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Assessment of Bedugul Geothermal Prospect Using A Numerical Reservoir Modeling

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Abstract - A numerical modeling was carried out to generate a numerical model of the Bedugul geothermal field located in Bali Island, Indonesia. This study presents a natural state model and updates the conceptual model of Bedugul based on published geological, geophysical, geochemical, and well data. The numerical simulation of the Bedugul geothermal field has been developed using the previous conceptual model and well data. The Bedugul reservoir model is properly aligned with actual Pressure and Temperature well data. Thus, the natural state model is used to update the Bedugul conceptual model. The main updated points of the conceptual model were the location of the heat source to be beneath Mount Tapak, adding the flow fluid pattern as outflow and upflow location, caprock, reservoir, recharge, discharge, and adding iso-temperature distribution. Based on the numerical model result, the Bedugul geothermal field is a water-dominated geothermal system. The results of this model have been applied to the heat stored method with the Monte Carlo simulation to generate a probabilistic distribution of the reserve potential estimation. The probabilistic for P50 of probable and proven reserve estimation for thirty years are 136.3 MW and 33.4 MW, respectively.

Keywords: Bedugul, numerical model, natural state, resource assessment, geothermal

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Introduction

The numerical model of the geothermal reservoir has become a standard practice for assessing, planning, and evaluating the reservoir condition and performance of the geothermal field worldwide. A numerical model could represent the geothermal system complexity, and it describes the reservoir fluid and heat conditions. Compared with the static resource assessment method, the resource assessment employing the numerical model is more reliable in assessing the reservoir capacity (Pasikki *et al.*, 2016; Ashat and Pratama, 2017; Quinao and Zarrouk, 2018; Ashat *et al.*, 2019a; Sutopo *et al.*, 2019; Ciriaco *et al.*, 2020; Pratama *et al.*, 2020, 2022). Moreover, reservoir simulation using a numerical model is an adequate tool for managing and predicting the reservoir condition and remaining reservoir capacity under the production stage. The numerical model also provides a valuable check for the consistency of conceptual models of geothermal fields. A numerical model of the geothermal system has been carried out in several geothermal fields in Indonesia.

The Bedugul geothermal field is located in the Bratan Caldera, approximately 60 km north of Denpasar, the capital of Bali Province, Indonesia (Figure 1). The Bedugul geothermal field is located in the Tabanan geothermal working area of about 104.5 km^2. Quenched fumarole is manifested at the centre, while most hot springs are outside the area. Based on the geoscience studies and well data, this field is a water-dominated system with a reservoir temperature of around 240-270ºC (Mulyadi *et al*., 2005). Based on the reservoir temperature, the geothermal system of this area can be classified as a high-temperature geothermal system (Hochstein, 1990). This field has a proven reserve of about 30 MW, a probable reserve of about 110 MW, and a possible reserve of approximately 86 MW (KESDM, 2017). These reserves were classified based on the classification of Indonesia's geothermal energy resources and reserves in SNI 6009:2017.

The concession area of the Tabanan geothermal working area was referred to Minister Decree 2067/K/20/MEM/2012. This field exploration activity began with the signing of the joint operation contract (JOC) by Pertamina and Bali Energy Limited in November of 1995. Bali Energy Limited (BEL) has completed geological, gravity,

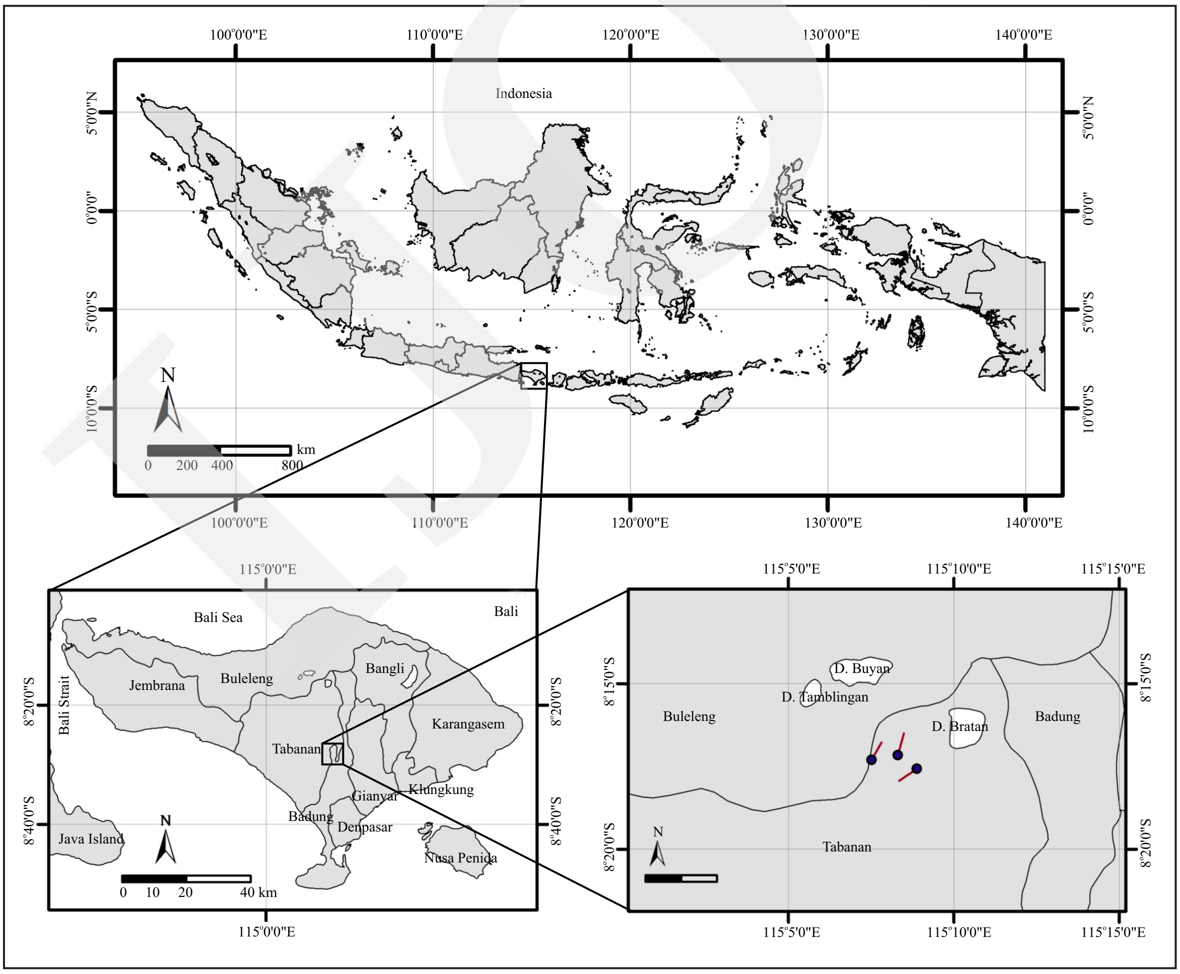

Figure 1. Location of Bedugul Geothermal Field, Bali Province, Indonesia.

and resistivity surveys and drilled six temperature gradient core holes to the depths of 685-1400 m and three deep exploration wells with a depth of 2686-2826 m in 1997. The current status of this field is still in the exploration phase. This field planned to have 10 MWe installed capacity from the first unit in 2020 and 55 MWe installed capacity from the second unit in 2025. Unfortunately, the Bedugul geothermal project was suspended in 2004 because of resistance from the residents near the area and the local government (ThinkGeoEnergy, 2019).

The initial conceptual model of the Bedugul geothermal field was first proposed by Mulyadi and Hochstein (1981) and updated by Tim Potensi Panas Bumi KESDM (1994), those initial conceptual models were based on the geoscience data since no deep core hole wells and exploration wells were drilled in the Bedugul area (Figure 2). The drilling on Bedugul geothermal field started in 1997. It is essential to update the conceptual model based on geoscience and well data since there are drilled wells in the geothermal area. Mulyadi *et al*. (2005) conducted the resource assessment, employing the volumetric method combined with Monte Carlo simulation. The reserve potential for P10, P50, and P90 are 183.2 MW, 317.9 MW, and 525 MW. However, the input parameters in volumetric resource assessment still have high uncertainty leading to overestimation (Sarmiento *et al*., 2013) of the resource and reserve of the reservoir of the Bedugul geothermal field.

This study aimed to verify and update the conceptual model and resource assessment of the Bedugul geothermal field by the numerical model calibration based on geosciences study and well data. The model's temperature, mass and heat flow, and fluid condition were calibrated using available data until achieving a well-matched natural state condition. The natural state modeling was carried out using TOUGH2 (Pruess *et al*., 1999). Some updated conceptual models of geothermal fields were successfully built using numerical simulation. The previous studies for this method were carried out for Ciwidey-Patuha geothermal field (Ashat and Pratama, 2017; Ashat *et al*., 2019a, 2019b), Songa-Wayaua geothermal field (Hasbi *et al*., 2020), Atadei geothermal field (Supijo *et al*., 2020, 2018), Lumut Balai geothermal field (Hamdani *et al*., 2020), and Cisolok-Cisukarame geothermal field (Sumartha *et al*., 2020). Some resource assessments of geothermal fields were successfully done using the results of the natural state model that were applied to the Monte Carlo simulation (Pratama and Saptadji, 2015, 2016, 2018, 2021; Sarmiento *et al*., 2013).

