Comparison of resource assessment methods with numerical reservoir model between heat stored and experimental design: case study Ciwidey-Patuha geothermal field

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Abstract. A successful geothermal field size assessment requires integrative data analysis of all aspects to determine the optimum capacity to be installed. Nowadays, numerical simulation becomes a powerful tool in a geothermal resource assessment process. However, this method involves significant uncertainty of subsurface information as an input. Then a study of resource assessment methods, such as heat stored and experimental design, needs inputs coming from the result/output of reservoir numerical. The calculation of both methods based on a range of reservoir parameter values can be carried out using stochastic methods (Monte Carlo Simulation). It applies a probabilistic method of resource assessment to capture uncertainties. A sophisticated numerical reservoir model of Ciwidey-Patuha Geothermal Field, West Java-Indonesia in the natural state condition was used as a case study to determine the generating potential of the reservoir.

1. Introduction

Geothermal resource assessment is a key information for the early phase of geothermal development. It is the basis for sizing and financing the power plant investment. Muffler & Cataldi [1] evaluated the method for assessing geothermal resources and divided it into 4 classes: a) surface thermal flux, (b) volume, (c) planar fracture and (d) magmatic heat budget. Moreover, in 2000, Grant [2], evaluated the method and divided it into 6 classes: a) Stored heat, b) Total well flows, c) Areal estimates (power density), d) Decline analyses, e) Lumped-parameter models, f) Reservoir simulation. In 2006, the updated evaluation of this method has been done by Clotworthy [3] and it can be grouped into 6 classes: a) Estimation of natural heat flow representing long-term sustainable energy available, b) Analogies based on other fields that have been produced for a long period, c) Volumetric assessment of heat in place and the portion that can be extracted, d) Decline analyses, e) Lumped-parameter models, f) Well decline analysis, Numerical reservoir models.

Numerical reservoir model is widely considered as the most powerful and trusted method. The method requires both a natural state and a history matching model. However, in the assessment of green fields or new geothermal fields, only natural state model is available. The input and output data of numerical method can be used in a heat stored and experimental design method using a probabilistic approach (Monte Carlo simulation).

The objective of this study is to compare the resource assessment method between the heat stored and the experimental design. Both methods use probabilistic approach with Monte Carlo simulation in
calculating the resource potential. The calculation itself involves significant uncertainties of subsurface information used as the inputs of the numerical geothermal reservoir model. The result of both methods is a probability distribution function to quantify the risk and upside potential in the geothermal resource estimates.

A sophisticated natural state model of Patuha geothermal field, West Java-Indonesia was used as a case study. The study focuses on Ciwidey prospect area is G. Patuha complex in which the steam supply for the commercial operation of Unit-I (60 MW) comes from.

2. Methodology
The workflow of this study is shown in Figure 1. Minitab statistical software is employed at a certain stage in the workflow. Monte Carlo simulation procedure using 50,000 random number is applied to resource assessment method of heat stored and experimental design. 30-year time is assumed for both methods as the common geothermal contractual period in Indonesia. Resource assessment are carried out only in the steam zone. Therefore, the result of both methods can be compared.

![Figure 1. Workflow of probabilistic resource assessment using numerical simulation.](image)

3. Ciwidey-Patuha Numerical Model
A numerical model was constructed based on the conceptual model. It uses a set of interconnected elements in which each element represents the actual subsurface condition. Thermal and rock properties of the materials represent the thermodynamic properties of fluids and rocks in the reservoir. To confirm whether the constructed numerical model represents the actual condition of Ciwidey-Patuha reservoir, it requires 2-step calibrations i.e. a natural state calibration and a history matching calibration. In this study, after the natural state condition was accomplished, the experimental design method was then applied. Table 1 shows material data for computer model.

| Parameter          | Value     |
|--------------------|-----------|
| Material properties|           |
| Core permeability  | 0.3       |
| Relative permeability and liquid saturation | 0.3 |

