APPLICATION OF MONTE CARLO TO ESTIMATE GEOTHERMAL RESOURCE USING VISUAL BASIC: A CASE STUDY OF SIBAYAK GEOTHERMAL FIELD IN KARO, NORTH SUMATRA, INDONESIA

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Abstract

The assessment of geothermal energy reserves within the Sibayak Geothermal Field employs both the volumetric method and Monte Carlo probability simulation. This approach hinges on reservoir physical parameters to derive meaningful insights. The simulation results yield a probability distribution for the comprehensive system value, thereby establishing a range of probability values that encompass proven (P90), probable (P50), and suspected (P10) geothermal reserves classifications. Executing the intricate Monte Carlo calculation process manually is notably time-intensive. Thus, this study pioneers the development of a specialized software using Visual Basic Application, amplifying calculation efficiency and efficacy. Parameters pivotal to these calculations are derived from assumptions rooted in SNI 13-6482- 2000 standards, along with geoscience data and production test analyses from preliminary survey activities. Through the input of P10, P50, and P90 values for each parameter, encompassing factors like area (4.5, 7, and 19 km²), reservoir thickness (1074, 1190, and 1275m), rock density (2400, 2500, and 2600 kg/m²), porosity (0.1, 0.125, and 0.15), reservoir temperatures (226, 270, and 300 °C), recovery factors (0.1, 0.2, and 0.3), initial saturations (0.9, 0.95, and 0.99), and estimated final saturations (50%, 80%, and 90%), a comprehensive analysis emerges. The envisioned operational lifespan is set at 30 years, while the rock's heat capacity is acknowledged as 1 kJ/kg °C, culminating in a final temperature of 180°C. Through this comprehensive approach, pessimistic (P10), optimistic (P90), and most likely (P50) estimates of geothermal energy yield from the Sibayak geothermal field stand at 34 MW, 60 MW, and 101 MW, respectively.

Keywords: Volumetrics, Monte Carlo Simulation, Software, Geothermal Energy

Introduction

Geothermal energy is fundamentally derived from the Earth's heat—a renewable energy source that boasts qualities such as consistency, substantial energy density, stability, and environmental friendliness, largely due to its minimal exhaust emissions[8]. Indonesia, colloquially known as the Ring of Fire, boasts a substantial geothermal prowess, housing nearly 40% of the global geothermal potential. This potential finds expression in approximately 252 geothermal fields that span Indonesia's volcanic formations, collectively holding a remarkable potential of about 28 GWe[4]. Estimating this geothermal potential assumes paramount importance for the industry, serving as a benchmark for devising technical and economic strategies. The pursuit of potential geothermal reserves estimation typically falls within four main methodological categories: the Surface Thermal Flux method, Volume method, Planar Fracture method, and Magmatic Heat Budget method. Among these, the Volume method emerges as particularly apt for reservoirs characterized by lower temperatures, systematically guiding hypotheses toward proven reserves[3].

This study aims to compute potential geothermal reserves through the application of the volume method within the Sibayak geothermal field, utilizing a Monte Carlo probability simulation. The volume method delineates three key categories for estimating geothermal reserves: proven reserves, probable reserves, and possible reserves[9]. These categories are respectively denoted by P90 (90% probability), indicating proven reserves; P50, signifying proven and probable reserves; and P10, encompassing proven, probable, and possible reserves. The outcomes generated by the Monte Carlo simulation manifest as a histogram, presenting a comprehensive probability distribution for the entire system's value, encompassing a spectrum of probability values[10].

2. The Monte Carlo Simulation

The Monte Carlo Simulation method is employed to assess deterministic models that incorporate random numbers as inputs. This approach finds particular utility when dealing with intricate, nonlinear models or those reliant on multiple uncertain parameters. Often utilized for dissecting uncertainty propagation, this simulation technique endeavors to elucidate the impact of random fluctuations or errors on the sensitivity, performance, or reliability of the modeled system [5].