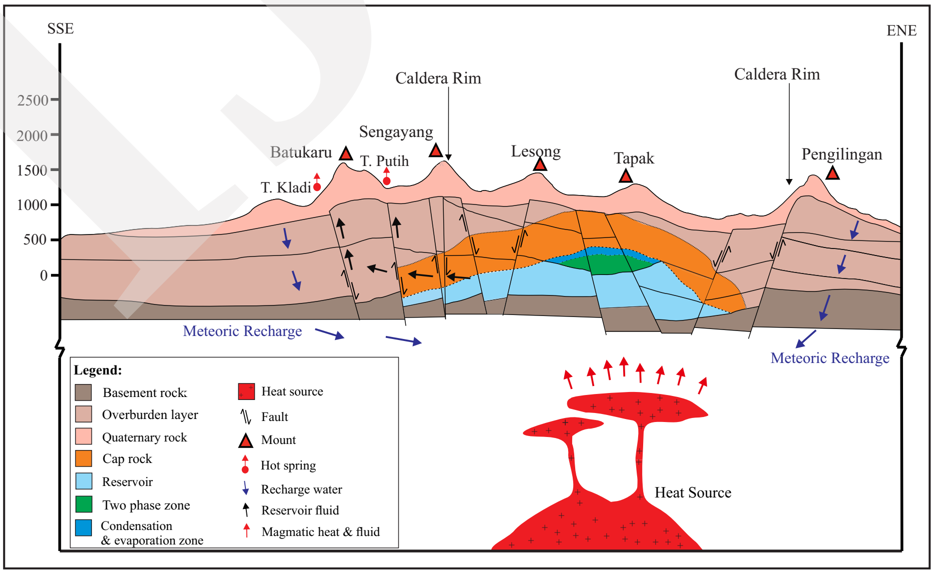

Figure 2. Initial conceptual model of Bedugul Geothermal Field (Modified from Tim Potensi Panas Bumi KESDM, 1994).

The previous studies for this method were carried out in some geothermal field, such as Kerinci (Hidayat *et al*., 2018), Arjuno-Welirang (Manggala Putra, *et al*., 2019), Ulumbu (Kurniawan *et al*., 2019), Mataloko (Pradhipta *et al*., 2019; Jatmiko *et al*., 2021), Karaha-Talaga Bodas (Prabata *et al*., 2019; Sutopo *et al*., 2019), and Danau Ranau (Afiat *et al*., 2021).

Geoscience Review

Integrating geoscience data and analysis is necessary to achieve a natural state condition of the numerical model of the geothermal field. Geology, geochemistry, geophysical, and well data analyses are described in a geoscience analysis based on several published papers. The previous studies in Bedugul geothermal field were conducted by Mulyadi *et al*. (2005), Bogie *et al*. (2010), and Purnomo and Pichler (2015).

Geology

The Bedugul geothermal system is associated with Quaternary volcanic activities in the Pleistocene to Holocene period. The system is in N-S trending volcanic activities in the giant Bratan caldera. Volcanic rocks are distributed in most prospect areas, and sedimentary rocks are near the lakes within the Bratan caldera. The surface layer consists mainly of tuff, tuff lapilli, and alluvium. Flowed pumice ash tuff covers most of Bali's central and eastern parts, which overlies andesitic rock (Mulyadi *et al*., 2005). The Mt. Tapak complex is the youngest complex expected to be associated with a heat source. The geological map of the Bedugul geothermal field is presented in Figure 3.

The distribution of thermal manifestations is primarily located in the southwestern part of the caldera (Figure 4). It is interpreted that the emergence of thermal manifestations within the caldera is associated with a NW-SE structure. The appearance of domes in the caldera, marked by

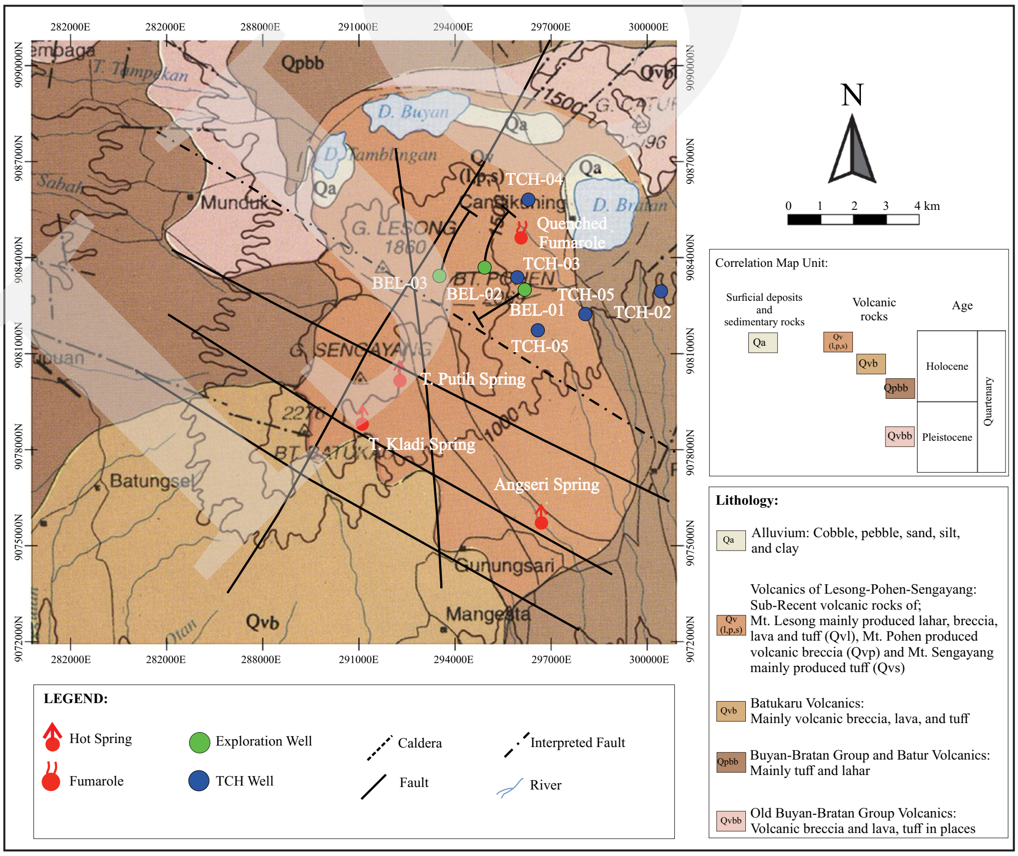

Figure 3. Geological map of Bedugul Geothermal Field (Modified from Purbo-Hadiwidjojo *et al*., 1998).

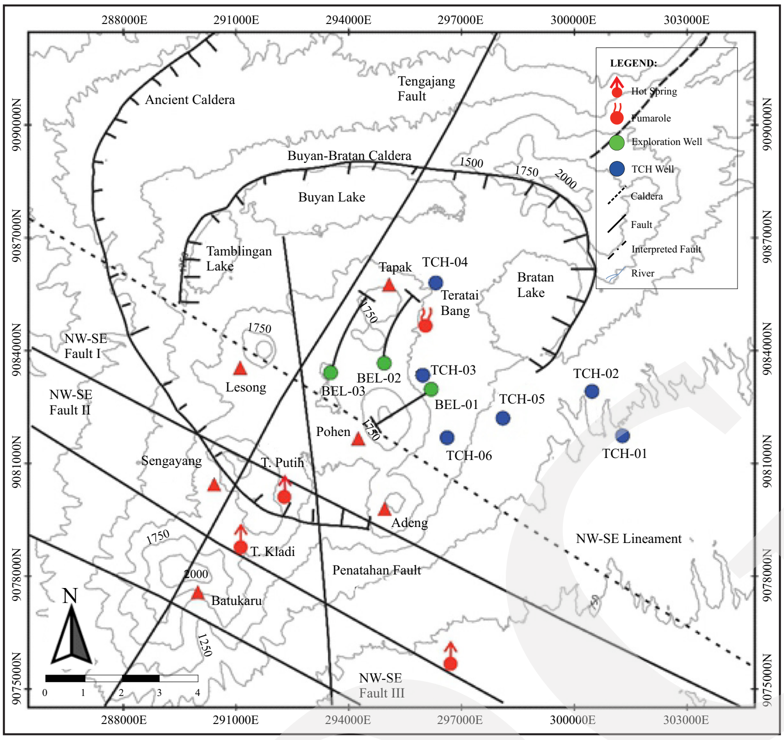

Figure 4. Surface manifestation and geological structures in the Bedugul geothermal area (Modified from Tim Potensi Panas Bumi KESDM, 1994 and Mulyadi *et al*., 2005).

young volcanic cones, indicates the possibility of a geothermal system controlled by resurgent domes (Figure 5).

