Application of Numerical Simulation to Update Conceptual Model and Resource Assessment of Songa-Wayaua Geothermal Field

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Abstract. A study of Songa-Wayaua geothermal field using TOUGH2 reservoir simulation was conducted. This study shows the workflow to update the Songa-Wayaua conceptual model based on geosciences data, and to assess its potential resource. Since this field still a green field, the model still has so many uncertainties because lack of the actual well data. The numerical simulation of Songa-Wayaua geothermal field has been developed and it showed a proper alignment with geosciences data but still requires validation from well data. This is the first numerical model of Songa-Wayaua geothermal field. The model provides additional insights which have been used to review and update the conceptual model. The conceptual model of Songa-Wayaua geothermal field has been successfully updated. The main updated points of the conceptual model were the location of the heat source to be beneath the Mt. Pele, adding the flow fluid pattern as outflow and upflow location, and adding iso-temperature distribution. By using the heat stored method with probabilistic approach (Monte Carlo Simulation), the resource calculation approximately 30 MWe.

1. Introduction

Songa-Wayaua geothermal field is located in Bacan Island, South Halmahera Regency, province of North Maluku, with geographic coordinate system between 127° 35’ 05” E - 127° 44’ 30” E and 0° 37’ 10” S - 0° 46’ 48” S as shown in Figure 1. The total working area of this geothermal area is about 42.540 Ha with possible reserve is about 62 MWe, that will be developed and installed 10 MWe by PT.PLN in 2020 [1].

Updating conceptual model using a numerical model has been done by several researchers [2] [3] [4]. The aim of this study is to update the conceptual model of Songa-Wayaua geothermal field using numerical simulation based on geology, geochemistry, and geophysics data that has been conducted [5]. This is the first numerical model of Songa-Wayaua geothermal field.
Figure 1. Location of Songa-Wayaua Geothermal Field [5]

2. Geosciences Review

2.1. Geological Review

Songa Wayaua geothermal area is a volcanic hydrothermal system and formed in a volcanic area where the oldest rock is Mesozoic metamorphic as a basement rock. The youngest Quaternary lava is derived from Bukit Langsa, Bukit Pele, and Mt. Bibinoi. The stratigraphic succession of rock from the youngest to the oldest rock has been discussed [6] and mentioned that the youngest stratigraphic rock is alluvium and the oldest is Metamorphic formation. It also reported that the youngest stratigraphic rock is sedimentary alluvium and the oldest is metamorphic formation with the presence of molybdenite and pyrite [5].

The Songa-Wayua geothermal field is primarily controlled by faults. Based on geological study [7] [5], it can be referred that Songa-Wayaua geothermal field is dominantly controlled by the normal fault of Songa located in NW-SE (N 140° E - N 145° E). This fault resulted in surface manifestations, including hot springs, fumaroles, mud pools, hot grounds, steaming ground, silica sinter, and altered rock along the NW-SE (trending Songa faults). The geological map and NW-SE cross-sectional area of Songa-Wayaua geothermal field are shown in Figure 2.
2.2. Geochemistry Review

Manifestations exist in Songa-Wayaau geothermal field spread along the Songa fault, shown in Figure 3. According to geochemistry data [8] and its interpretation [5], it can be seen that the type of water in this area is chloride water, which is reservoir water with neutral pH (about 5.86-6.49). The high composition of Cl on the geothermal fluid in this area shows that the fluid is from reservoir fluid. While the one cluster of Cl-Li-B composition from water samples indicates the fluid is from the same reservoir, as shown in Figure 4 and Figure 5.

Figure 2. Geological map and NW-SE cross sectional area of Songa-Wayaau [5].
Figure 3. Surface manifestation map of Songa-Wayaua [5]

The ratio of Na/K and HCO$_3$/SO$_4$ indicates that the geothermal comes out as manifestations in Songa-Wayaua area is a direct flow from the reservoir (upflow). It can be seen from Na/K<15 and a low ratio of HCO$_3$/SO$_4$.

According to Giggenbach’s Na-K geothermometer analysis and Na-K-Mg diagram, as shown in Figure 6, it can be seen that the reservoir temperature of Songa-Wayaua geothermal system is about 240-250°C.

