

Reservoir Modeling for Development Capacity of Dieng Geothermal Field, Indonesia

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ABSTRACT

Dieng geothermal field is a volcanic geothermal reservoir located in Central Java, Indonesia, about 120 km from Semarang the capital city of Central Java Province. Since 2002, Geo Dipa Energi started to operate commercially Dieng Unit 1 with an installed capacity of 60 MW. The generated electricity is transferred to the Java – Madura – Bali interconnection system to support the electricity needs in this network system. According to the Statistic PLN 2013, the electricity needs in Java at the end of December 2013 amount to about 26,768 MW (78.3% of total needs in Indonesia). About 1.67% of total electricity generated in Indonesia is produced from geothermal power plants mostly located in Java.

After more than 12 years operation of Dieng Unit 1, new data from production monitoring, down-hole logging, sampling and analysis of the geothermal fluid, combined with initial data measurements and geoscience interpretation were integrated to update the conceptual model and the 3D model of Dieng geothermal field (PWC et al., 2013). The numerical simulation model was developed to evaluate the reservoir performance since the start-up of Dieng Unit 1 and to assess the reservoir capacity to sustain the planned development of Dieng Unit 2 and 3. The simulations were performed using Petrasim V.5.2 pre- and post-processor for the TOUGH2 V.2.0 (Pruess et al., 1999) numerical reservoir simulator developed at LBNL, Berkeley (USA). The EWASG EOS module (Battistelli et al., 1997) for mixtures of water-NaCl-CO₂ has been used.

1. INTRODUCTION

The concession area of Dieng geothermal field is 63 km² spreading in 4 districts of Central Java Province. The area is located in the volcanic arc which is corresponding to the active andesitic volcanism related to the subduction along the Java Trench of the Indo-Australian Plate below the South-East Asian Plate. The area is characterized by 10 lithological units (Figure 1) which include products of G. ("Gunung" or Mount) Prau (lava and tuffaceous breccias, 3.6 ma), G. Nagasari (andesite, 2.99 ma), G. Bisma (basaltic andesite, 2.53 ma), G. Pagerkandang (andesite, 0.46 ma), G. Merdada and Pangonan (andesite, 0.37 ma), G. Kendil (dacitic andesite lava, 0.19 ma), G. Pakuwaja (quartz latite, 0.09 ma), G. Seroja (lava dome, 0.07 ma), volcanic plain and hydrothermally altered rocks (Boedihardi et al., 1991). The concession area includes 3 geothermal active sectors named Sileri, Sikidang and Pakuwaja.

The geothermal resource in Dieng was recognized since Dutch colonial period and in 1964/1965 the area was identified as one of the best geothermal prospect in Indonesia by UNESCO team. In 1970 an initial survey was conducted by USAID and USGS: it included the drilling of six temperature gradient holes, drilled to depths of about 150m. Two of them encountered high-temperature geothermal brine. Further reconnaissance works were then conducted in 1977 by Pertamina. Another series of gradient holes was drilled in the Sikidang sector and in September 1977 well DNG-1 was drilled and completed in April 1978 at depth of 1,903 m. By the end of 1993, Pertamina had completed 27 full-sized wells within the Dieng prospect (Boedihardi et al., 1991). From 24 wells tested, 13 wells (54%) were producing at commercially exploitable pressure. In early 1990s, a private Indonesia firm (Himpurna) was granted the right to further develop the Dieng geothermal field. In December 1994, HCE signed an ESC (Energy Sales Contract) with PLN for delivery of 150 MW of electricity to PLN from Dieng geothermal field. During 1995 to 1998, HCE (Himpurna California Energy, the consortium company between Himpurna and CalEnergy) drilled 25 wells, including 5 temperature gradient holes, to feed planned Dieng Unit 1 and Dieng Unit 2 (Layman et al., 2002). Based on the resources assessment performed in 1997, an updated probabilistic model indicated reserves in the 132 to 527 MW range, with a most likely potential of 260 MW for a project life of 30 years (GeothermEx, 1998).

