a more accurate representation of the reservoir's behavior and characteristics.

The lithology within the Sibayak Geothermal Field comprises pyroxene andesite, dacite, diorite, pyroclastic breccia, volcaniclastic tuff-lapilli, as well as Tertiary to Pre-Tertiary metasediments consisting of fine-grained sandstone and silt. As a geothermal system that developed within a caldera, volcanic activity in the area plays a crucial role in generating primary permeability, with lateral permeability largely controlled by the volcaniclastic lithologies. The main reservoir is hosted within the metasedimentary sandstone, as indicated by the occurrence of epidote alteration and the total to partial loss of circulation observed during well drilling. Additionally, faults and fractures within the field significantly enhance the secondary permeability of the reservoir.

4. NUMERICAL SIMULATION

4.1 Data Preparation

The development of a reliable reservoir simulation model for geothermal systems fundamentally relies on comprehensive and integrated data preparation. The input data must represent all subsurface disciplines, including Sibayak geological, geophysical, and geochemical components that form the geothermal conceptual model. These data typically consist of static model reports, rock properties, structural models and geochemical trends for both wells and surface manifestations, such as non-condensable gas (NCG) content, total dissolved solids (TDS), chlorides, silica, and pH values. Geophysical information, including micro-seismic monitoring, resistivity, gravity, and magnetic surveys, further contributes to defining the subsurface conditions and supporting the construction of a robust numerical model.

In addition to the conceptual model, historical performance data of Sibayak wells and power plants play a critical role in describing reservoir dynamics. This includes production and injection rates (steam, brine, and total mass), wellhead pressures, production enthalpy, flow control valve positions, and downhole pressure monitoring results. Data from temperature and flow tests (TFT), pressure-temperature (PT) measurements, and PTS surveys provide further insights into the subsurface conditions. The results of the SBY PT survey data analysis encompass undisturbed temperature, static pressure, and pivot point pressure. These data points will be utilized for reservoir simulation calibration during the Natural State modeling phase.

The results of the pivot point pressure analysis indicate that all wells exhibit a consistent trend, with pivot values converging over a significant depth range (Figure 5). Similarly, the static pressure plots for each well demonstrate a corresponding trend.

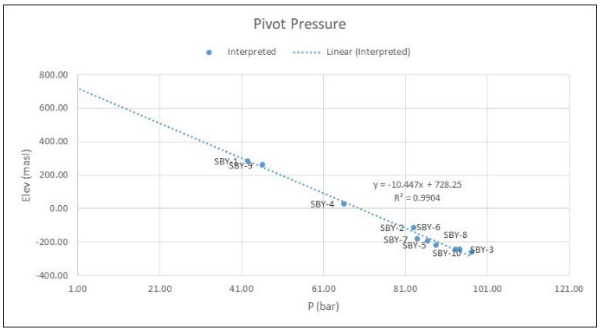


Figure 5. QC Process of SBY Pressure Data

The Injectivity Index from Gross Permeability test is utilized to calculate the permeability. The multiplier for Productivity Index was assumed to be 0.7. This data is obtained base on empirical study.