The outcomes of the Monte Carlo simulation computation materialize as a cumulative frequency distribution, which in turn confers a measure of confidence. Concerning price distribution, a collection of observed prices for a variable takes shape as a histogram frequency distribution, delineated by n observations within a price interval of Δx. In parallel, the frequency per unit price x across the interval Δx corresponds to the density of specific frequencies, denoted as w(x), expressed by the equation W(xi) = wi / Δx. To observe a variable within the price distribution, two distributions are utilized: the triangular distribution and the rectangular distribution. The triangular distribution postulates that variable observations fall within three estimated categories—most likely, minimum, and maximum. Fulfilling two conditions x ≤ b and x > b characterizes the triangular distribution [8]. Should the area of the triangle equate to one, the formulation aligns with the specifications detailed in Table 1, with the corresponding flowchart presented in Table 2:

Table 1. Formulation of the Triangular Distribution for x ≤ b and x>b and the Quadrilateral Distribution

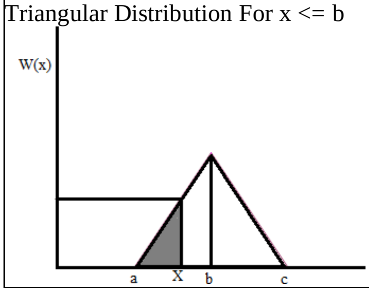
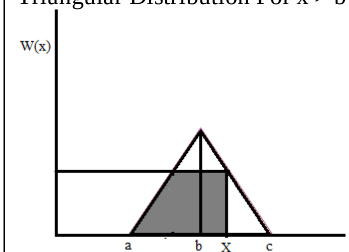
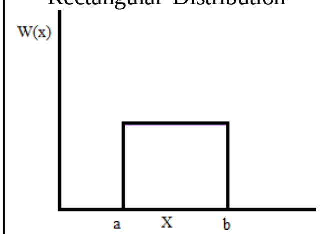
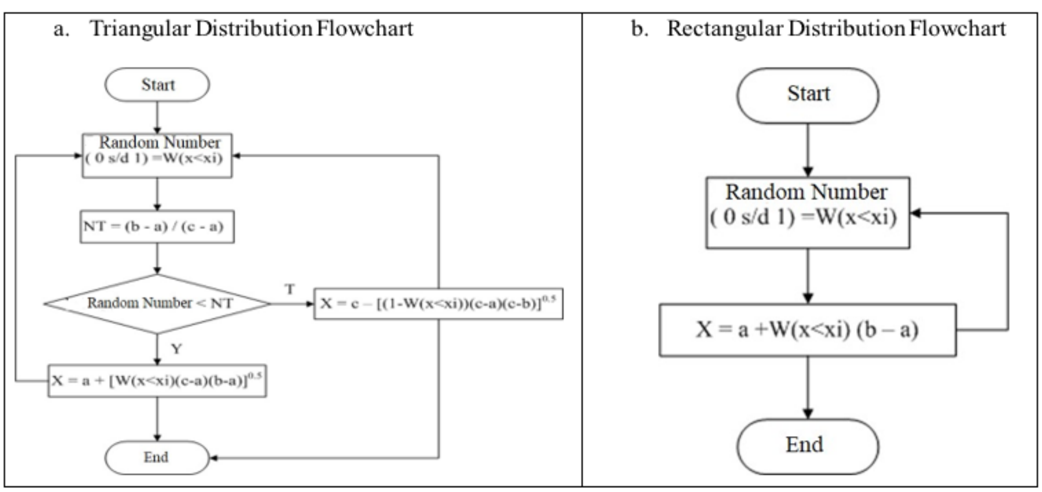
Triangular Distribution For x <= b	Triangular Distribution For x > b	Rectangular Distribution
		
Formulation: $W(x \le x_i) = \frac{(x-a)^2}{(b-a)(c-a)}$ (1)	Formulation: $W(x \le x_i) = 1 - \frac{(c-x)^2}{(c-b)(c-a)}$ (2)	Formulation: $W(x \le x_i) = \frac{(x-a)}{(b-a)}$ (3)

Table 2. Monte Carlo Flowchart Distribution of Triangles (a) and Quadrilaterals (b)