Isotope analysis has been conducted [8] [5] and showed that the recharge of this system is not only from meteoric water but there also contribution from sea water, as shown in Figure 7.
The presence of high Hg concentration around Mt. Pele and Mt. Lansa indicates the high permeability and good porosity. This area also shows high temperatures anomaly and relatively acid pH, around 4.48 – 7.9, which is derived from manifestations around Mt. Pele and Mt. Lansa. It indicates that this area is an upflow zone of Songa-Wayaua geothermal system.
Figure 6. Na-K-Mg diagram showing fluid equilibrium in Songa-Wayua area [8]

Figure 7. Stable isotop δ18O and δD diagram [8]

2.3. Geophysics Review
It has been interpreted the geophysical data, such as Geomagnetic, Gravity, and Magnetotelluric [5] [8]. As shown in Figure 8, there is an area with low magnetic value in the NW of Songa-Wayua area (around Mt. Pele) which is affected by horizontal fault as hydrothermal fluid flow path resulting in demagnetization. It is interpreted that there is a heat source beneath this area.
According to density 2D modelling conducted by [5], there is a contrast of density value around Mt. Pele and Mt. Lansa. The model shows that metamorphic rocks act as basement rocks at 500-3000 m depth.

Figure 8. Complete bouguer anomaly map of Songa-Wayaua geothermal field with 2.4 gr/cm$^3$ density correction [8]
According to Magnetotelluric results, as shown in Figure 9 [8], it can be referred that there is low resistivity zone with 4.7 – 15.9 Ohm.m at 100 through -900 masl depth, which is interpreted as caprock with 500-900 m thickness. There is reservoir below the caprock as indicated by low resistivity zone with 25.9-295.8 Ohm.m at 800-1900 masl depth and 900-1200 m thickness [5]. The caprock is estimated to be composed of Mt. Pele lava and Mt. Lansa lava units, while the reservoir is composed of metamorphic rocks.

2.4. Initial Conceptual Model
According to the previous study of geosciences data [5], conceptual model of Songa-Wayaua geothermal field been proposed as shown in Figure 10. Geological play type of this model consists of heat source, reservoir, caprock, recharge, upflow and outflow area.

The heat source is estimated as a volcanic body eruption of Lansa and Pele. It is located between Mt. Lansa and Mt. Pele. The reservoir is metamorphic rocks with a thickness of 900 - 1200 m at 800 -1900 masl depth. Top of reservoir varies from about 500 - 700 masl depth, so the estimated thickness of caprock is about 500 - 900 m. The recharge area of this system is estimated originate from NW-W of Songa-Wayaua area (around Sibela) which is a higher area than the others. The upflow area is located around Mt. Pele and Mt. Lansa, and outflow area is located at the South of Wayaua.
Figure 10. Conceptual model of Songa-Wayaua geothermal field [5].

3. Computer Model

3.1. Model Description
The numerical model of Songa-Wayaua using EOS1 for water and water with tracer to simplify the modeling process. The modelling process was carried out by using a pre- and post-processor of TOUGH2. Figure 11. shows the area planned to be the boundary of the model and gridding and layering system of the model, respectively. This model has a total area of 4.5 km x 9.5 km with a vertical extent of about 2.7 km, covers the reservoir, manifestations, and the recharge and discharge area. The maximum elevation of the surface model is 733 m, and the lower is -2000 m. The model consists of 10 layers with some of the top layers follow the real topographical condition. The model was rotated by -10° to accommodate the governing structure and flow direction.

3.2. Boundary Condition
Boundary condition was defined to simulate the reservoir. At the initial condition, the atmospheric conditions were set into the top boundary. It was assigned for the fixed value of 25°C and 1 bar. This layer used significant volume factor to keep the properties output constant at their initial conditions. Therefore, the top layer cannot be influenced by reservoir conditions over time. The side boundary was assumed to be no flow boundary and was treated to be relatively impermeable. Figure 12. shows the side boundary of Songa-Wayaua computer model that covers the reservoir.

The bottom boundaries are the heat source, which set to the fixed state with temperature 300°C and pressure 160 bar, and the other is as basement layers that treated as an impermeable layer. The heat source location was initially based on gravity anomaly data, but it needed to be adjusted to achieve the best model output, which corresponds to the actual data. The location of the heat source (red blocks) and bottom condition in this model shown in Figure 12.
Figure 11. Gridding and Layering System of the model. Gridding area (shown in yellow grid) of Songa-Wayaua Model. The red lines are faults.