The model output and well data show a good match of pressure and temperature for TCH and PPL wells. The simulated pressure and temperature profiles at existing production wells can reproduce the
steam dominated at the top of the reservoir underlying liquid dominated reservoir. The gas saturation of the steam cap zone has a maximum value of 65% [4].

| Material | Porosity | $k_{xy}$ (m$^2$) | $k_z$ (m$^2$) |
|----------|----------|-----------------|---------------|
| RESV1    | 0.10     | 1.00E-13        | 5.00E-14      |
| RESV2    | 0.10     | 8.00E-14        | 4.00E-14      |
| RESV3    | 0.10     | 8.00E-14        | 4.00E-14      |
| RESL1    | 0.10     | 5.00E-14        | 2.00E-14      |
| RESL2    | 0.07     | 4.00E-14        | 2.00E-14      |
| RESL3    | 0.05     | 2.00E-14        | 1.00E-14      |
| RSVG     | 0.08     | 2.00E-15        | 1.00E-15      |
| FCIWI    | 0.15     | 3.00E-14        | 3.00E-14      |
| FBDTL    | 0.125    | 2.50E-14        | 2.50E-14      |
| FCIMA    | 0.125    | 2.00E-14        | 2.00E-14      |
| FBLTG    | 0.10     | 3.00E-15        | 3.00E-15      |
| SEAL1    | 0.05     | 8.00E-15        | 8.00E-15      |
| UPZ05    | 0.10     | 8.00E-14        | 4.00E-14      |
| UPZ02    | 0.10     | 8.00E-13        | 4.00E-13      |
| SEAL2    | 0.05     | 1.00E-17        | 1.00E-17      |

Figure 2. Ciwidey-Patuha numerical block at steam cap layer (a) and liquid reservoir layer (b). [4]

4. Resource Assessment

4.1. Heat Stored

Heat stored is the oldest method [1]. The basic theory is very simple assuming isotherms to estimate energy contained in the reservoir. The reserve is the amount of recoverable energy which can be taken from the rock and fluid at initial condition subtracted to final or abandoned condition multiplied by the electrical conversion factor. The factor which determines the amount of energy that can be recovered is expressed as Recovery Factor (RF).
\[ \text{MW}_e = (H_{ei} - H_{ef}) \times RF \times \eta / (t \times 365 \times 24 \times 3600) \] (1)

where:
- \( H_{ei} \) = heat content in rock and fluid at initial condition, kJ
- \( H_{ef} \) = heat content in rock and fluid at final condition, kJ
- \( \text{A} \) = reservoir area (m\(^2\))
- \( \text{h} \) = reservoir thickness (m)
- \( \text{T} \) = reservoir temperature (°C)
- \( s_L \) = water saturation (fraction)
- \( s_V \) = vapour saturation (fraction)
- \( u_L \) = internal energy of water (kJ/kg)
- \( u_V \) = internal energy of vapour (kJ/kg)
- \( \phi \) = rock porosity (fraction)
- \( c_r \) = rock heat capacity (kJ/kg°C)
- \( \rho_r \) = rock density (kg/m\(^3\))
- \( \rho_L \) = water density (kg/m\(^3\))
- \( \rho_V \) = vapour density (kg/m\(^3\))
- \( \eta \) = electrical conversion factor (fraction)
- \( \text{RF} \) = recovery factor (fraction)
- \( \text{t} \) = project lifetime (years)
- Subscript \( i \) refers to initial condition while subscript \( f \) refers to final/abandoned condition where its utilization for electrical use is no longer economical.

An extra care analysis is needed in interpreting the result of this method as sometimes it yields overestimated results. The main source of weakness of this method is the difficulty in selecting the appropriate value of RF. The simple meaning of RF is all unknown factors or variables is represented by this magnitude. In practice, the value of RF is determined arbitrarily or taken from other fields which have similarities in reservoir systems. Until now, there are not many studies done to give satisfied insights into this factor. Another weakness in applying this method is the difficulty in determining a reservoir volume which will be considered as a reservoir. Differences will appear as it is not easy to have the same criteria to determine the bottom of the reservoir (BOR), top of the reservoir (TOR) and lateral extent of the reservoir.