Geochemistry

The geochemistry study was done using surface manifestations, warm springs, and well fluid data. The type of reservoir fluid is indicated using the Cl-SO_4-HCO_3 ternary diagram (Figure 6). The type of reservoir fluid is indicated as mature waters based on the high Cl content of BEL-03 fluid and marked as the upflow zone. It is stated that the BEL-03 having reached the T. Putih, T. Kladi, and Angseri warm spring fluid are peripheral water with high HCO_3 content and indicated as the outflow zone.

The reservoir temperature of the Bedugul geothermal field was estimated from Na-K-Mg geothermometer calculations using samples from liquid manifestation and exploration well. The BEL-03 is in partial equilibrium condition and indicates that the fluid comes from the reservoir directly, while the warm springs (T. Putih, T. Kladi, and Angseri) were in immature water suggesting that the fluid had been mixed with groundwater and reacted with the rock (Figure 7). The reservoir temperature based on the Na-K-Mg geothermometer is estimated at around 280-300 ºC.

The BEL-03 gas geochemistry data were collected on May 17th, 2004 (Table 1). The gas geochemistry data of BEL-03 can indicate the heat source of the Bedugul geothermal field. Based on the data, the BEL-03 fluid contains low H_2S and SO_2, indicating that the Bedugul geothermal system was the magmatic system with the heat source of the cooling dyke (Mulyadi *et al*., 2005).

Geophysical

The geophysical study was conducted using Magnetotelluric-TDEM and Gravity method. The geophysical data could point out the location of the heat source, reservoir, and caprock of the geothermal system. The gravity method was used to determine the location of the heat source based on the density distribution of the rocks with residual anomaly data as the reference for interpretation. The gravity study of the Bedugul tends to show that the area with high density was

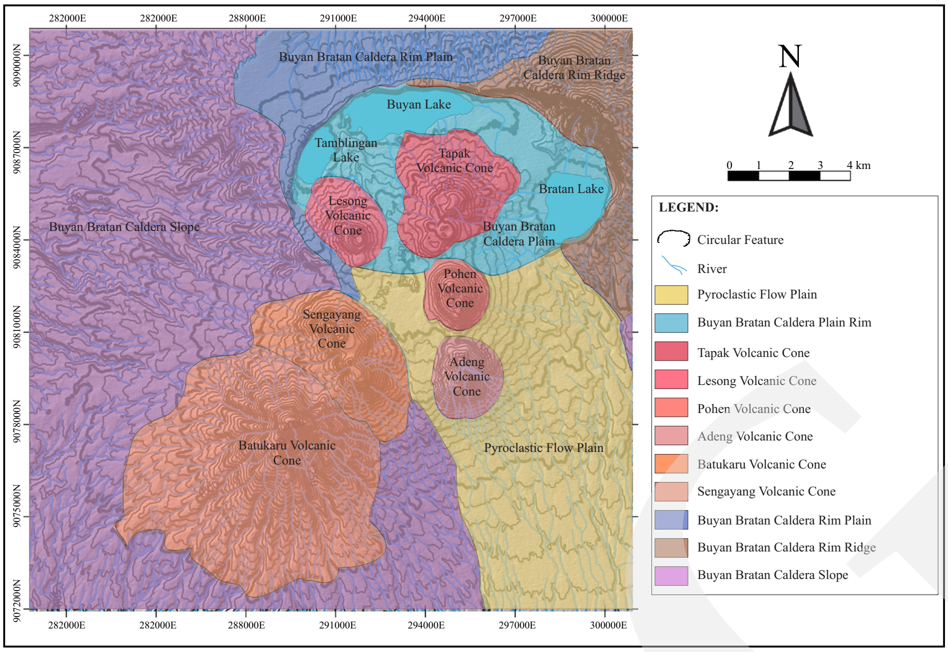

Figure 5. Geomorphology map of Bedugul geothermal field.

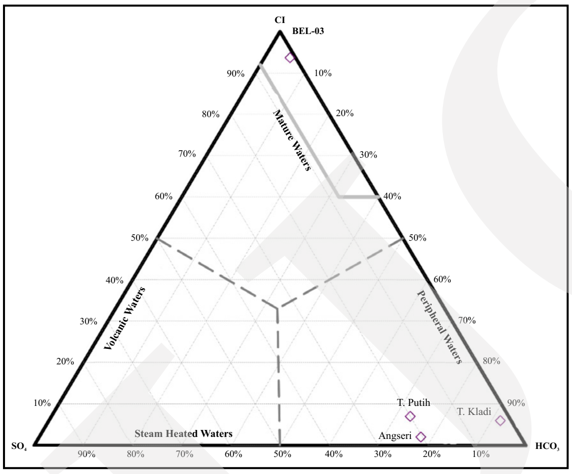

Figure 6. Cl-SO_4-HCO_3 diagram of Bedugul manifestation and exploration well fluid.

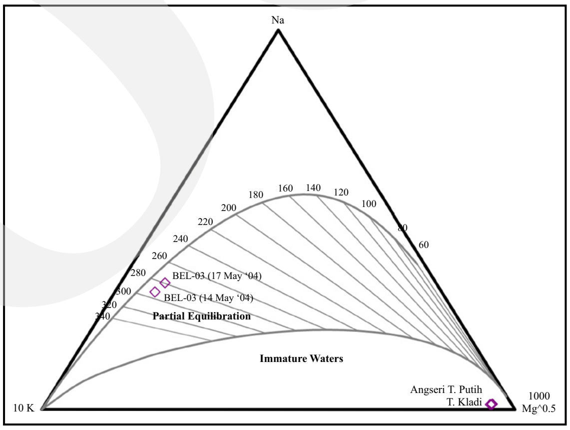

Figure 7. Na-K-Mg geothermometer.

suggested as the system heat source and located beneath Mount Tapak (MT). Three wells were drilled with a trajectory to Mount Tapak, namely BEL-02, BEL-03, and TCH-4. The MT data was used to determine the caprock and reservoir from the resistivity of the rocks. The interpretation of MT data indicates that the low resistivity layer, lower than 10 ohm m, can be found in the Bedugul Field. Based on the resistivity on -1000 - 0 m above sea level (m asl.), the distribution of the low resistivity layer in the Bedugul Field is from

Table 1. BEL-03 Gas Geochemistry Data (Mulyadi *et al*., 2005)

Parameter	% Mole	% Weight
CO_2	95.67	96.99
H_2S	2.93	2.3
SO_2	0.0005	0.0008
HCl	0.0045	0.0038
HF	0.0407	0.0188
H_2	0.33	0.02
O_2	0.332	0.282
N_2	0.411	0.265
CO	< 0.0001	< 0.0001
CH_4	0.0081	0.003
C_2H_6	0.0084	0.0058
Total Gas	1.81	4.26
H_2O	98.19	95.74

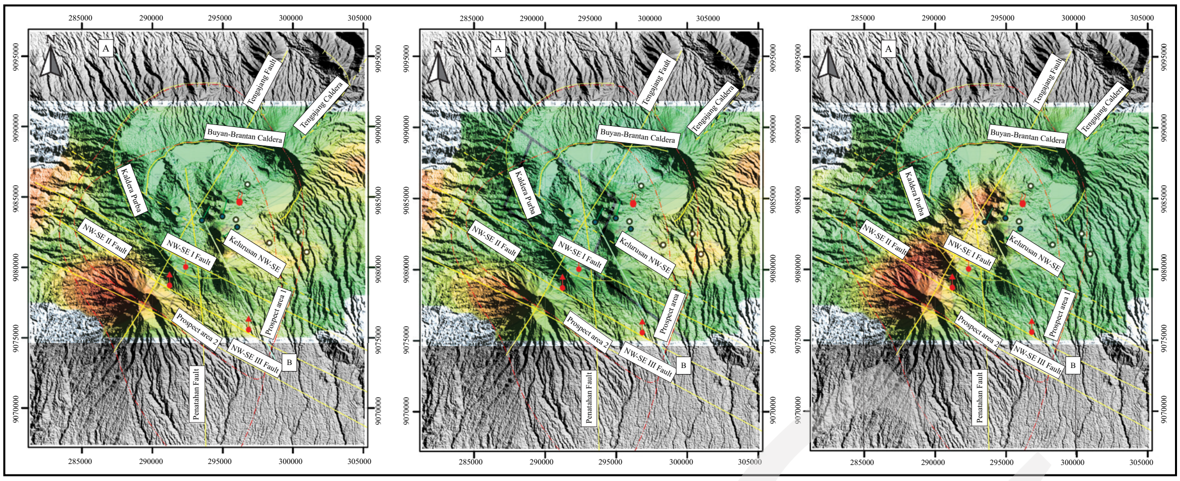

Figure 8. Overlay of resistivity map (Modified from Bogie *et al*., 2010).

the SW to NE (Figure 8). The low resistivity layer can be interpreted as the caprock layer of the Bedugul Field. The caprock formed a dome shape with the thick layer is in the SW area and thinning towards the NE. The top of the caprock is situated around Mount Lesung to Mount Tapak, and the reservoir is shown beneath the caprock. The caprock distribution formed a doming shape, and was distributed from NE to SW area of the Bedugul Field (Bogie *et al*., 2010).