Dieng Unit 1, with an installed capacity of 60 MW, was completed in July 1998 but was not brought into commercial operation due to the issuance of Presidential Decree No. 5/98 which suspended the Dieng project as well as several others. The construction of Dieng Unit 2 was also suspended in 1998. In 2002, re-commissioning of Dieng Unit 1 was performed under Geo Dipa Energi and on September 2002 the Dieng Unit 1 started to operate commercially. Until now, Dieng Unit 1 is fed by 9 HCE wells located in the Sileri sector; for injection purposes it utilizes 1 HCE well in Sileri and 4 Pertamina wells in Sileri and Sikidang sectors.

After 12 years of operation and having the target to fulfil the commitment with PLN to deliver another 110 MW, Geo Dipa Energi planned in 2013 to develop Dieng Unit 2 and Dieng Unit 3, both with an installed capacity of 55 MW, within the next 5 years. According to the development plan, these 2 additional units will be operated in 2017 and 2018. To support these 2 units, additional steam is of course required since 2017 and 2018. The updating of the previous conceptual model of Dieng geothermal field (West JEC, 2006) and the numerical reservoir modeling were performed with the aim to assess the Dieng reservoir capacity to support the 3 units and to analyze and forecast the reservoir behavior during 30 years of additional field exploitation (PWC et al., 2013).

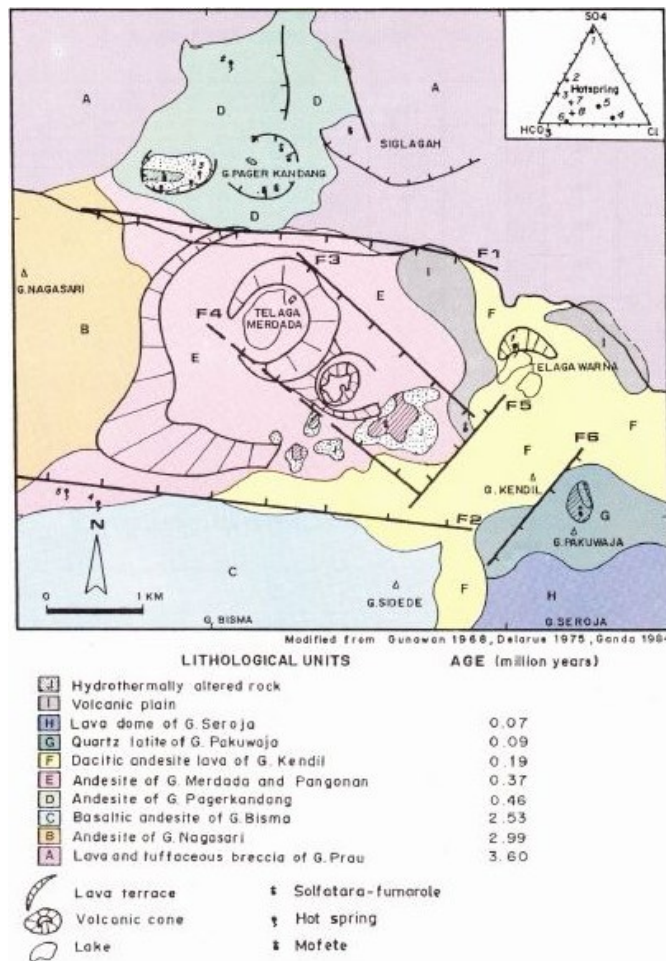


Figure 1: Geological map of Dieng concession area, Central Java (Boedihardi et al., 1991).

2. RESERVOIR GEOMETRY

The conceptual model of a geothermal field is the synthesis of all the information obtained by the analysis and interpretation of the available data from the surface studies and from the drilling of exploration and development wells. The previous model was built from the initial data measurement (MT/TDEM, geology and geochemistry surveys), the geoscience interpretation, the exploration wells and drilling campaign performed before 1997 by HCE. The Dieng conceptual model was updated based on the results of 12 years operation monitoring and studies, including down-hole pressure and temperature surveys, production and injection history data, geochemistry and scaling analysis and studies, work-over histories, and production optimization studies. The updated conceptual model gives information on Dieng reservoir features, including heat source, reservoir boundaries, thermodynamic conditions, up-flow and lateral out-flow with specific reference to the Sileri sector.