3. Calculation of Thermal Energy

The widely adopted technique for assessing geothermal resources is the volumetric method, elucidated by O'Sullivan (1986). This approach hinges on calculations grounded in the heat energy encapsulated within both the rock and fluid, as expressed in equation (6). Central to the volumetric method is the conceptualization of a geothermal reservoir resembling a rectangular (box) shape, the volume of which can be derived by multiplying the projected area containing geothermal fluid by its corresponding thickness. Within this method, the estimation of potential energy resources or reserves is underpinned by the reservoir's heat energy content. This content encapsulates the cumulative thermal energy enshrined in both the geothermal rock and fluid.

$$H_E = Q_r + Q_e \tag{4}$$

Where:

$$Q_r = Ah(1-\phi)\rho_r c_r (T_i - T_f) \tag{5}$$

$$Q_e = Ah\phi(S_L \rho_L u_L + S_v \rho_v u_v) \tag{6}$$

The amount of heat energy that can be utilized and converted into electrical energy can be calculated using the following procedure:

Calculate the energy content in the initial state or the amount of geothermal resources with the following equation (7).

$$H_{Ei} = Ah\left[(1-\phi)\rho_r c_r T_i + \phi(S_L \rho_L u_L + S_v \rho_v u_v)_i\right] \tag{7}$$

Calculate the energy content in the final state (T final):

$$H_{Ef} = Ah\left[(1-\phi)\rho_r c_r T_f + \phi(S_L \rho_L u_L + S_v \rho_v u_v)_f\right] \tag{8}$$

Calculate the maximum usable energy:

$$H_{th} = H_{Ei} + H_{Ef} \tag{9}$$

Calculate geothermal energy that can be utilized in reality (= the amount of reserves when expressed in kJ):

$$H_{de} = R_f H_{th} \tag{10}$$

Calculate the amount of reserves, namely heat energy that can be utilized for a period of t years (usually 25-30 years) with the following equation: Hthermal has units of MWthermal

$$H_{thermal} = \frac{H_{de}}{t x 365 x 24 x 3600} \tag{11}$$

Calculate the magnitude of the electric potential, namely the electrical energy that can be generated for a period of t years (MWe) in the following way:

$$H_{el} = \eta H_{thermal} \tag{12}$$

where:

T_i = Reservoir temperature at initial state (^{0}C)
T_f = Reservoir temperature at final state (^{0}C)
H_{Ei} = Energy content in rocks and fluids at the initial state, kJ
H_{Ef} = Energy content in rocks and fluids in the final state, kJ
H_{th} = Maximum utilization of geothermal energy, kJ
H_{de} = Geothermal energy that can be utilized in fact, kJ
$H_{thermal}$ = Geothermal energy that can be utilized for a certain period of time, MWe
H_{el} = Electrical energy that can be generated for a certain period of time, MWe
R_f = Gain factor, %
t = Length of time (age) of electricity generation (years)
η = Electrical conversion factor

Result and Discussion

The determination of reserve resources and the potential for geothermal electricity is impeded by the limited availability of comprehensive "data." This data availability hinges on the extent of activities and surveys conducted within the region. As exploration and exploitation endeavors intensify, more precise and reliable data are acquired, enhancing the confidence level of the calculations. Beyond survey data, a multitude of parameters remains uncertain and often necessitates assumptions. Predominantly, uncertainty revolves around factors like water saturation and vapor saturation in the final state (Tfinal)[8]. This uncertainty spectrum, stemming from data quality and quantity, leads to the classification of geothermal electricity resources, reserves, and potential into three categories: proven, probable, and possible[7]. Expressing the probability that recoverable reserves match or exceed estimations, percentile values come into play. The utmost assurance lies with the Proven potential at P90 (90th percentile), derived from data encompassing a minimum of one exploration well and two delineation wells. The Probable class potential (P50) carries a diminished level of certainty compared to the Proven category and relies on data from one exploration well. Further down the certainty scale, the Predicted potential (P10) is grounded solely in geological, geochemical, and geophysical survey data, bringing about the lowest level of certainty[3].