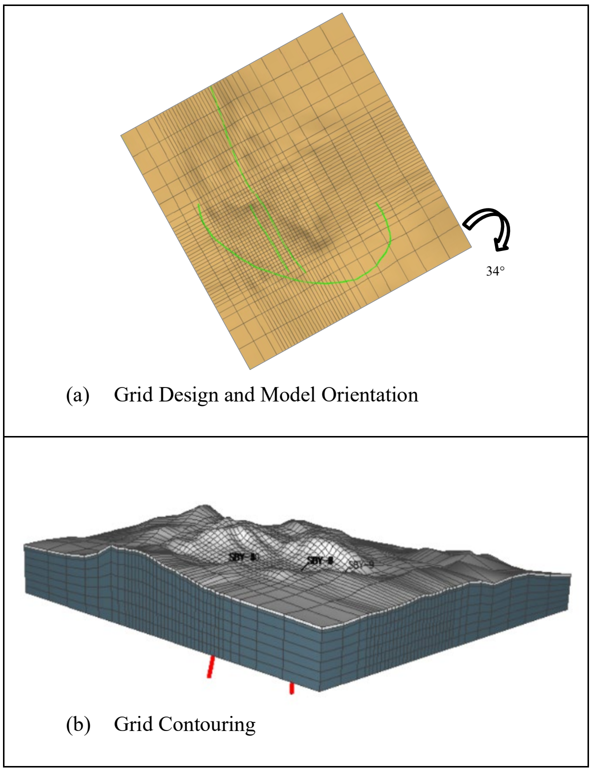
Similarly, gross and net power generation, along with operating pressures at separators and plant inlets, are essential for representing surface plant performance and for calibrating the model against actual field operation data.

Furthermore, technical records such well completion data, drilling and workover histories, and initial and comprehensive well test reports are necessary to refine the model's accuracy, surface piping system layouts, and previous numerical model reports provide valuable context for future field development and model validation. The availability and quality of these datasets significantly influence the reliability of the simulation results, which ultimately support scenario analysis, resource management, and decision-making for sustainable geothermal development.

4.2 Grid Design

The Sibayak reservoir model was developed using TOUGH2-based software, employing the first Equation of State module (EOS1). EOS1 assumes that the fluid within the system consists of pure water. The model covers an area of 60 km², with dimensions of 7.5 km by 8 km, and is oriented northwest–southeast, rotated 34° clockwise from the north to align with the main fault.

The x-axis of the model grid is discretized into 35 cells, while the y-axis consists of 38 cells (Figure 6). The topography of the Sibayak field was incorporated into the model, with elevations ranging from a maximum of +2100 m above sea level to a depth of -2000 m. The model comprises 20 layers, which are further categorized into five distinct zones: atmosphere, groundwater, caprock, reservoir, and basement. The cell size within the grid varies between 100 and 800 meters, depending on the area of interest and data availability. The model consists of a total of 26,600 cells, including additional cells at the base to enhance boundary representation. This updated model provides significantly greater detail and resolution compared to the previous model developed by Atmojo et al. (2001), which comprised 165 lateral cells across 7 layers, totaling 1155 cells.