Well Data

There are six temperature core hole wells and three deep exploration wells in Bedugul geothermal field (Figure 4). Well BEL-01, BEL-02, BEL-03, TCH-04, TCH-3, and TCH-06 were drilled inside the Buyan-Bratan Caldera, while well TCH-05 and TCH-01 were drilled outside the caldera. The TCH wells were drilled with vertical configuration, while the BEL wells were drilled with directional configuration. BEL-2 and BEL-03 were drilled directionally to Mount Tapak, and BEL-01 was drilled directionally to Mount Pohen. This research uses three deep exploration wells (BEL-01, BEL-02, BEL-03) and five temperature core hole wells (TCH-02, TCH-03, TCH-04, TCH-05, TCH-06) (Figure 9). BEL-02, BEL-03, and TCH-04 reached a temperature higher than 240ºC, while TCH-01 well is not accompanied in this research because it is based on the mode gridding area; the pressure and temperature profile of these wells is shown in Figure 10. The convective zone, an area with good permeability, is recognized at elevation 100 to -400 m asl. with temperatures of 240-270ºC based on the temperature profile of BEL-02 and BEL-03 (Figure 10). However, the convective zone does not exist in BEL-01, because of the thick caprock layer beneath Mount Pohen (Mulyadi *et al*., 2005).

Natural State Model

The numerical model of the Bedugul geothermal field was built and simulated using TOUGH2. The result of the natural state model was used as the base for updating the conceptual model and resource estimation of the Bedugul geothermal field.

Model Structure

The model in this study has a total area of 10 x 10 km^2 with a vertical extent of approximately 4.8 km. The model covers the reservoir, well, and the recharge-discharge area. The model was rotated clockwise to accommodate the prominent structure and flow direction also the gridding area of the model (Figure 10).

The model consists of eighteen layers, with some of the top layers following the actual topographical condition. The model was divided into

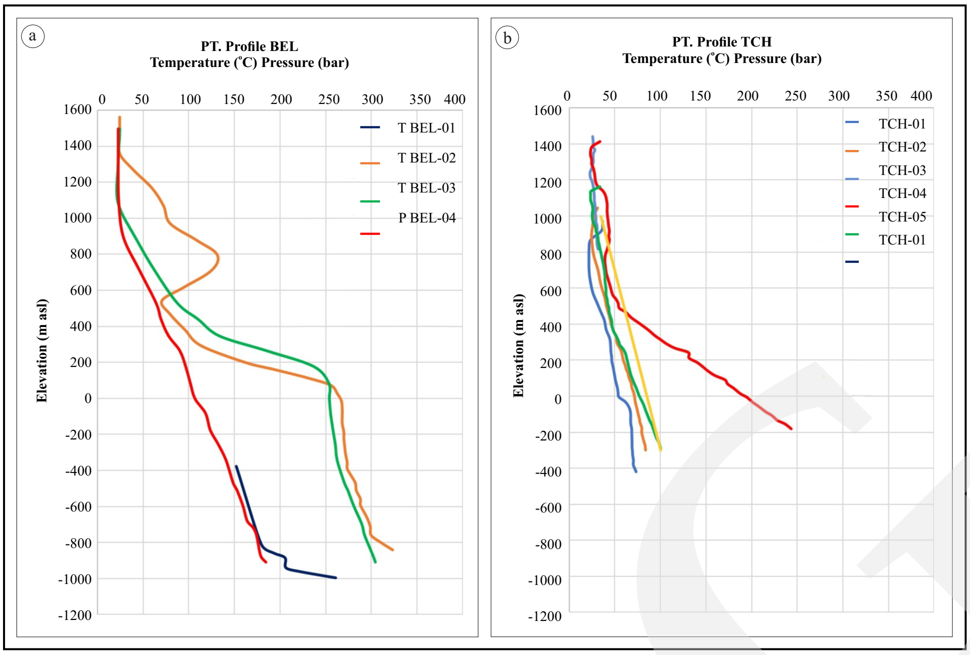

Figure 9. (a).PT profile BEL wells; (b) T profile TCH wells (Modified from Mulyadi *et al*., 2005).

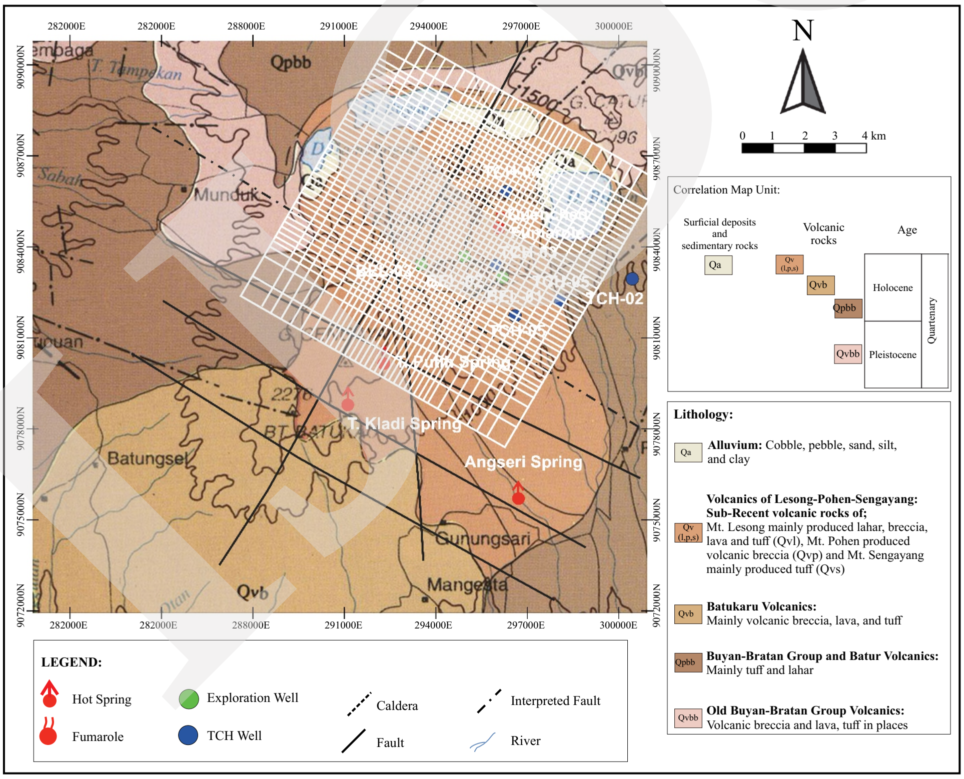

Figure 10. Model gridding area on the Bedugul geological map (Modified from Purbo-Hadiwidjojo *et al*., 1998).

27,864 active grid blocks using a rectangular grid type with various sizes depending on the geological condition. The grid block dimension varies from the smallest 200 x 200 m to the largest 810 x 810 m. Each layer of the model is 200 m thick except for layers 17 and 18 are 250 m thick each one. Tengajang Fault is prominent in this area. The model was rotated by 330º in the same

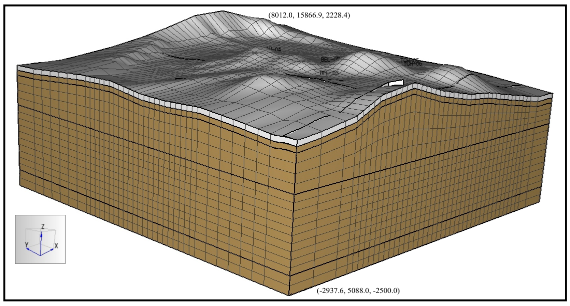

Figure 11. Gridding and layering system.

direction as the Tengajang Fault. Figure 11 shows the gridding and layering system of this model.

Initial and Boundary Conditions

The initial condition is needed to input each grid block of initial temperature and pressure on the model. The normal gradient is used for pressure and temperature at the initial condition. The boundary condition of the model is presented in Figure 12. The top layer is set to constant atmospheric conditions, with the pressure set at 1 bar and the temperature set at 25ºC. The bottom boundaries are the heat source and impermeable rocks (Figure 12b), whilst the side boundary is assumed to be no flow boundary, and its materials are set to impermeable materials.

Rock Properties

Determining the permeability structure is the essential step during numerical modeling. The permeability structure is iteratively adjusted during the numerical modeling until the steady-state condition is achieved with several trials and errors. The relative permeability uses Corey's Curves. The distribution of rocks and materials in the grid model is based on the delineation of the reservoir from the previous studies (Figures 13 and 14).

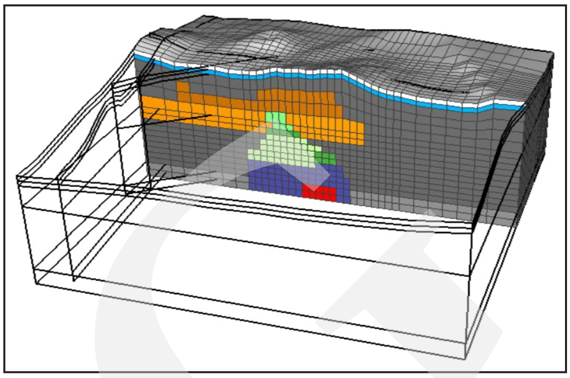

Figure 13. Material distribution in the model.