The fundamental approach of the volumetric method centers on quantifying the thermal energy contained within the Sibayak geothermal reservoir. This intricate evaluation hinges on a set of interconnected parameters, encompassing rock attributes (such as area, thickness, initial water saturation, and porosity) as well as energy-related factors (comprising rock temperature and heat capacity). This reservoir's heat content is subsequently transmuted into electrical power, a process that duly considers temporal aspects, reservoir yield factors, and the efficacy of electricity conversion. The precision of each parameter influencing volumetric reserve calculations, as elucidated earlier, is governed by its own realm of uncertainty. These uncertainties are rooted in the diverse distribution of physical properties of the rock, temperature variations, the intricate geometry of the reservoir, and operational fluctuations that reverberate through recovery and conversion efficiency factors. To effectively address these complexities, a Monte Carlo simulation is employed, engendering a probabilistic spectrum of potentials. The meticulous definition of the lower and upper bounds for each variable becomes imperative in order to accurately pinpoint potential risks.

4.1 Reservoir thickness

To determine the distribution of reservoir thickness, reservoir thickness data from each well are collected. The determination of the thickness of the reservoir for each well is the difference in height between the top reservoir and the inner reservoir boundary. Top reservoir delineation from well data is based on findings which include:

- Conductive and convective zone transitions (sometimes it is difficult to distinguish for two-phase reservoirs because the pressure gradient for each is high so that the temperature gradient is also high, except when cases of interzonal flow or cold-water intrusion are encountered)
- Permeable zone of drilling break data during drilling
- High temperature >225 0C
- Subsurface alteration
- Epidote minerals

Due to the lack of sufficient information regarding alteration and minerals, the determination of the top reservoir is only based on the findings of the first 3 points. The results are shown in Table 3.

Table 3. Sibayak Field Top Reservoir Distribution

Wells	Reservoir Top Elevation (masl)
SBY-1	230
SBY-2	Not Penetrating Reservoir
SBY-3	200
SBY-4	35
SBY-5	210
SBY-6	180
SBY-7	90
SBY-8	180
SBY-9	380
SBY-10	Not Penetrating Reservoir

In order to project the reservoir's thickness, insights into its lower boundary are imperative. Consequently, a pragmatic approach is adopted: over the upcoming 30-year developmental span, production contribution will exclusively emanate from the reservoir's upper strata, specifically limited to an elevation no lower than -1000 masl. Beyond this depth, the reservoir's permeability diminishes in efficacy. This framework enables the computation of the reservoir thickness frequency, culminating in the derivation of a probabilistic distribution depicted in Table 5.2 and Figure 1. The resultant reservoir thickness metrics, representing the p10, p50, and p90 percentiles, materialize at 1074, 1190, and 1275 meters, respectively.

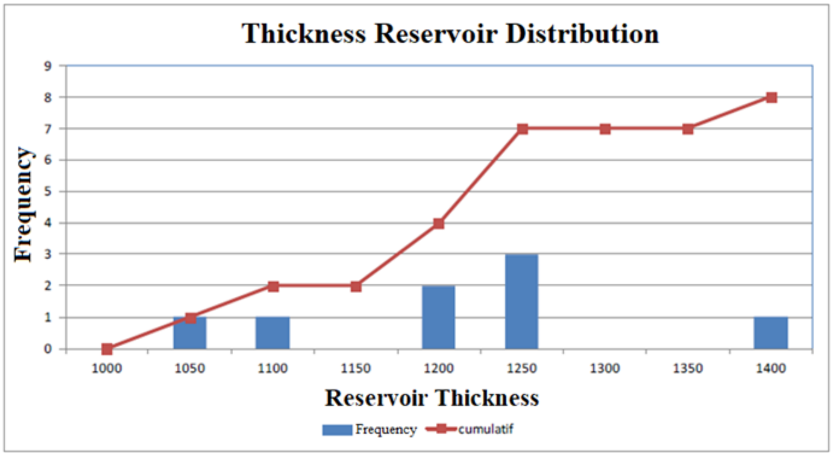


Figure 1. Reservoir Thickness Distribution

4.2. Area

The Sibayak prospect area encompasses a total expanse of 4.5 km² for P10, P50, and P90 metrics, while extending to 7 km² and 19 km² for the P50 and P90 levels, respectively. These spatial confines are meticulously delineated through a synthesis of drilling data and comprehensive geoscientific analyses. The northern extent of this promising zone is demarcated by the last fumarole manifestation plus an additional 500 meters, as this distance signifies the outermost boundary influenced by fumarole impacts on both surface and subsurface dynamics. The western border finds its definition in the Singkut rim caldera, supplemented by geophysical gravity data showcasing elevated anomalies contiguous with the caldera's periphery. On the opposite side, the southern and eastern perimeters are established via reference to the Singkut rim caldera, while the eastern boundary gains precision from additional input provided by MT data.