(a) Grid Design and Model Orientation

(b) Grid Contouring

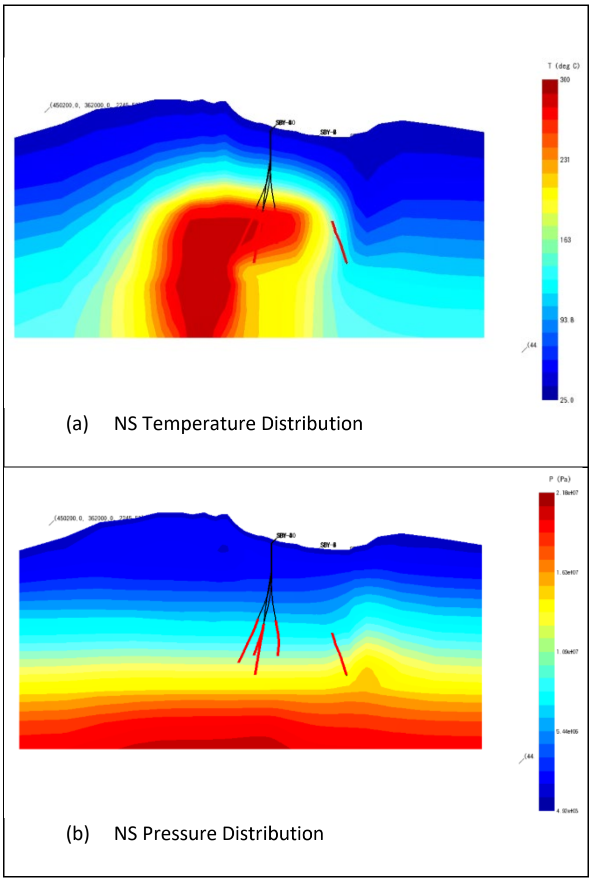
Figure 6. Grid design of SBY model

The reservoir section exhibits greater complexity due to reduced uncertainty stemming from the known temperature and pressure distributions of the wells. Feedzone data indicates that permeability in most wells is primarily controlled by the Tengkorak Fault and the Semangat Gunung Fault, both of which must be incorporated into the model. Furthermore, temperature distribution analysis suggests the need to divide the reservoir into two sections, as wells SBY-01, SBY-02, and SBY-09 exhibit lower temperatures.

3.1 Natural State

In this model, all available wells were incorporated into the P-T matching process to achieve a more comprehensive calibration. The natural state (NS) simulation was performed for 3.16 × 10^{12} seconds to ensure steady state were reached. Figure 7 presents the pressure-temperature distribution generated from the simulation alongside the actual measured data for each well. Overall, the simulated profiles exhibit a good agreement with the measured data, particularly within the reservoir zone. Satisfactory matches were obtained for wells SBY-3, SBY-4, SBY-6, SBY-7, SBY-8, and SBY-9. Although minor discrepancies are observed in some wells, the temperature trends generally remain consistent, especially in the reservoir zone. Deviations from the model are primarily located in the cap rock and shallower zones, which are of lesser concern, as the focus of the natural state calibration is on accurately representing the reservoir conditions.

The natural state model shows that the temperature distribution in the Sibayak field forms a tongue-shaped pattern extending southeast, indicating an outflow zone. In contrast, heat in the upflow region rises vertically from a heat source beneath Mount Sibayak. This behavior is clearly illustrated in the vertical cross-section presented in Figure 7. Overall, the natural state model effectively represents the updated conceptual model of the field.



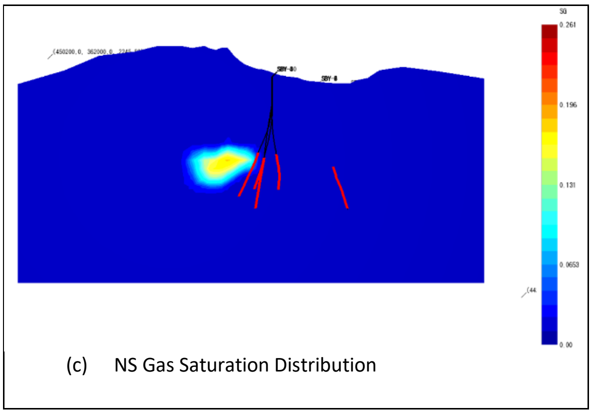


Figure 7. NS distribution

4.3 Production History Match

Sibayak field production and injection history data was collected on a time interval basis. Sources of information used were obtained from digitized presentation files and reports, and in certain time intervals information was taken from raw data in MS Excel format. The data obtained for production wells is the mass of vapor after separation, separator pressure, and wellhead pressure. The data obtained for the injection wells is the mass of brine.

The history matching was carried out using production-injection history data from 2004-2011. The calibration was done to match both the enthalpy from the production data and the static pressure from the PT shut-in data. In general, the history match showed fairly good results for wells SBY-3, SBY-5, and SBY-8. At SBY-3, the pressure matched at 80 bar, and the enthalpy also matched at around 1200 kJ/kg. The SBY-5 well also showed reasonably good matching for a pressure of around 90 bar, as well as for the enthalpy. Meanwhile, for the SBY-8 well, the actual and simulated pressures also matched fairly well. However, the enthalpy did not match very well, with the simulated enthalpy was lower than actual data.