The properties of each material and rock type used in the modeling to reach the natural state (Table 2). A k_{xy} indicates the rock permeability in the horizontal direction, and k_z indicates the permeability in the vertical direction with the millidarcy (mD) unit. The reservoir numerical model of the Bedugul area consists of seven materials, and the permeability ranges between 0.1 to 100 mD.

Model Result

Geological, geochemistry, and geophysical surveys, supported by well data were used to

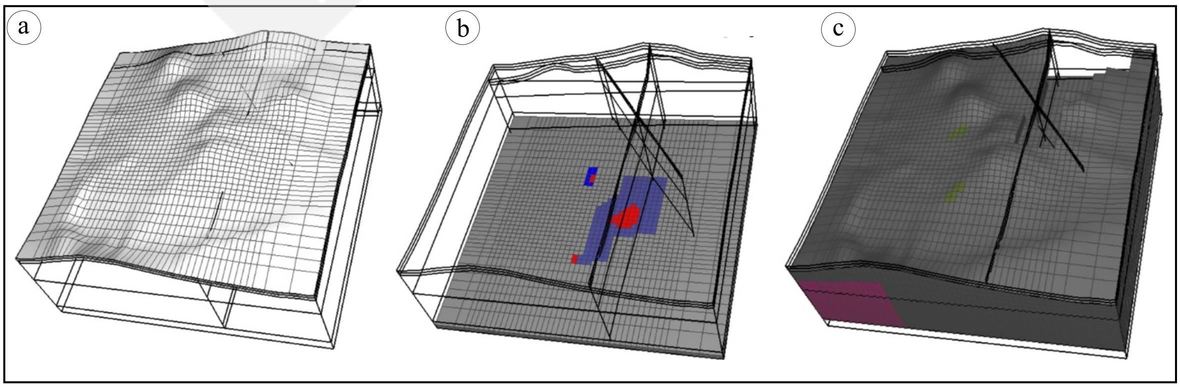

Figure 12. Boundary conditions. (a) Top Boundary. (b) Bottom Boundary. (c) Side Boundary.

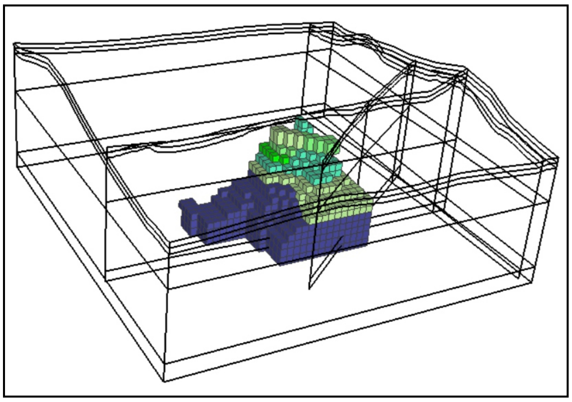

Figure 14. Reservoir material distribution of the model.

Table 2. Material Properties

Material	Type	k_{xy} (mD)	k_z (mD)	Color
ATM	Atmosphere	10	10	
GW	Ground Water	0.002	0.002	
HEAT	Model Base	100	100	
BASE		9	9	
BON	Boundary	0.005	0.005	
ROCK1		0.00001	0.00001	
ROCK2		0.001	0.001	
CAP	Caprock	0.02	0.002	
CAP2		0.006	0.002	
RES1	Reservoir	0.1	0.1	
RES2		50	50	
RES3		95	100	
RES4		30	10	
RES5		12.5	20	
RES6		2	3	
RES7		0.5	0.3	

build a comprehensive natural state model of the Bedugul geothermal field. Iterative adjustment of the rock parameters, especially permeability, porosity, and density is required to reach the steady-state condition of the model. The result consists of temperature and pressure for well BEL-01, BEL-02, BEL-03, TCH-02, TCH-03, TCH-04, TCH-05, and TCH-06. The temperature and pressure of the model result and actual data were matched by adjusting the permeability of the materials in an iterative process. The actual temperature and pressure data coincide with the model result (Figure 15). It shows a good alignment between the model result and the actual temperature. However, only well BEL-03 having actual pressure data, which fits the model result.

Evaluation of the matching result of actual temperature and pressure data with model result employs the root-mean-square error (RMSE) equation from (Seyedrahimi-Niaraq *et al.*, 2019; Lesmana *et al.*, 2019; and Pratama *et al.*, 2020),. The RMSE formula is:

$$\mathrm{RMSE} = \sqrt{\frac{1}{N}\sum_{i=1}^{N}\left(X_{actual} - X_{actual}\right)^2} \quad \text{......... (1)}$$

The RMSE method was applied for each well to validate the temperature and pressure matching. The RMSE calculation for well BEL-01, BEL-02, and BEL-03 used the pressure and temperature data from -900 - 1,600 m asl., and for well TCH-02, TCH-03, TCH-04, TCH-05, and TCH-06 used the pressure and temperature data from -300 - 1,400 m asl. Figure 16 shows the matching result of the RMSE method for temperature (left) and pressure (right). The RMSE shows the margin of error from temperature and pressure from actual and model results. Well TCH-04 has the highest deviation in temperature, which may be caused by limited temperature data. Based on RMSE, the temperature ranges from 1.65 to 24.59 °C, and the pressure at 5.48 bar (Table 3).

The steady-state condition of the numerical model was reached by adjusting the rock parameters iteratively until the time step of the model was more significant than 1 x 10^{14} seconds, which means that the heat and mass flows were stable. The numerical model of the Bedugul geothermal field reached a running time of more than twenty-nine million years. From the temperature and pressure data, it can be inferred that the reservoir is a single-phase liquid system, because there is no indication of the steam zone in the model, which is consistent with the logging data. The mass flow and the heat flow of the model result show a good agreement that the heat and mass come from beneath

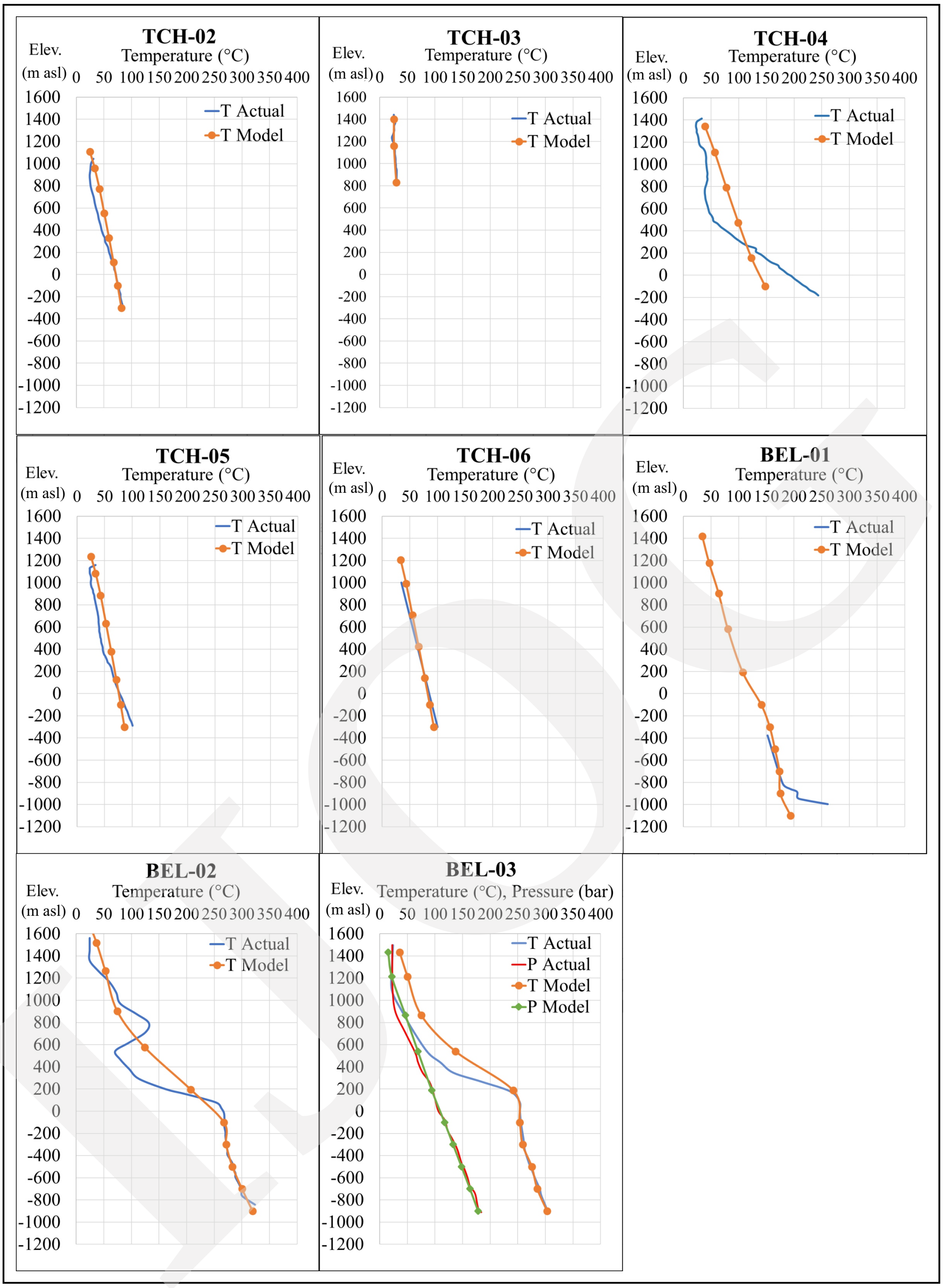

Figure 15. P-T matching of actual data and model result.