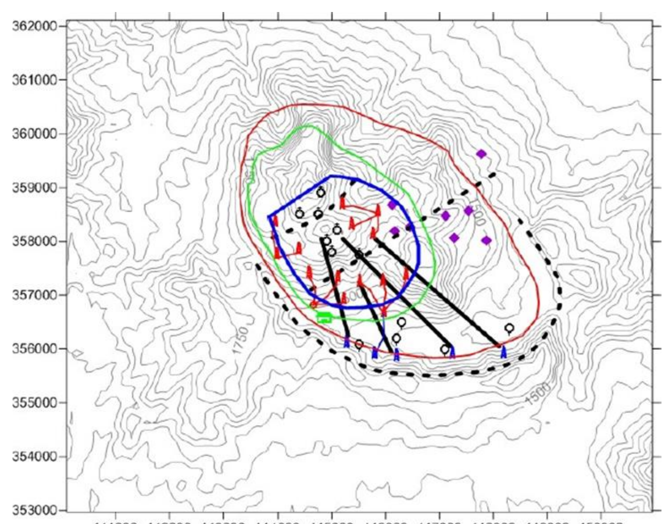


Figure 2. Minimum, maximum, and most likely values of area (km2)

4.3. Reservoir Temperature

The evaluation of reservoir temperature entails the compilation of temperature data from each well. The lower threshold for temperature, conservatively indicative of the reservoir zone, is established at 220°C. Through the determination of temperature ranges and subsequent frequency calculations across all wells, a graphical representation in Figure 3 illustrates the resultant probabilistic distribution. Within this context, the p10, p50, and p90 percentiles manifest as 226°C, 270°C, and 300°C, respectively. Notably, within the p90 range, the potential for even higher temperatures emerges, with projections hovering around ~300°C. This anticipation stems from the contemplation of drilling activities being directed towards the Northwest vicinity of the SBY-05 well.