2.1 Heat Source

The heat source of the Dieng geothermal system can be referred to the magmatic body/bodies responsible for the recent volcanic activity of the Dieng plateau. All features associated with the assessment of potential heat sources result to be favourable: 1) Age: the volcanic products in the central and SE sector of the concession area have been dated at less than 0.5 Ma, witnessing the very recent age and sub-active nature of the magmatic chamber which originated these products. 2) Persistency: volcanism has been active in the Dieng plateau since the middle Pleistocene. 3) Volume: The large volume of erupted volcanics within the concession area is an indirect indication of the volume of the magmatic chamber/s. 4) Depth: Due to the rather pronounced differentiation of the volcanic products, it is possible to hypothesize a relatively shallow heat source, probably located at a depth between 5 and 10 km.

2.2 Reservoir Boundaries

The top of the geothermal reservoir can be inferred on the basis of the secondary mineralogy, and in particular the elevation of the top of the propylitic zone, the MT data, the first occurrence of total circulation losses and the static temperature profiles where indicating the start of convective circulation section. From the MT survey, drilling and PT survey, it was inferred that the top of reservoir can be set at an elevation of 400 m asl in the NW area of Sileri sector, rising to about 700 m asl in the SE Sileri sector.

No direct elements are available for the definition of the bottom of the reservoir, inasmuch as nowhere the relative basement of the volcanic sequence, consisting of clastic products with intercalations of limestone, has been intersected by the wells and important circulation losses have been recorded up to the bottom of some wells. At the same time, the MT survey cannot identify deep resistivity changes which may be correlated with variations of the thermal and hydrogeological conditions. Under this situation, it is deemed surely realistic and even conservative to assume that the reservoir extends just below the largest depth intersected by well HCE-32 which is down to an elevation of -1,000 m asl. Under this hypothesis the reservoir would have a thickness ranging between 1,400 and 1,700 m, in line with the values normally observed in other geothermal fields.

The definition of the areal extent of the reservoir is mostly based on the structural setting, on the geophysical data (in particular MT) and on the results of the deep wells, which may define reservoir boundaries as expressed by the chemical composition, temperature and production characteristics. In the case of Sileri sector, three major elements have been identified, which can assist in the definition of the extent of the geothermal resources (Figure 2):

- a. **Calderic structure.** Several geological elements concur in pointing out the existence of a calderic structure, presumably developed in correspondence of Late Pliocene strato-volcanoes. The rims of the caldera are presently visible only along its NE side, wherefore the true extent of this structure is largely hypothetical. Based on the age of the outcropping formations, on some morphological evidences and on the results of the MT survey, it is inferred that the caldera has a diameter of 6-7 km and its rim passes in correspondence of G. Prau, G. Nagasari and G. Bisma. As found in many geothermal systems, the calderic rim is deemed to represent a boundary of the reservoir, due to the expected decrease of widespread fracturing and hence of permeability outside of the sector affected by down-throwing. This assumption is supported by the MT data, which in correspondence of the SW show an abrupt variation of the conductive unit, which takes a sub-vertical configuration. Based on the above assumptions, the northern and western limits of the Sileri reservoir have been set in correspondence of the calderic rim.
- b. **NNE-SSW structure.** The NNE-SSW structure passing through G. Pangonan has been identified on the base of the configuration of the andesite complex/microdiorite and of the sharp lateral discontinuity recognized in the MT survey. This structure, which brought about the down-throw of the NW block, is deemed to constitute a sharp hydrogeological barrier (possibly due to phenomena of self-sealing which determined its imperviousness), which separates from the hydraulic point of view the Sileri and Sikidang geothermal systems. The numerical simulation considered such structure as the SE boundary of the Sileri reservoir.
- c. **MT data.** MT data present the important structure identified as a calderic rim and show that the conductive unit extends up to this structure. Wherefore the reservoir has been assumed to extend up to the caldera rim. The same profiles also show in the NE extremity a disappearance of the conductive unit and this has been taken as the NE limit of the reservoir. In the NW the conductive unit is poorly developed, suggesting the progressive disappearance towards the north of the cap-rock unit. The sector where no conductive unit has been encountered may indicate the eastern limit of the Sileri and Sikidang reservoir. Favourable electro-stratigraphic conditions appear to be present again in the SE corner of the concession area around G. Sikunir.