5. EXPERIMENTAL DESIGN

The experimental design (ED) methodology was applied to the Sibayak reservoir numerical model with the objective of evaluating the dependency of production capacity (MW) along production life on key uncertain reservoir parameters. Additionally, the study aimed to develop a proxy model in the form of a polynomial equation that represents the reservoir simulation results, to enable its integration into probabilistic Monte Carlo simulations. In this case, full factorial design was implemented to test all level combinations.

Five primary reservoir parameters were selected for investigation such as liquid saturation (S_L), matrix porosity (ϕ_m), fracture permeability (k_f), fracture volume fraction, and fracture spacing. The liquid saturation was set within a range of 0.3 to 0.5. While the remaining four variables were assigned ranges corresponding to ±25% deviation from their respective base values, as summarized in Table 1.

Table 1: Selected reservoir parameters and their corresponding levels for experimental design

Parameter	Low (-1)	High (+1)
Liquid Saturation, S_L	0.3	0.5
Matric Porosity, ϕ_m	-25%	25%
Fracture Permeability, k_f	-25%	25%
Fracture Vol Fraction, *FVF*	-25%	25%
Fracture Spacing, S_f	-25%	25%

Given the number of parameters, the total number of simulation runs was 32 (2^5). The experiments were conducted in random order, as presented in Table 2, which summarizes the run combinations for the experimental design.

Table 2: Experimental design run combinations

Run	S_L	ϕ_m	k_f	*FVF*	S_f
1	-1	-1	-1	-1	-1
2	-1	-1	-1	-1	1
3	-1	-1	-1	1	-1
4	-1	-1	-1	1	1
5	-1	-1	1	-1	-1
6	-1	-1	1	-1	1
7	-1	-1	1	1	-1
8	-1	-1	1	1	1
9	-1	1	-1	-1	-1
10	-1	1	-1	-1	1
11	-1	1	-1	1	-1
12	-1	1	-1	1	1
13	-1	1	1	-1	-1
14	-1	1	1	-1	1
15	-1	1	1	1	-1
16	-1	1	1	1	1
17	1	-1	-1	-1	-1
18	1	-1	-1	-1	1
19	1	-1	-1	1	-1
20	1	-1	-1	1	1
21	1	-1	1	-1	-1
22	1	-1	1	-1	1
23	1	-1	1	1	-1
24	1	-1	1	1	1
25	1	1	-1	-1	-1
26	1	1	-1	-1	1
27	1	1	-1	1	-1
28	1	1	-1	1	1
29	1	1	1	-1	-1
30	1	1	1	-1	1
31	1	1	1	1	-1
32	1	1	1	1	1

The reservoir simulation was conducted using a wellhead pressure (WHP) of 10 bar and a productivity index (PI) value of 4.32 $\times 10^{13}$ m^2. The model included 213 production wells targeting feedzones within a depth range of 330 to −164 masl (Figure 8). In addition, the model incorporated 34 reinjection wells operating at a flow rate of 115 kg/s with an enthalpy of 251 kJ/kg.

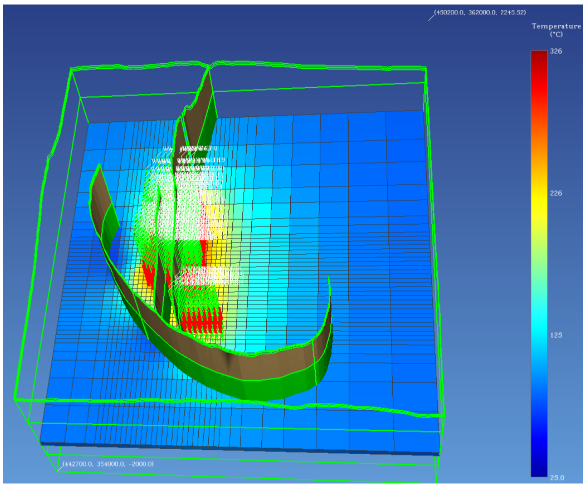


Figure 8. Experimental design wells setup

The power output was calculated using the following equation:

$$MW_e = \frac{\sum m \times \Delta t}{L \times SSC} \qquad (3)$$

where:

m = steam production rate (kg/s)

Δt = time interval (years)

MW_e = electric power output (megawatts)

SSC = specific steam consumption (kg/s per MW)

The output results of the experimental design indicate that the Sibayak geothermal field has an estimated electric power output (MWe) within the range summarized in Table 3.