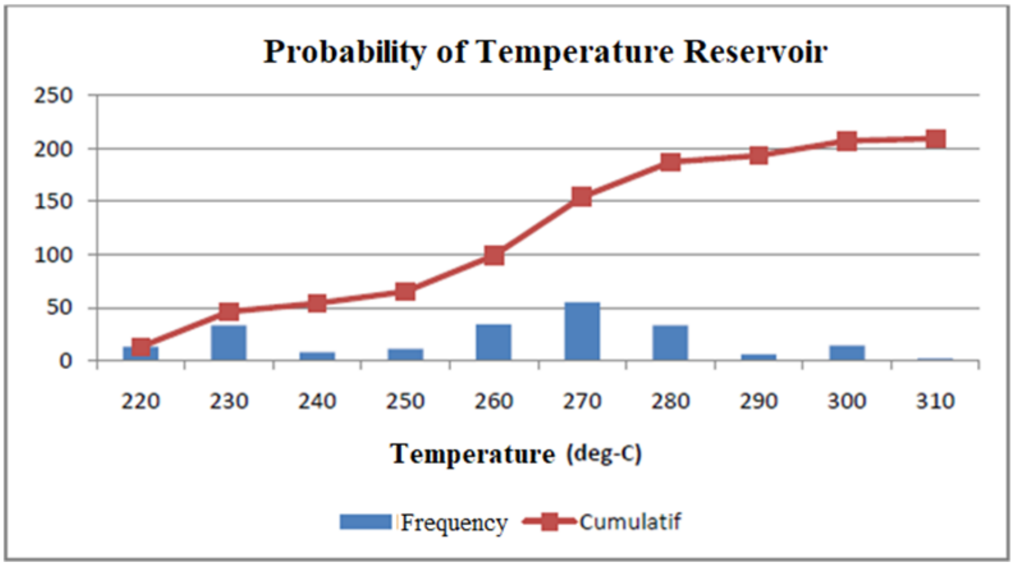


Figure 3. Probability of Temperature Reservoir

4.4 Gain Factor

The formulation of the recovery factor distribution is grounded in two pivotal factors: the integrity of the reservoir's fracture network and the efficacy of injection practices. Delving into reservoir attributes garnered from production test analyses, a notable observation emerged concerning the relatively modest permeability quality, measuring below 1.5 kg/s. In contrast, a reservoir of superior caliber is typified by permeabilities exceeding 3 kg/s-bar, and in select instances, surpassing the 10 kg/s-bar benchmark. It is against this backdrop that the P10, P50, and P90 metrics for the recovery factor crystallize at 0.1, 0.2, and 0.3, respectively.

4.5 Initial and Final Water Saturation

The considerations underlying the determination of the initial reservoir saturation encompass insights derived from the reservoir's characteristics, as revealed through production test data, and the presence of fumaroles indicating a two-phase zone within the reservoir. Driven by a working hypothesis, the reservoir is conceptually partitioned into two segments: a two- phase reservoir and a water reservoir. Drawing from the enthalpy, which falls within the 1400 KJ/kg range, an inference can be drawn that vapor saturation in the reservoir is unlikely to exceed 5%. Thus, the p10, p50, and p90 values for initial saturation crystallize at 0.9, 0.95, and 0.99, respectively. Intriguingly, the interplay of cold-water influx in deep reservoirs and the evolving dynamics of shallow reservoirs contributes to distinct outcomes. Deep reservoirs are anticipated to maintain conditions akin to 100 percent water, while shallow reservoirs exhibit potential for the emergence of a steam cap. Consequently, the p10, p50, and p90 values for these scenarios are projected at 50%, 80%, and 90%, respectively. Through a comprehensive assessment, the most plausible spatial extent is identified at 7 km², while the spectrum of pessimistic and optimistic estimates encompasses 4.5 km² and 19 km², respectively.

4.6 Results of Potential Geothermal Reserves

Utilizing gas geothermometer analysis, the pivotal temperature determination rests at 275°C, flanked by a spectrum of both cautious and optimistic values: 230°C and 315°C. Geological investigations, intricately considering rock lithology and structural compositions, yield an estimated reservoir porosity range of 10-15%, thereby yielding minimal, most probable, and maximal porosity benchmarks of 10%, 12.5%, and 15%. Delving into a comprehensive review of geothermal prospect regions in Indonesia, the reservoir thickness parameter is imbued with minimal, maximal, and most likely estimates of 1074, 1190, and 1275 meters. Introducing

the reservoir gain factor, we encounter values of 0.1, 0.3, and 0.2. By adopting a conservative stance of 0.1, the consideration encompasses the potential absence of tightly spaced fractures within the reservoir, coupled with accommodating minimal recharge. It is worth noting that the determination of these parameters, often rooted in assumptions, adheres to the guidelines set by SNI 13-6482-2000 concerning Assumed Parameter Values of Possible Reserve Levels, delineating their role within the broader framework.

Table 4. Assumed Value of Possible Reserve Level Parameters (BSNI, 2000)

Parameter	**Medium temperature (125-225 ^{0}C)**
Rock Porosity (%)	10
Rock Heat Capacity (kJ/kg ^{0}C)	0.9
Rock Density (kg/m^3)	2.65 x 10^3
Project Age (years)	30
Electrical Conversion Factor (%)	10
Gain Factor (%)	25

The comprehensive spectrum of parameters employed for the computation of the Sibayak geothermal prospect area's potential is vividly portrayed in Figure 4. This depiction encapsulates the core design input parameters harnessed through the Visual Basic Application.