The 3D numerical model of the Dieng Field covers an area of 110 km², which includes the 3 sectors of Sileri, Sikidang and Pakuwaja (Figure 3, left), and extends for ground elevation (maximum at 2100 m asl) down to -2500 m asl. The main structural elements included in the numerical model are shown in Figure 3 (right).

2.3 Thermodynamic conditions

P-T logging under shut-in conditions clearly shows that the Sileri geothermal reservoir is high temperature liquid-dominated, with about 330°C at -800 m asl. In well HCE-7C, a liquid column was detected in the open hole section (below 400 m asl), which extends up to about 1,300 m asl. Above that elevation a gas column is present up to the surface, giving a WHP of 47 bar a. The P-T plot of HCE-7C log data suggests that a partial pressure of NCG in the order of 10 bar is present at the Gas/Liquid level, where the temperature is about 262°C. While the pressure gradient within the cased well section is that of a liquid column, the P-T data suggest that the fluid column is close to boiling conditions with an NCG partial pressure in the order of 10 bar above approximately 600 m asl. From the P&T conditions and the estimated elevation of the reservoir top, the entire reservoir section may be under single-liquid conditions, or at boiling conditions with a liquid-dominated pressure gradient. These liquid-dominated conditions were found to switch to two-phase around producing wells.

As far as Sikidang reservoir is concerned, the NCG content is much higher than in Sileri, while the TDS content is lower. The simulation of a hypothetical isoenthalpic flow of Sikidang fluid has been performed starting from a temperature of 320°C, pressure of 180 bara, NaCl content of 6,000 ppm, and NCG contents of 1 %, 3 %, and 5 % by mass. The simulation shows that a NCG content of 5 % is already enough to have two-phase conditions at the starting pressure of 180 bara, which can be expected in Sikidang at elevations in the order of -800 m asl, or lower. As liquid-dominated conditions were found in wells like DNG-17 and HCE-17A, it is likely that the content of dissolved NCG in the uprising brine in Sikidang is lower than 5 % by weight, and that the higher contents found in several Sikidang wells are due to extraction from an overlying two-phase steam dominated section at the top of the reservoir (Boedihardi et al., 1991), where NCG accumulated because of brine boiling at the top of the liquid dominated section.