### 4.2. Experimental Design

Experimental Design (ED) is a systematic approach to simulate a probabilistic resource assessment. This method was applied in Ciwidey-Patuha numerical model [4] in order to calculate the resources.

The relationship of 2 level between all the 3 parameters may be estimated by a response polynomial or proxy equation:

\[ Y = \beta_0 + \beta_1 S_L + \beta_2 \phi + \beta_3 kxyz + \beta_4 S_L \times \phi + \beta_5 S_L \times kxyz + \beta_6 \phi \times kxyz + \beta_7 S_L \times \phi \times kxyz \] (2)

Where \( \beta_0 \) is the average value of the response and \( \beta_1, \beta_2, \ldots, \beta_7 \) is regression linear. The polynomial equation describes the behaviour of the response between parameters including the interaction effects between parameters.

### 4.3. Monte Carlo Simulation

Dealing with uncertainty will yield different use of assumption, hence generally Monte Carlo simulation is employed in evaluating reserve of geothermal field. To be able to apply this method, frequency distributions for each variable are required. To simplify the calculation, the most often frequency distribution applied in Monte Carlo simulation is Rectangular (Uniform) and Triangular.
5. Discussion

Resource assessment using a numerical model coupled with the heat stored method has been done by several researchers [5, 6, 7, 8, 9, 10]. On the other side, experimental design has been done by numerous researchers [11, 12, 13, 4]. Both methods used widely to determine the resources of the geothermal field. The heat stored method and experimental design were limited to a life time of 30 years. Therefore, the resource could be compared equally. The input data for calculation in the heat stored method are shown in Table 2.

Table 2. Input data for Experimental Design.

| Parameter              | Steam Cap           | Liquid Reservoir |         |
|------------------------|---------------------|------------------|---------|
|                        | Min | Max | Most | Min | Max | Most |         |
| Area (km$^2$)          | 15  | 16  |      | 15  | 16  |      |         |
| Thickness (m)          | 700 | 1000| 800  | 800 | 1000| 900  |         |
| Rock Density (kg/m$^3$)| 2500| 2600| 800  | 2500| 2600| 900  |         |
| Porosity (fraction)    | 0.08| 0.15| 0.10 | 0.08| 0.15| 0.10 |         |
| Rock Heat Capacity (kJ/kg.°C) | 1 | 1.1 |      | 1   | 1.1 |      |         |
| Temperature Initial (°C)| 220| 230 |      | 230 | 250 |      |         |
| Temperature Final (°C)| 180 |      |      | 180 |      |      |         |
| Initial Water Saturation| 0.35| 0.50| 0.70 | 1.00| 0.00| 0.30 |         |
| Final Water Saturation | 0.00| 0.10|      | 0.20| 0.38| 0.25 |         |
| Recovery Factor        | 0.20| 0.38| 0.25 | 0.20| 0.38| 0.25 |         |
| Electrical Efficiency  | 0.105| 0.110| 0.105| 0.115|      |      |         |

Figure 3. Heat stored at the steam cap (left) and the liquid reservoir (right).

Theoretically, heat contained in both the liquid and steam cap zone should be calculated independently [15]. The area is based both on the steam cap and the liquid reservoir that have an extent of 15-16 km$^2$. The thickness is determined based on the zone penetrated by wells in each the steam zone and the liquid reservoir. The maximum and minimum value of rock density and porosity are based on reservoir rocks which is andesite to rhyolite. Rock heat capacity is from the common assumption about 1-1.1 kJ/kg.°C. The temperature is based on both the steam cap and the liquid reservoir temperature. Final temperature is based on abandonment temperature which is 180°C. The initial water saturation is taken from natural state model. The value of the final water saturation is 0.0-0.1, it is based on an assumption that the reservoir achieves a superheated condition when there is no liquid exists in the reservoir. Recovery factor is a function of porosity [1]. Electrical efficiency is a function of the reservoir...
temperature [16]. Based on the calculation by using 50,000 random numbers, the resources (P50) of the steam cap and the liquid reservoir are 54 MW and 89 MW respectively as shown in Figure 3.