Mount Tapak (Figures 17 and 18). The appearance of quenched fumarole indicates an upflow zone of the system. Based on the model result, there is no indication of an outflow zone near Mount Tapak. The isothermal profile generated from the numerical model serves as necessary information in updating the conceptual model of the Bedugul geothermal system (Figures 19 and 20). The isothermal profiles show that only BEL-02 and BEL-03 reaching the high-temperature zone, which is interpreted as the reservoir of the Bedugul geothermal system.

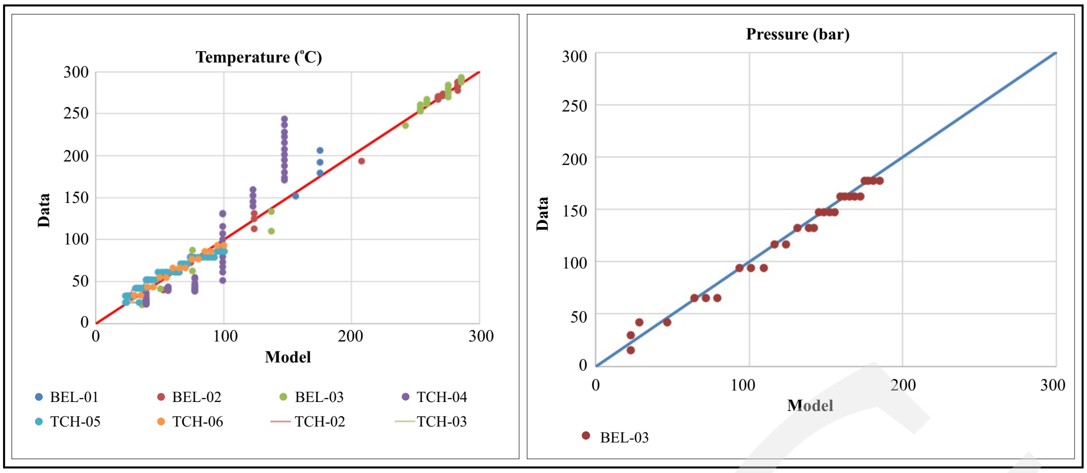

Figure 16. Comparison of actual temperature and pressure data with the model result.

Table 3. RMSE of the Natural State Model

Well	Pressure	Temperature
BEL-01	-	16.06
BEL-02	-	6.43
BEL-03	5.48	8.44
TCH-02	-	5.89
TCH-03	-	1.66
TCH-04	-	24.59
TCH-05	-	7.94
TCH-06	-	3.50

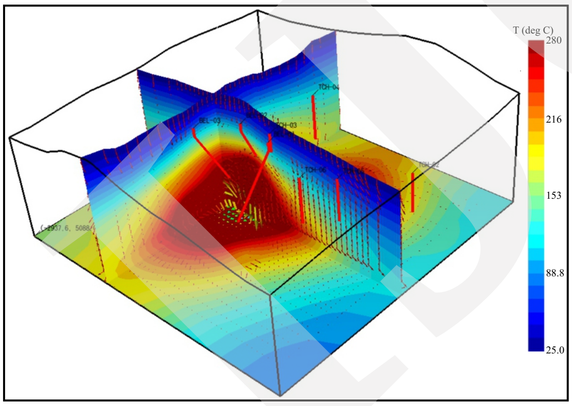

Figure 17. Fluid flow profile of the numerical model.

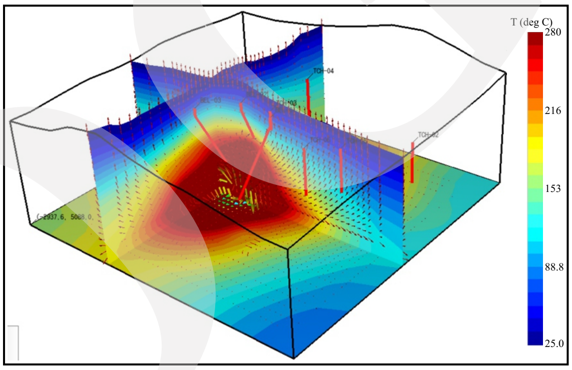

Figure 18. Heat fluid flow profile of the numerical model.

Conceptual Model Update

The conceptual model from Mulyadi and Hochstein (1981) inferred that the Bedugul geothermal system was a vapour-dominated system capped by a doming condensate layer that consisted of HCO_3-SO_4 water. The lack of discharge feature inside the caldera was caused by the doming structure of the condensate layer. From the conceptual model, it can be inferred that the Bedugul geothermal system is categorized as a deep geothermal system. This conceptual model cannot clearly describe the Bedugul geothermal field reservoir condition, because of insufficient data available at that time. An update of the Bedugul geothermal field conceptual model is proposed by Tim Potensi Panas Bumi KESDM (1994). Consent with the previous model, this model concludes that the Bedugul geothermal system is a vapour-dominated system, with high H_2S content in the upper part of the reservoir and high Cl and CO_2 content in the deeper part of the reservoir. The hot spring water is dominated by HCO_3, which interprets the outflow zone. The previous conceptual model, proposed by Mulyadi and Hochstein (1981) and Tim Potensi Panas Bumi KESDM (1994), did not accompany the exploration well data as the necessary information

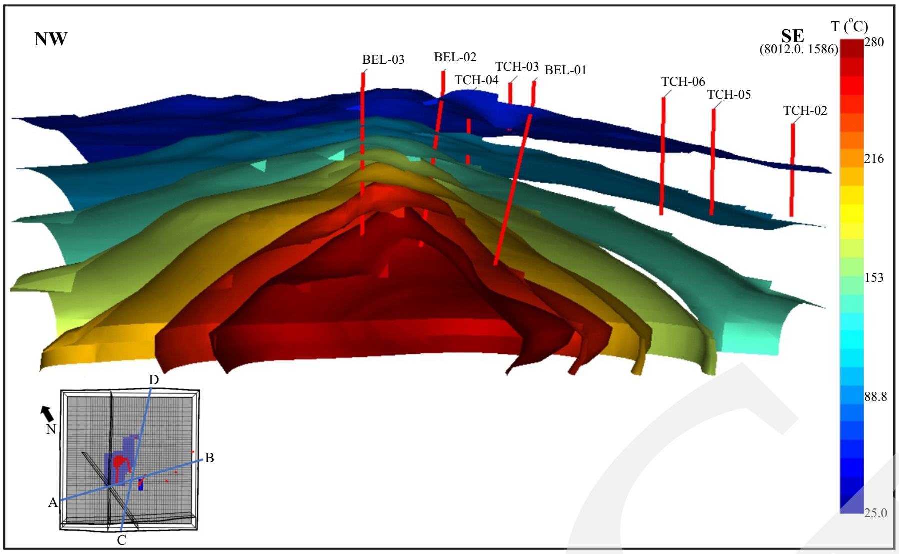

Figure 19. Isothermal profile of A-B cross-section.

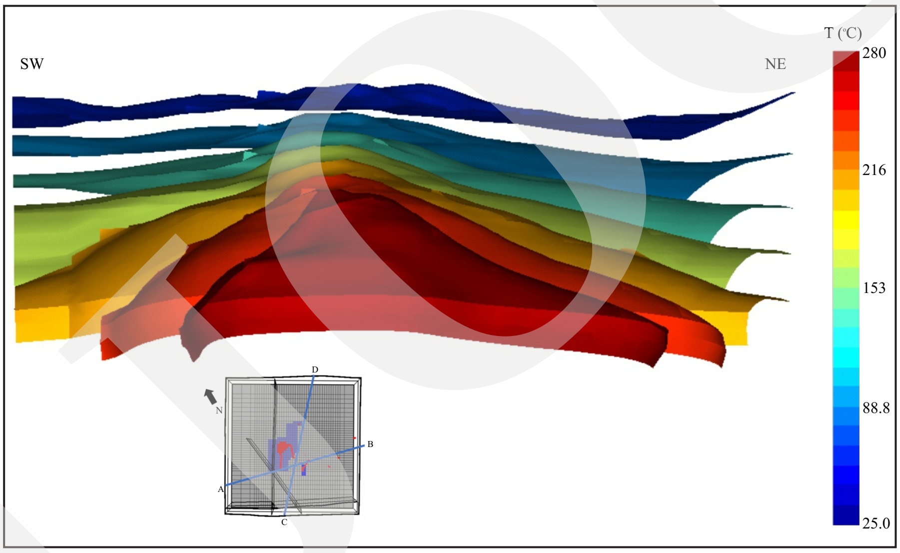

Figure 20. Isothermal profile of C-D cross-section.

of the reservoir condition. The susceptibility of that previous model is lack of available data that required for more preferable interpretation and analysis to build the comprehensive conceptual model of Bedugul geothermal field.