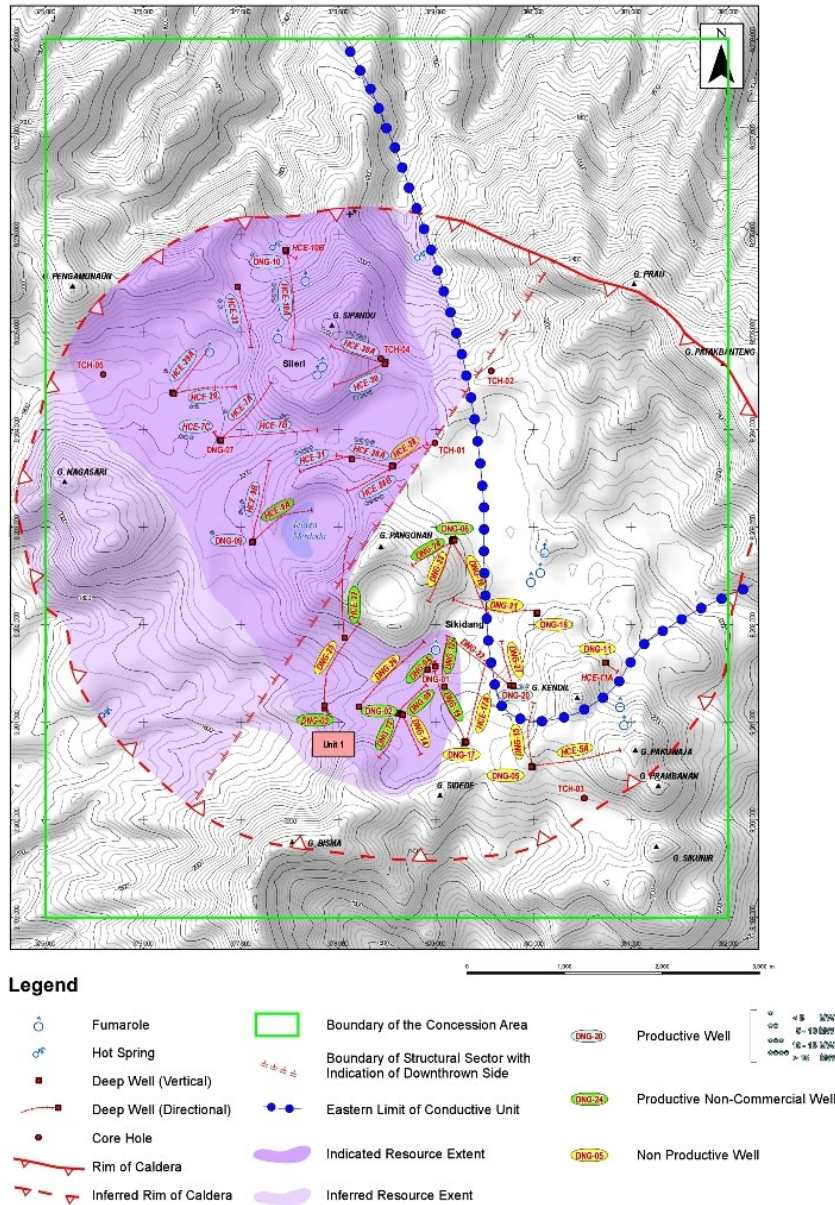


Figure 2: Geometry of Sileri (NW) and Sikidang (SE) Reservoir sectors.

2.4 Upflow and Lateral Flow

According to the conceptual model findings, two main upflows of geothermal brine at constant rate and temperature were assigned in the numerical model beneath the Sikidang crater and the Sileri crater, the latter along the approximately N-S structure separating blocks with different elevation of the andesite complex. The up-flow zones are represented in Figure 4 (left) by the red (Sileri) and purple (Sikidang) grid elements. Assigned up-flow enthalpy in Sileri corresponds to a temperature of 340°C, with brine containing 23,000 ppm of NaCl and 3,000 ppm of CO₂. Total rate amounts to 100 kg/s, for a convective thermal power of about 150 MW. Assigned up-flow enthalpy in Sikidang corresponds to a temperature of 330°C, with brine containing 1,000 ppm of NaCl and 35,000 ppm of CO₂. Total rate amounts to 50 kg/s, for a convective thermal power of about 73 MW. Finally, a third upflow is set beneath pad 6 to simulate a high NCG fluid recharge. It has an enthalpy corresponding to a temperature of 330°C with brine containing 5,000 ppm of NaCl and 50,000 ppm of CO₂. Total rate amounts to 10 kg/s, for a convective thermal power of about 14 MW.

The lateral outflows were located in the numerical model as inferred in the conceptual model. Two lateral outflows were included for the Sileri sector, directed to NW of pad 10, and to the E in the Pulosari area, where hot springs are located. The lateral outflow of Sikidang, which was not clearly located in the conceptual model, is assumed to take place to the SE. The lateral outflows have been located in the upper section of the reservoir, between elevations of 500 and 100 masl. Their location is shown in Figure 4 (right), which also reports the inferred NE-SW structure separating the Sileri and Sikidang sectors. The Pakuwaja hydrothermal area is highlighted in purple to the SE of Sikidang.