Table 3: Experimental design run results and corresponding power output (MWe).

Run	MW	Run	MW	Run	MW	Run	MW
1	29.45	9	30.26	17	29.33	25	29.84
2	29.17	10	29.79	18	28.89	26	29.51
3	30.19	11	30.35	19	29.89	27	30.33
4	29.87	12	29.94	20	29.54	28	29.94
5	30.53	13	31.56	21	30.08	29	30.89
6	30.45	14	31.03	22	29.86	30	30.55
7	31.65	15	31.82	23	30.85	31	31.51
8	31.36	16	31.20	24	30.71	32	31.16

Subsequently, a correlation was established between each parameter and the power output (MW), resulting in the following equation:

$$\begin{aligned} MW_e \; = \; & 30.3595 - 0.1803S_L + 0.2450\emptyset_m \\ & + 0.5907k_f + 0.2847FVF \\ & - 0.1732FS + 0.0408S_L\,\emptyset_m \\ & - 0.0693S_Lk_f + 0.0254S_LFVF \\ & + 0.0136S_L\,FS + 0.0193\emptyset_m\,k_f \\ & - 0.1081\emptyset_m\,FVF - 0.0413\emptyset_m\,FS \\ & + 0.0469k_f\,FVF + 0.0137k_f\,FS \\ & - 0.0061FVF\,FS \end{aligned} \qquad (5)$$

After establishing the correlation from the experimental design (equation 5), a Monte Carlo simulation was carried out with 50,000 iterations. This generated cumulative probability curves and power output estimates, as illustrated in Figure 9. The results indicate that the Sibayak Geothermal Field has a P10 power output of 29.80 MW, a P50 of 30.35 MW, and a P90 of 30.95 MW.

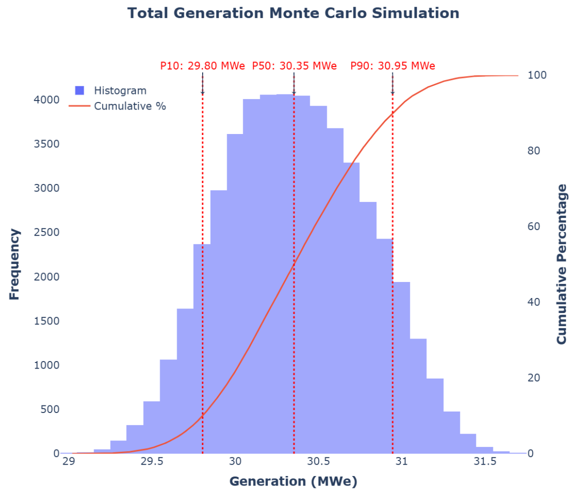


Figure 9. Results of the Monte Carlo simulation showing power output (MW) and cumulative frequency distribution.

6. CONCLUSION

1. The numerical model of the Sibayak geothermal field has been successfully developed and calibrated, demonstrating a strong correlation with the conceptual model and historical production data. Where upflow of sibayak is located beneath the mount sibayak and the outflow flowing to southeast. This validation confirms the reliability of the model as a foundation for further scenario analysis.
2. The implementation of experimental design techniques within the numerical simulation process has proven effective in optimizing the calibration workflow. By systematically varying key reservoir parameters, the approach enabled identification of the most influential variables affecting reservoir performance, thereby improving model robustness and predictive capability.
3. A probabilistic power potential assessment was also conducted using Monte Carlo simulations in combination with experimental design results. The outcome indicated an estimated generation capacity of approximately ±30 MW.

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