The updated conceptual model of the Bedugul geothermal field is based on the integrated result of numerical simulation, geological-, geochemical-, and geophysical studies, and three wells data (Figures 21 and 22). The Bedugul geothermal system is a hydrothermal geothermal system associated with a magmatic and cooling dike as the heat source. Based on the numerical model result, the geothermal system in the Bedugul Field is hosted by a cooling dike with conductive heat flow, and was estimated beneath Mount Tapak. Bedugul geothermal field is categorized as a high-temperature reservoir with a water-dominated system. Contradicting the previous conceptual models that conclude the Bedugul system is a vapour-dominated system, the result of the numerical model validated with the pressure and temperature profile of the explorations and temperature gradient wells indicated that the Bedugul system was

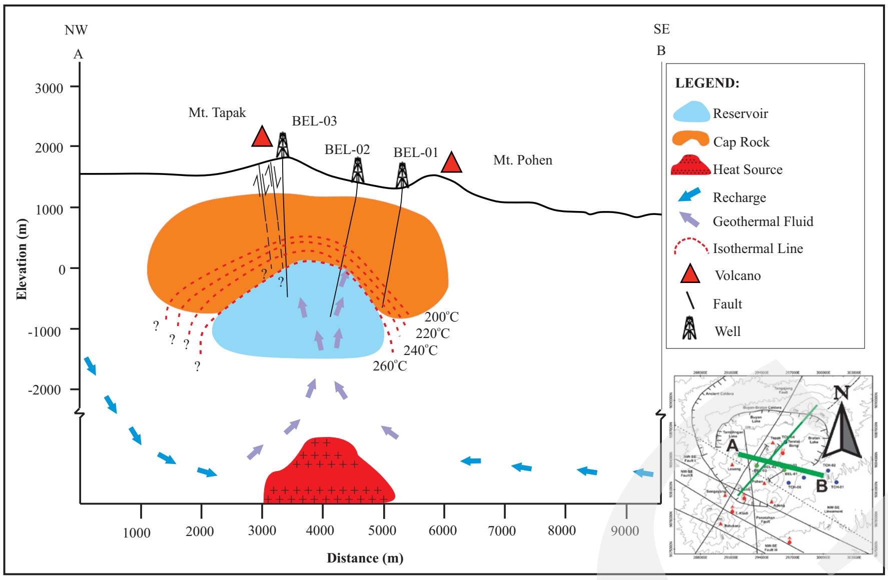

Figure 21. Conceptual model A-B cross-section.

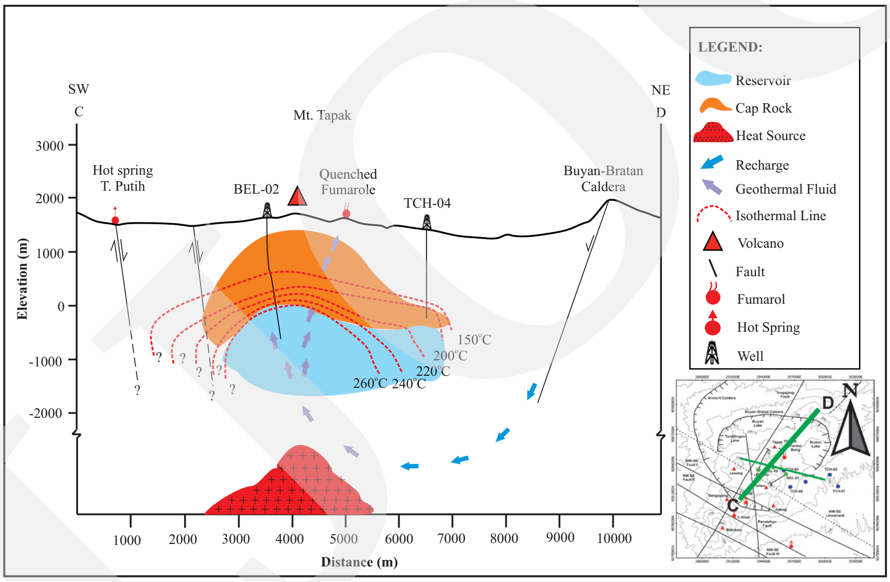

Figure 22. Conceptual model C-D cross-section.

water-dominated. The analysis of geochemical data inferred that the fluid from BEL-03 well was reservoir fluid, characterized by high Cl content and the location in the mature water area based on the Cl-SO_4-HCO_3 diagram. There is an impermeable structure along Mount Tapak. The upflow zone is located in Bedugul, which is shown by the presence of quenched fumaroles.

The hot springs in the southwestern caldera are indicated as the outflow of the Bedugul geothermal system, as shown by the Cl-SO_4-HCO_3 diagram. The hot spring water had been mixed with groundwater and interacted with the rock, characterized by high HCO_3 content and those type of water known as bicarbonate water. The recharge water of the reservoir originated from the caldera rim of Buyan-Bratan Caldera. Doming-shaped caprock overlies the reservoir, and consists of impermeable clay. The updated conceptual model built from comprehensive analysis and integration of geoscience and well data is adequate to represent the Bedugul geothermal system.

Resource Assessment

The heat stored method with the probabilistic approach (Monte Carlo simulation) was conducted to assess the resource estimation of the Bedugul geothermal field. The reservoir characterization was performed to determine the several parameters needed for resource assessment calculation. The calculation was done for the probable area and proven area.

Reservoir Parameters

Several parameters are needed for resource assessment calculation. The reservoir area in the model was obtained from delineating a high-temperature reservoir, 225ºC (Hochstein, 1990). The probable area is approximately 8 km^2 (Figure 23). The proven area is approximately 4 km^2 (Figure 24). The proven area was obtained from a delineation area of BEL-02 and BEL-03. The reservoir thicknesses for the probable area are based on the natural state model temperature and the model reservoir material. The reservoir thicknesses for the proven area are based on the natural state model temperature, the model reservoir material, and the convective zone based on the BEL-02 and BEL-03 temperature profiles.

The rock porosity and density are obtained from common rock properties. The rock porosity values range from 6 - 0%, and the rock density values vary between 2565 to 2700 kg/m^3. The rock heat conductivity values are 950-1,000 J/kg-ºC. The initial water saturation is 1.0 based on the natural state model, and the final water saturation is 0.3-0.5. The initial reservoir temperature is 265-290ºC, obtained from the model temperature. The abandonment reservoir temperature is 180ºC based on SNI 13-6171-1999 for a high-temperature geothermal system.

The recovery factor is based on the correlation proposed by Muffler and Cataldi (1978). The recovery factor is about 22.5 - 25%. The electrical conversion efficiency is obtained from the function of reservoir temperature proposed by Nathenson (1975). The reservoir temperature is 265 - 290ºC. Thus, the electrical conversion

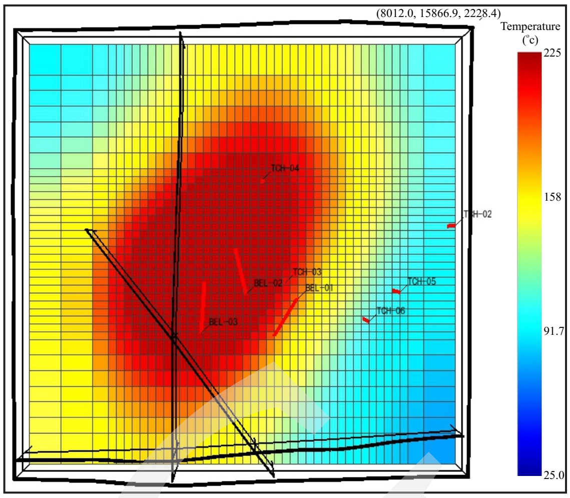

Figure 23. Probable area delineation.

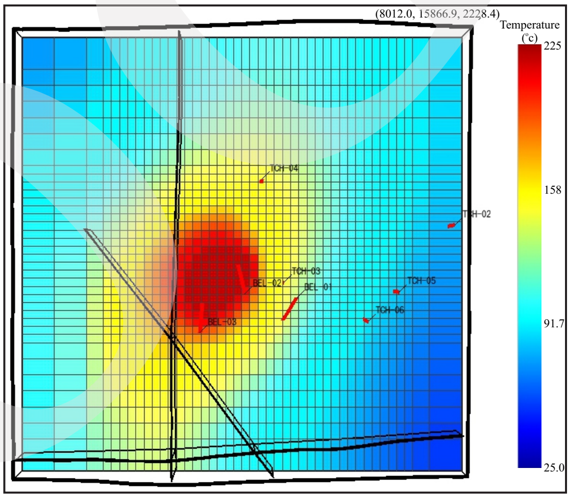

Figure 24. Proven area delineation.

efficiency is 12.5 - 13.5%. The project lifetime is assumed to be thirty years based on SNI 13-6482-2000 (Tables 4 and 5).