Parameter	Min	Max	Most
Area (km^2) =	4,5	19	7
Thickness (m) =	1074	1275	1190
Rock Density (kg/m^2) =	2400	2600	2500
Porosity (Fraction) =	0,1	0,15	0,125
Rock Heat Capacity (kJ/(kg.^{0}C)) =	1		
Life Time (Years) =	30		
Recovery Factor (Time) =	0,1	0,3	0,2
Elect. Eff. (Fraction) =	0,1	0,12	
Initial Temperature (^{0}C) =	226	300	270
Final Temperature (^{0}C) =	180		
Initial Fluid Saturation (fraction) =	0,9	0,99	0,95
Final Fluid Saturation (fraction) =	0,5	0,9	0,8

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Figure 4. Data Value for Determining Geothermal Potential Reserves

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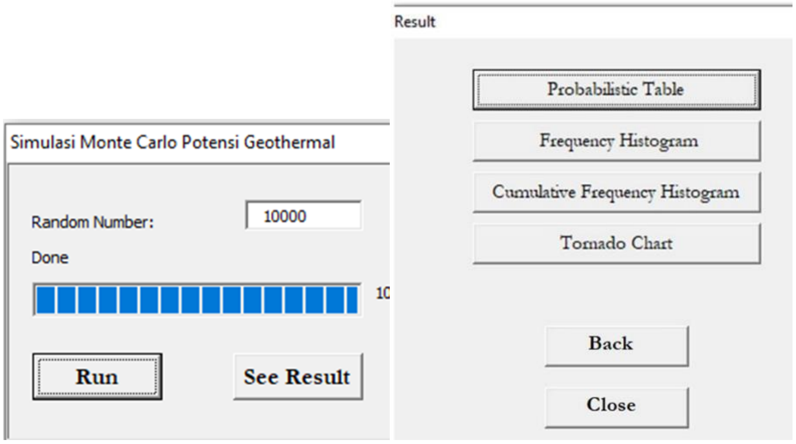
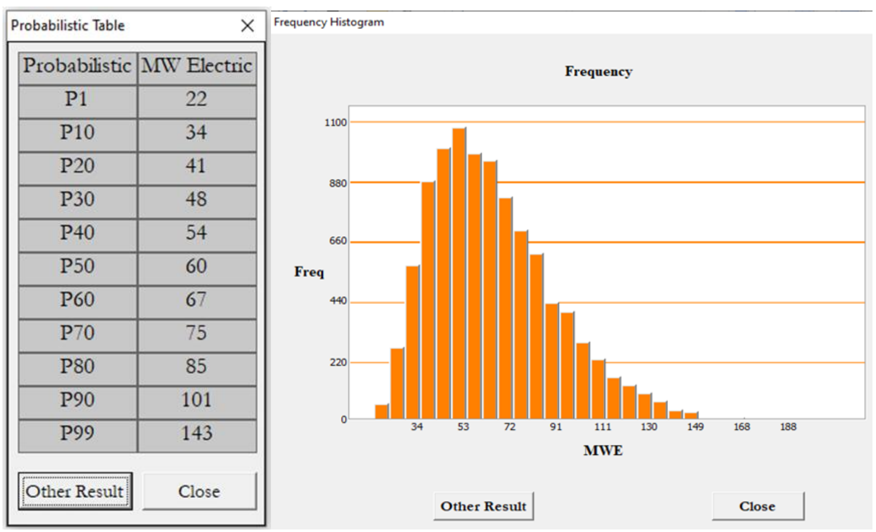


Figure 5. Form Running for Determining Random Numbers and Results

Through the Montecarlo simulation method, the computation of volumetric reserves, grounded in the parameter distributions elucidated above, yields an illustrative potential distribution as depicted in Figure 6. This probabilistic approach signifies that the potential of the Sibayak geothermal field, in P10 (pessimistic), P90 (optimistic), and P50 (most likely) contexts, manifests at 34 MW, 60 MW, and 101 MW, respectively. The Frequency Histogram, meticulously outlined in Figure 6, is accompanied by insights gleaned from the Cumulative Probability and Cumulative Frequency illustrated in Figure 7. A comprehensive understanding is further augmented by the Tornado Analysis Diagram, meticulously presented in Figure 8.