Figure 12. Side boundary of Songa-Wayaua Model (left) and Bottom boundary of Songa-Wayaua computer model (right).
3.3. Rock Properties
The rock properties such as specific heat, wet heat conductivity, rock density, and porosity were kept constant as at the initial condition since only the permeability is considered to be the most significant parameter in natural state modeling. Rock porosity, permeability, and density are obtained from common rock properties [9] before the values were continuously adjusted until the pressure as well as the temperature distribution of the simulation model correspond to the geochemical and geophysical data and initial conceptual model. Based on [9], for volcanic and sedimentary rocks at 230-240°C, the heat conductivity values are 950-1000 J/kg°C. The final permeability values were obtained from more than hundreds of trial and error attempts. Table 1 shows the final permeability values of each rock type.

Table 1. Final permeability values for each rock.

| Material | $k_x$ (mD) | $k_y$ (mD) | $k_z$ (mD) | Color |
|----------|------------|------------|------------|-------|
| ATM      | 1x10^2     | 1x10^2     | 1x10^2     |       |
| BOND     | 2x10^-2    | 2x10^-2    | 1x10^-2    |       |
| CAPR     | 1x10^-4    | 1x10^-4    | 1x10^-4    |       |
| RES1     | 60         | 60         | 3          |       |
| RES2     | 20         | 20         | 10         |       |
| GW       | 5x10^-2    | 5x10^-2    | 2.5x10^-2  |       |
| HEAT     | 1x10^2     | 1x10^2     | 1x10^2     |       |
| SEA      | 1x10^2     | 1x10^2     | 1x10^2     |       |

3.4. Modelling Results
The objective of this numerical simulation is to reproduce the initial temperature and pressure distribution before any exploitation. The model was run until the steady-state condition and its simulation time was the same or greater than geological time. The results of the simulation were analyzed and compared into the geology, geochemistry, and geophysics [5] and actual data in terms of mass rate of manifestation. The dummy well located between Mt. Pele-pele and Mt. Lansa, shown in Figure 13, was also used to match the reservoir temperature by using Na-K-Mg geothermometer. The manifestation AP3, AP5, and AP6 located in Songa area were used to match the manifestation mass rate. The use of these three manifestations is because only these manifestations have mass rate data. The steady-state condition was achieved by adjusting the permeability structure, temperature and pressure of heat source, location of the heat source, and productivity index of the wells representing the manifestation. The representation of manifestation was done by producing the dummy wells at an atmospheric pressure condition to reach the total amount of mass rate of about 4.9 kg/s, 0.08 kg/s, and 0.16 kg/s from AP3, AP5, and AP6 respectively. This attempt was done by adjusting the productivity index (PI) value of those dummy wells, and it has gained the PI in AP3 about $7.56 \times 10^{-14}$ m$^2$, 1.28$ \times 10^{-15}$ m$^2$ in AP5, and 2.73$ \times 10^{-15}$ m$^2$ in AP6.

Figure 14 shows the temperature matching of dummy well TW1. Due to this data, the reservoir temperature was estimated at 240°C. It was confirmed by geothermometer calculation [5] which resulted in a temperature reservoir of around 240 – 250°C. Furthermore, the depth of the top of the reservoir is 800 masl, consistent with MT resistivity data. Based on the temperature of the dummy well TW1 it can be inferred that the reservoir is a water dominated reservoir. The pressure shows the nearly hydrostatic profile and the temperature profile falls below the boiling point with depth curve.

Based on the results of numerical simulation, upflow zone is between Mt. Lansa dan Mt. Pele, while outflow zone is further to the South-East from Mt. Lansa, as shown in the fluid flow pattern in Figure 15. This model shows the contribution of sea water as recharge to the reservoir.
3.5. Reservoir Characterization

Resource assessment calculation is based on the parameters that acquired from reservoir characterization. Based on modeling results, Songa-Wayaua reservoir has 5.37 km$^2$. The lateral distribution of the reservoir is shown in Figure 16. is delineated based on the high temperature reservoir defined by Hochstein of 225°C. This area is smaller than the area proposed by [5], which has an area of 15.5 km$^2$, as shown in Figure 17. The porosity values are in range of 7% while the density values are 2400-2650 kg/m$^3$. The rock heat conductivity values of 950-1000 J/kg°C. The initial water saturation
based on the model is 1. The initial reservoir temperature is obtained from the dummy well (TW1). The initial temperature is 240°C.