Resource Estimation Results

The resource estimation of the Bedugul geothermal field was estimated using the heat stored method with the probabilistic approach (Monte Carlo simulation). This simulation was run using 60,000 random numbers from the previous section parameter values.

The calculation result is a probability distribution function of the resource estimation covering the range of possible P10, P50, and P90 of MWe. The probable reserve estimation calculation P10, P50, and P90 are 116.3 MW, 136.3 MW, and 157.8 MW, as shown in the cumulative distribution of probable reserve estimation for thirty years of project lifetime (Figure 25). The result is close to the probable reserve estimation calculated by KESDM (2017), of 110 MW. The P10, P50, and P90 of proven reserve estimation calculation are 28 MW, 33.4 MW, and 39.1 MW respectively (Figure 26). The result is close to the proven reserve estimation (KESDM, 2017) of 30 MW.

Discussion

The numerical model represents the subsurface condition of the Bedugul geothermal field from the Natural State model, based on integrating the geological, geophysical, geochemistry, and well data. The RMSE analysis based on validation of the pressure and temperature matching between the model and actual data shows that the RMSE value from the numerical model ranges from 1.66-24.59ºC for temperature and 5.48 bar pressure. The temperature deviation for BEL-02 and BEL-03 are 6.43 and 8.44 ºC, while TCH-02, TCH-03, TCH-05, and TCH-06 have temperature deviations of 5.89, 1.66, 7.94, and 3.5ºC, respectively. However, the BEL-01 and TCH-04 have a higher deviation than the other well (16.06 and 24.59ºC) (Figure 16). An indication of cold water intrusion on TCH-04 caused the low-temperature gradient in -1,400 - -400 m asl. Coldwater intrusion is also indicated in BEL-02 and BEL-03, proven by a low-temperature gradient at 1,200-800 m asl. in BEL-03 and reverse temperature at 700-500 m asl. BEL-03. Furthermore, running of PTS tools is required to verify the well condition and determine the feed zone location, particularly for exploration wells.

Resource assessment using a numerical model and volumetric method combined with Monte

Table 4. Input Data for Probable Reserve Monte Carlo Simulation

Parameter	Minimum	Maximum	Most	Remarks
Area (km²)	7	9	8	Natural state model
Thickness (m)	1713	2094	1903	Natural state model and reservoir material
Porosity (%)	6	10	8	Reservoir material in model
Rock density (kg/m³)	2565	2700	2633	Reservoir material in model
Rock heat capacity (kJ/kg.ºC)	0.95	1	0.98	Schon (2011)
Initial water saturation (fraction)	1	1		Natural state model
Final water saturation (fraction)	0.3	0.5		Common assumption
Initial temperature (ºC)	265	290	278	Natural state model
Final temperature (ºC)	160	200	180	SNI 13-6171-1999
Recovery factor (%)	22.5	25	23.8	(Muffler and Cataldi, 1978)
Electric conversion factor (%)	12.5	13.5	13	(Nathenson, 1975)

Table 5. Input Data for Proven Reserve Monte Carlo Simulation

Parameter	Minimum	Maximum	Most	Remarks
Area (km²)	3	4.2	4	Natural state model
Thickness (m)	900	1100	1000	Natural state model, reservoir material, well data
Porosity (%)	6	10	8	Reservoir material in model
Rock density (kg/m³)	2565	2700	2633	Reservoir material in model
Rock heat capacity (kJ/kg.ºC)	0.95	1	0.98	Schon (2011)
Initial water saturation (fraction)	1	1		Natural state model
Final water saturation (fraction)	0.30	0.5		Common assumption
Initial temperature (ºC)	265	290	278	Natural state model
Final temperature (ºC)	160	200	180	SNI 13-6171-1999
Recovery factor (%)	22.5	25	23.8	(Muffler and Cataldi, 1978)
Electric conversion factor (%)	12.5	13.5	13	(Nathenson, 1975)

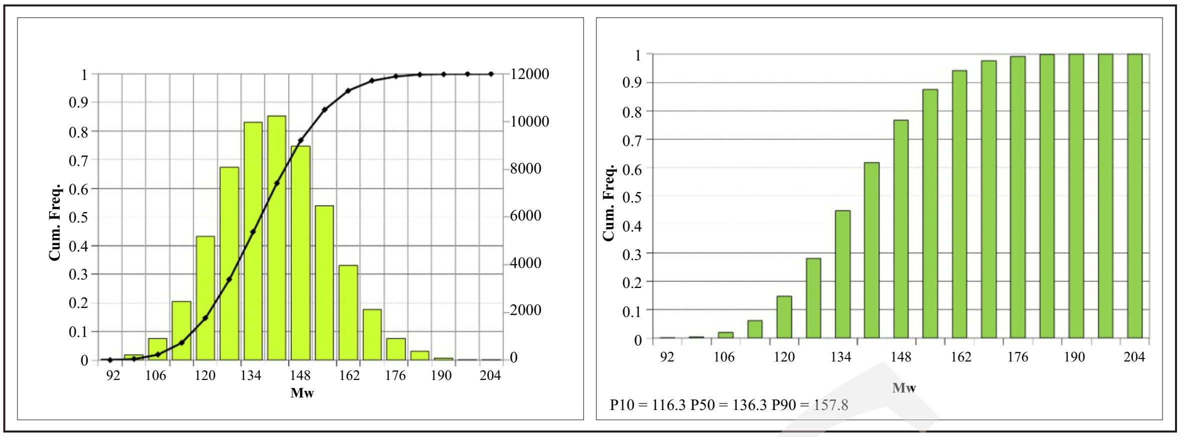

Figure 25. Distribution of Monte Carlo result for probable reserve.

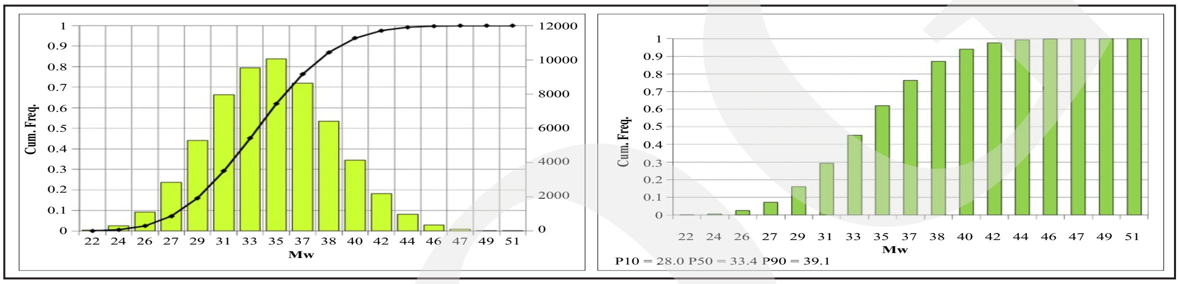

Figure 26. Distribution of Monte Carlo result for proven reserve.

Carlo simulation can reduce the over estimation of the geothermal resources, particularly in the development stage of the geothermal field. The result of resource assessment using a numerical model and volumetric method combined with Monte Carlo simulation emphasizes that the Bedugul geothermal field reserve is sufficient for generating the 10 MWe for the first stage of field development. The Bedugul geothermal field is planned to generate 10 MWe for the first stage of development according to RUPTL (Mulyadi *et al*., 2005).

Further validation with production data (history matching) will increase the accuracy of this model. Furthermore, another method of resource assessment, such as probabilistic resource assessment with Experimental Design and Response Surface Method, should be accommodated for future resource assessment of the Bedugul geothermal field. The ED&RSM method for geothermal resource assessment was previously conducted to assess the reservoir capacity of the geothermal field in Indonesia, namely, Ulumbu geothermal field (Ciwidey-Patuha geothermal field (Ashat *et al*., 2019b), Lumut Balai geothermal field (Hamdani, 2019), Kurniawan *et al*., 2019), Karaha-Bodas geothermal field (Sutopo *et al*., 2019), Tompaso geothermal field (Lesmana, 2019) and Atadei geothermal field (Pratama *et al*., 2020). It will provide a more confident resource assessment by reducing the uncertainty of reservoir parameters compared with the volumetric method.

Conclusions

The model of Bedugul geothermal field with a 10 x 10 km^2 area was successfully developed, showing a good match of pressure and temperature profile of BEL-01, BEL-02, and BEL-03 wells. Based on the natural state matching of the model and actual well PT data, it is indicated that the Bedugul system is water dominated. The numerical reservoir model result shows that the probable area of the reservoir is approximately 8 km^2, and the proven area is approximately 4 km^2. Based on the RMSE analysis, the numerical model temperature ranged from 1.65 to 24.59 °C, and the pressure at 6.91 bar from the actual well data. The conceptual model of the Bedugul geothermal field has been built based on the natural state model. In estimating the potential reserve of the Bedugul geothermal field, the heat stored method resource estimation calculation was conducted with the probabilistic approach (Monte Carlo Simulation). The probabilistic probable reserve potential for P10, P50, and P90 is 116.3 MW, 136.3 MW, and 157.8 MW respectively. The probabilistic proven reserve potential for P10, P50, and P90 are 28 MW, 33.4 MW, and 39.1 MW, respectively.

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