Probabilistic	MW Electric
P1	22
P10	34
P20	41
P30	48
P40	54
P50	60
P60	67
P70	75
P80	85
P90	101
P99	143

Figure 6. Probability Value and Histogram Frequency Results

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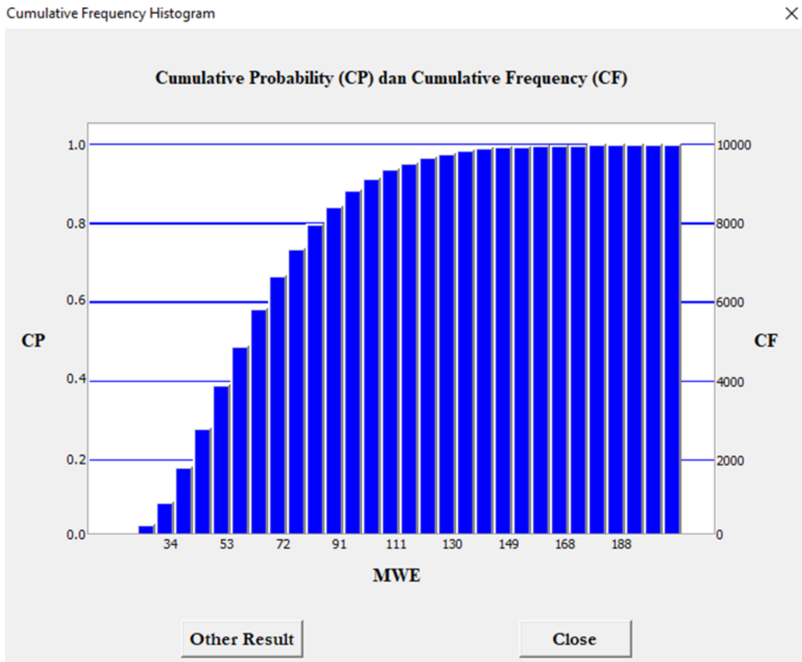

Figure 7. Probabilistic Distribution of Potential Sibayak Geothermal Prospect Areas

Figure 8. Tornado Sensitivity Analysis Diagram for Parameters Determining the Size of Reserves

The insight gleaned from Figure 8's Tornado diagram underscores the influence of four key variables—namely, area, thickness, gain factor, and initial temperature—on the potential assessment. Remarkably, it's the gain factor that emerges as the most pivotal determinant, wielding the most substantial impact. This observation emphasizes the paramount importance of executing thorough surveys and analyses during the exploration phase. Such endeavors are essential to curtail the range of uncertainties enveloping the aforementioned parameters. A case in point is the exploration well drilling, which incorporates comprehensive formation evaluation to ascertain reservoir parameters governing well deliverability—parameters like permeability, fracture spacing, vapor saturation, and more. This meticulous approach positions us to critically evaluate the uncertainty range associated with the recovery factor, thereby ensuring robust potential assessments.

Conclusion

Utilizing the Visual Basic Application, a meticulous implementation unfolds, entailing the computation of prospective geothermal reserves via the Volumetric Method and Monte Carlo Simulation, within the Sibayak Geothermal Field. The foundational parameters pivotal to these calculations are harnessed through methodical assumptions, drawing guidance from SNI 13- 6482-2000—a framework encapsulating plausible and existing reserve level parameter values gleaned from preliminary survey activities and enriched by geoscience data and production test analyses. Within this contextual framework, the minimum, most likely, and maximum input values for each parameter find definition:

- Area: 4.5 km^2, 7 km^2, and 19 km^2
- Reservoir Thickness: 1074 m, 1190 m, and 1275 m
- Rock Density: 2400 kg/m^3, 2500 kg/m^3, and 2600 kg/m^3
- Porosity: 0.1, 0.125, and 0.15
- Reservoir Temperatures: 226°C, 262°C, and 286°C
- Gain Factors: 0.1, 0.2, and 0.3
- Initial Saturation: 0.9, 0.95, and 0.99
- Final Saturation: Estimated at 50%, 80%, and 90%
- Lifetime: 30 years
- Rock Heat Capacity: 1 kJ/kg °C
- Final Temperature: 180°C

Emanating from this comprehensive analysis, a probabilistic perspective emerges, encapsulating the Sibayak geothermal field's energy reserve potential. Pessimistically (P10), the potential stands at 34 MW; optimistically (P90), it escalates to 101 MW; while the most likely projection (P50) hovers at 60 MW. Notably, the scrutiny of the tornado diagram lends credence to the understanding that the potential scope is fundamentally shaped by four key variables: area, thickness, gain factor, and initial temperature—wherein the recovery factor emerges as the pivotal determinant of potential size.

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