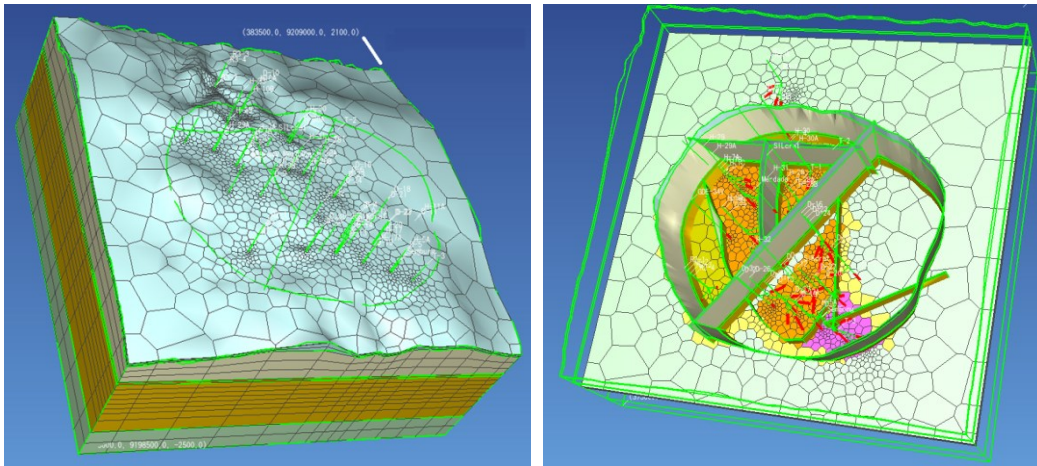


Figure 3: 3D view of numerical model (left) and the main structural features included in the numerical model (right).

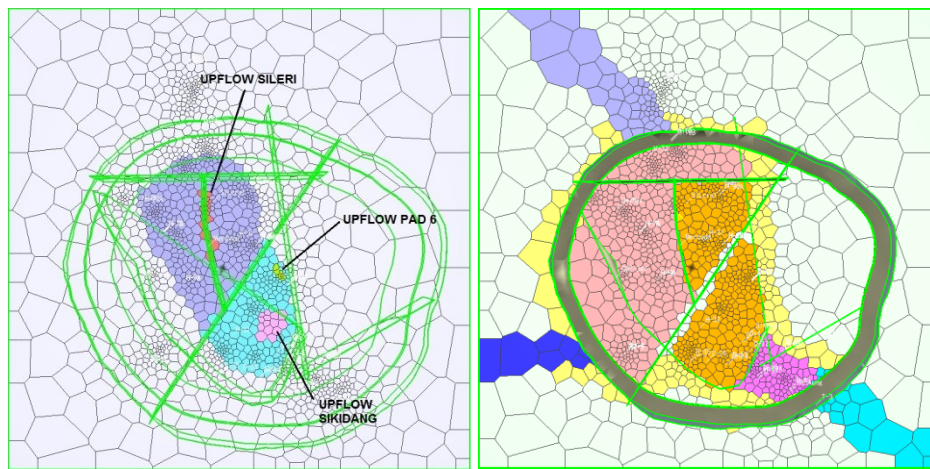


Figure 4: The inferred upflows beneath the Sileri crater, the Sikidang crater and well pad 6 (top view of bottom model layer @ -2490 m asl, right). View of model grid @ + 500 m asl with the inferred lateral outflows at Sileri and Sikidang-Pakuwaja (left).

3. RESERVOIR MODELING

The purpose of the numerical model was to assess the capability of the reservoir to support Dieng Unit 1 and also the planned Dieng Unit 2&3. With the consideration that most of the Sikidang wells are either low producers with a high NCG content or non-productive, then the development for Unit 2&3 is foreseen within the Sileri sector.

The numerical model was developed based on the reservoir geometry described above and was used to simulate initial natural conditions close to steady-state. The simulated natural state conditions for the Sileri sector are represented as vertical P-T profiles computed on West Sileri (below well pads 7, 9, and 29) and on East and North Sileri (below well pads 28, 30, and 33) in Figure 5 and 6, respectively, were they are compared with P-T logs recorded under static conditions in 1996-1998.