![Figure 15. Temperature and mass flow pattern of Songa-Wayaua Modelling.](image)

![Figure 16. Reservoir area delineation.](image)

![Figure 17. Comparison of reservoir area resulted from simulation and area proposed by [5].](image)

3.6. Updated Conceptual Model

The conceptual model of Songa-Wayaua geothermal field were updated by integrating data from geology, geochemistry, geophysics and the results of numerical model. Figure 18. shows the vertical section directed NW-SE of the updated conceptual model of Songa-Wayaua, the heat source in this system is located beneath Mt. Pele with more than 2000 m depth. The reservoir has thickness up to 1200 m with top of reservoir at 800 m depth. It was confirmed by MT Resistivity data conducted by [5]. This system is high temperature, as the reservoir has temperature 240°C, and it was confirmed by Na-K-Mg
geothermometer data and temperature profile of dummy well TM1 from numerical model. Caprock has a thickness up to 900 m. Upflow zone is located between Mt. Pele dan Mt. Lansa, while outflow zone is further to the South-East from Mt. Lansa. Discharge area is located vertically from heat source, i.e. around Mt. Pele, and recharge area was predicted from South-Eastern Mt. Lansa and North-Western Mt. Pele. It is also predicted that there is recharge from sea water.

3.7. Resource Assessment

Resource assessment using heat stored method in numerical model has been done by several researchers [4][10][11]. To assess the power generation ability of Songa-Wayaaua geothermal field, the heat stored method with a probabilistic approach, Monte Carlo Simulation was conducted. This simulation was run by using 60,000 random numbers.

![Figure 18. Conceptual model of Songa-Wayaaua geothermal field](image)

Parameters values used in the calculation were mentioned in the previous section, such as area, thickness, and temperature of reservoir, porosity and density of rock, and heat conductivity value. The others are initial water saturation, which is based on the numerical model, while the final water saturation is assumed to be 0.3-0.5.

The abandonment reservoir temperature is 180°C based on the National Standard of Indonesia for high temperature geothermal system. The recovery factor is obtained by the correlation proposed by [12], which is 2.5 times the porosity value. The recovery factor used in this calculation is about 20%. The conversion efficiency was selected using [13], which is a function of reservoir temperature. It is obtained that for the reservoir temperature of 240°C, the thermal conversion efficiency values are about 11.3%. The project lifetime is assumed to be 30 years.

In Monte Carlo simulation, the result is divided into 3 type of confidence rank. The highest degree confidence respectively from P10, P50, and P90. The result of Monte Carlo simulation as show in Figure 19, the resource of Songa-Wayaaua geothermal P10 is 30 MWe, P50 is 36.7 MWe and P90 is 44.1 MWe. The result is different with reserve estimation calculated [1] by 62 MWe. It is because of several different parameters used in the calculation, as shown in Table 2.
Table 2. Parameters used in the resources assessment.

| Parameters                     | ESDM (2017) | This Model |
|-------------------------------|-------------|------------|
| Area of Reservoir (km²)       | 8           | 5.37       |
| Thickness (km²)               | 1250        | 1200       |
| Porosity                      | 10%         | 8%         |
| Rock Density (kg/m³)          | 2500        | 2600       |
| Reservoir Temperature (°C)    | 260         | 240        |

Figure 19. Heat stored with Monte Carlo Simulation results.

4. Conclusion
The numerical simulation of Songa-Wayaua geothermal field has been developed using limited data and it showed a good match with geochemical and geophysics data but still required validation from actual well data.

The conceptual model of Songa-Wayaua geothermal field has been successfully updated by using the numerical simulation.

The resource calculation by using heat stored method with probabilistic approach (Monte Carlo Simulation) results is 30 MWe. This resource calculation still in the probable classification since this model still has a low confidence due the absence of well data to be considered as a proven resource classification.

5. Next Phase
The numerical simulation of Songa-Wayaua geothermal has been developed using limited data and the uncertainties of this model still quite high. The next phase of this study is to validate the model with the well data.
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