There are 3 main parameters being investigated: liquid saturation (SL), matrix porosity (ϕ), and permeability (k<sub>xxyz</sub>). The parameters are summarized in Table 3 with the low and high value of matrix porosity and permeability are ±20% deviations from the initial material properties. The full factorial experimental design has been run for 8 simulations as shown in Table 4. The proxy equation resulted from this experimental design is shown by Equation 3, this function can be used in economic evaluation of geothermal resources [13]. The detail of this calculation is based on previous study [4]. The result of this calculation is 128 MW (P50) as shown in Figure 4.

**Table 3. Parameter for ED.**

| Parameter           | Low (-1) | High (1) |
|---------------------|----------|----------|
| Liquid Saturation (S<sub>L</sub>) | 0.3      | 0.5      |
| Porosity (ϕ)        | -20% from base | +20% from base |
| Permeability (k<sub>xxyz</sub>) | -20% from base | +20% from base |

**Table 4. Full factorial design and results.**

| Std. Order | Run. Order | S<sub>L</sub> | ϕ       | k<sub>xxyz</sub> | Power (MWe) |
|------------|------------|---------------|---------|-----------------|-------------|
| 1          | 1          | -1            | 1       | 1               | 128.4       |
| 2          | 2          | 1             | -1      | -1              | 126.5       |
| 4          | 3          | 1             | 1       | -1              | 126.3       |
| 1          | 4          | -1            | -1      | -1              | 125.3       |
| 5          | 5          | -1            | -1      | 1               | 129.9       |
| 3          | 6          | -1            | 1       | -1              | 124.5       |
| 6          | 7          | 1             | -1      | 1               | 131.1       |
| 8          | 8          | 1             | 1       | 1               | 130.4       |

The experimental design calculation has a lower power capacity value than heat stored method (Figure 5) for P50. The difference between those values were resulted from different assumptions used in the calculations. The heat stored method calculates heat and mass contained in the reservoir. From the sensitivity analysis of the heat stored method, the recovery factor becomes the most sensitive component of all input parameters.
Figure 5. Cumulative probability comparison result.

The experimental design is based on different production scenarios with different values of some parameters such as water saturation, porosity, and permeability. These scenarios have an identical condition in terms of production-injection scenario, number of wells, as well as have the same value of productivity index (PI) as constraint parameters. To get a better comparative result, then the selected parameters should be a constraint. Therefore, it can be kept to only know the influence of these parameters. Hence, the application of experimental design in the assessment of geothermal resource is considered. However, this method would be effective if the model in the natural state of the green field while the history matching condition of the producing/brown field.

Figure 6. Analysis of sensitivity for heat stored.

The heat stored method is generally used in the estimation of geothermal resources at the early phase development or exploration stage. The disadvantage of this method is the presence of recovery factor as an independent parameter (Figure 6). Nonetheless, this parameter depends on both thermodynamic and hydraulic characteristics of the reservoir such as reservoir area, temperature, permeability, porosity and recharge [17]. The uniform single value of recovery factor in the calculation of resources could yield a misleading result.
6. Conclusion
- A study to compare resource assessment in Ciwidey-Patuha model uses 2 (two) methods (heat stored method and experimental design) has been successfully implemented.
- The estimated resource value by using the heat stored method and the experimental design are 143 MWe and 128 MW respectively.
- The experimental design based on production is preferred than the heat stored method to provide a better estimate in the resource assessment process.
- The recovery factor should be applied cautiously.

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