The simulation for past 12 years production was difficult because of the complexity of historical production and injection data. Scaling in production wells, reinjection wells, and two phase lines, affecting also measurement activities, was the main problem during the exploitation determining work-over operations, coming on-line of new wells and switching brine reinjection among different wells in both Sikidang and Sileri sectors. The simulation of this initial period was conducted considering the measured cumulative steam rate at average separation pressure, average production enthalpy, and average dryness fraction at the separators, and computed cumulative reinjection rate. The simulated cumulative steam rate increases from an initial 114.6 kg/s to a final 122.1 kg/s as a result of an increment of average enthalpy from an initial 1425 kJ/kg value to a final 1466 kJ/kg value. As a consequence of enthalpy increment also the average dryness fraction at the separators increases from 0.315 to 0.336, while the available brine injection rate slightly decreases from 249.3 kg/s to 241.3 kg/s.

Forecast simulation was conducted for Dieng Unit 1 and Unit 2&3, for 30 years since the beginning of January 2018 to the end of December 2047. For this simulation it is assumed that a final new gathering system is in place and that reinjection of Unit 2 takes place to a new reinjection pad planned in the SW Sileri, while that of Unit 3 takes place to a new reinjection pad planned in the NW Sileri. The reinjection for Unit 1 is assumed to continue in the former injection wells located in the Sikidang sector. In this simulation, all the production wells are simulated using the well on deliverability option available in TOUGH2, at constant flowing bottom hole pressure

evaluated for each well in order to supply the initial estimated rate at the fixed separation pressure. The production rate decline is not compensated by the increment of average discharge enthalpy and then the cumulative steam rate at the separators declines with time. The cumulative steam rate was monitored during the simulation to determine when it was declining below the 95% of target rates for Unit 1 (114 kg/s @ 12 bar a separation pressure) and Unit 2&3 (180 kg/s @ 25 bar a separation pressure). As reinjection is assumed to take place in Sikidang and on the outer boundaries of Sileri sector, no major thermal breakthrough has been simulated within the Sileri reservoir. The reinjection to the NW and SW Sileri sector proved to be efficient in supporting the reservoir pressure in the areas feeding Unit 2 and 3, while a greater pressure decline is experienced in the SE Sileri area supporting the Unit 1 wells, as it is less affected by the reinjection support. The pressure decline is compensated by the increment of average discharge enthalpy of wells feeding Unit 1.

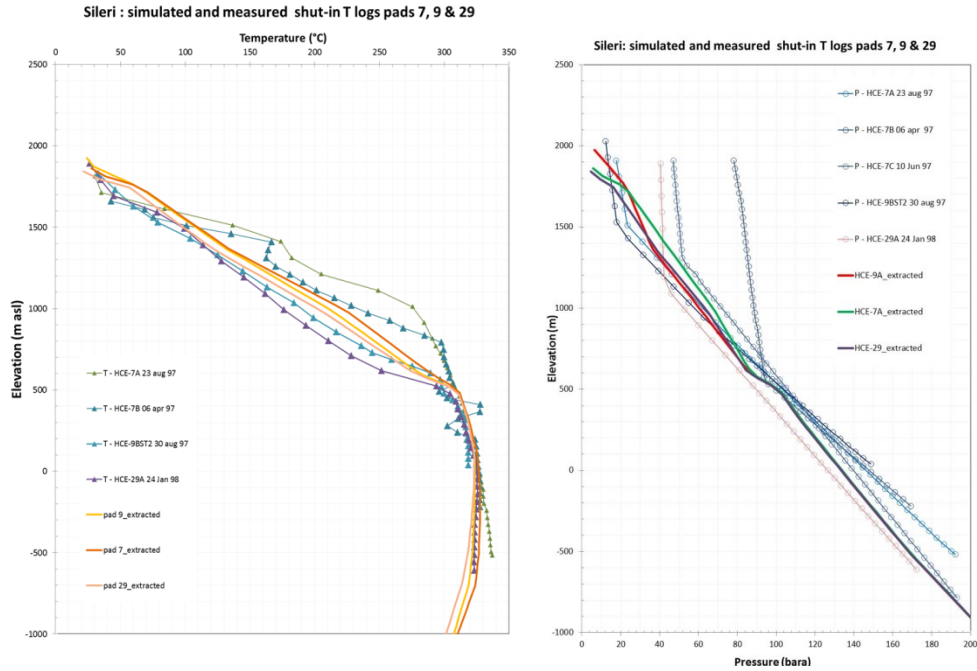


Figure 5: Simulated vertical T-P profiles below pads 7, 9 and 29 (Sileri sector) compared with selected T-P logs recorded on wells drilled from the same pads.

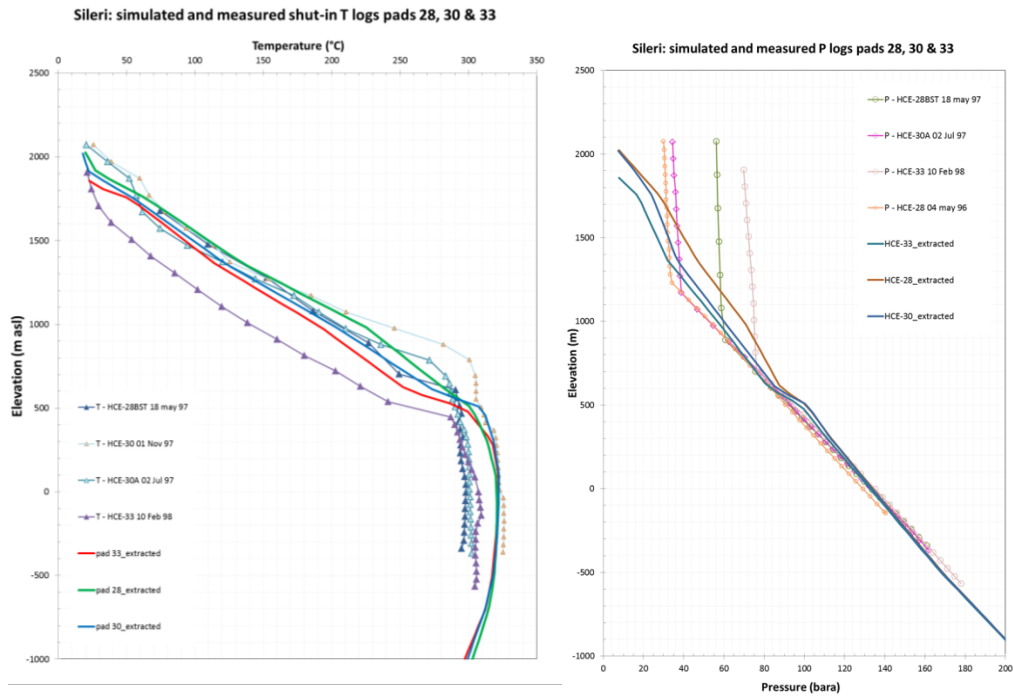


Figure 6: Simulated vertical T-P profiles below pads 28, 30 and 33 (Sileri sector) compared with selected T-P logs recorded on wells drilled from the same pads

4. CONCLUSIONS

The numerical simulation of Dieng geothermal field suggested that 4 make-up wells are needed to support Unit 1 till 2047, and 10 make-up wells are needed to support Unit 2&3. Additional make-up wells would have been necessary from mid-2046 for Unit 2&3, but it was decided to accept a small decline below the 95% of target steam rate. It must be noted that Unit 1 is estimated to still produce above 95% of target steam rate after about 43.7 years of continuous operation since the coming on-line planned in 2014.

In future simulation studies of Dieng field exploitation, additional efforts should be performed to reproduce in a more accurate way the reinjection rate evolution as function of time. In fact, reinjection in areas hydraulically connected to the production sectors has already been proven to be effective in supporting the reservoir pressure during exploitation of liquid-dominated reservoirs.

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