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Responses of Wayang Windu Geothermal Reservoir to Over 20 Years of Production

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ABSTRACT

Wayang Windu is one of the largest geothermal fields in Indonesia that has been operating for more than 20 years and has evolved since the early development in 1996 to date. The field is transitional between a vapor-dominated and liquid-dominated reservoir, where the steam cap is more developed toward the north of the field. Commercial operations commenced in 2000 for Unit-I (110 MW) and in 2009 for Unit-II (117 MW).

During the 20 years of operation, the production is mainly located in the northern and central part of the field while the injection takes place in the lower topography toward the south. In the early production, the steam cap and deep brine reservoir were produced proportionally in an area of 10 km^2. After three years of initial production, however, the declining performance of the brine wells in the northern area has led the field to be developed with 90% of the total production from the northern steam cap. After 20 years of production, the field-wide pressure has been dropping low to moderately at 18 and 10 bar in both the northern steam cap and liquid reservoir, respectively. In the meantime, the liquid pressure was relatively stable in the central, mainly due to limited production from the area. As of today, the pressure of the northern steam cap is dropping at a rate of around 0.8 bar/year with steam production equivalent to 200+ MW generation. On the other hand, the rate of the pressure drop was roughly at 0.5 bar/year in the deep brine reservoir. Up to date, the injection in the southern area has been reliable and providing adequate pressure support with no adverse impact to production wells.

Along the 20-year journey, the Wayang Windu Geothermal Field has been facing some challenges like other geothermal fields of similar age around the world. Silica scaling that is always being one of the field's challenges has successfully been mitigated by the current approach which is mechanical clean outs; however, other effective and efficient method such as downhole scale inhibitor is currently being evaluated to increase the success rate even more. In addition, having a sustainable production from the deep brine reservoir is preferable for the Wayang Windu Geothermal Field to have. Efforts to better characterize the permeability, especially in the deep brine reservoir, is currently underway to enhance the deep production. The increased deep production is to sustain the long-term steam cap performance with the objective of not only prolonging the production plateau at the current generation level, but also providing an expansion opportunity for the field to maximize its value.

1. INTRODUCTION

The Wayang Windu geothermal field operated by Star Energy Geothermal (Wayang Windu) Ltd., is located in the West Java Province, Indonesia which is around 150 km southeast of the Indonesian capital of Jakarta or 40 km south of Bandung. The field is a high-terrain geothermal system associated with a series of quaternary volcanoes such as Mt. Malabar, Mt. Gambung, Mt. Bedil, Mt. Wayang, and Mt. Windu, and is surrounded by high-temperature geothermal fields, including one other Star Energy Geothermal field of Darajat (Figure 1).

Figure 1: The location of the Wayang Windu geothermal field along with other high-temperature geothermal fields nearby.

The earliest 3G surveys and few exploratory drilling were executed by Pertamina (now PT Pertamina Geothermal Energy, or "PGE"). The first 3G survey was conducted in 1982 which consists of DC-resistivity surveys, heads-on resistivity profiling, MT (magnetotelluric) and SP (self-potential) surveys, as well as gravity and temperature-gradient studies measured in six 170 m slim holes, resulted in confirming a potential resource of approximately 220 MWe (Hochstein & Sudarman, 2008). Subsequently, more MT-Resistivity surveys were conducted in the next decade in the area around Mt. Malabar, where low resistivity anomaly extended further beneath Mt. Malabar was encountered, doubling the resource potential to 440 MWe (Hochstein & Sudarman, 2008). In 1991, Pertamina drilled the first deep exploratory well in the central, WWD-1 (now called WWA-1), followed by a shallower well around

5 km north of WWD-1, MSH-1, in 1993 (Hochstein & Sudarman, 2008). The drilling at WWD-1 confirmed that the reservoir is a transitional liquid-vapor dominated geothermal system with a vapor-dominated layer of around 350 m thick overlying the liquid-dominated reservoir (Hochstein & Sudarman, 2008).

In 1994, Magma Nusantara Ltd. (MNL) signed an Energy Sales Contract (ESC) and Joint Operation Contract (JOC) to supply up to 400 MWe for 30 years. Under MNL, fast track development with a combination of 1500-m deep slim holes and deeper production well drilling was implemented (Bogie et al., 2008). A total of 26 production and injection wells with a maximum depth of around 2500 m were drilled until 1998 to provide the steam supply for Unit-1, 1x110 MW generation, commercially operated starting in June 2000. Later in 2001, UNOCAL became the 50% shareholder of the Wayang Windu project followed by Star Energy's 100% acquisition in 2004. Thereafter, additional Unit-2 came online in 2009 with a gross capacity of 1x117 MWe, making the total installed capacity in the field to be 227 MW. Since then, the two units combined have been operating steadily with a capacity factor of approximately 97%, except during the 2015 landslides forcing the two units to cease operations for around four months.

After 20 years of production, a total of 60 wells have been drilled since the exploration stage. Figure 2 depicts all the Wayang Windu wells that have been drilled throughout the field. The figure also shows the three development areas in the field (e.g.: north, central, and southern areas), including the potential resource boundary defined mainly by magnetotelluric (MT) survey data. The depth of the wells drilled within the reservoir varies from 1120 to 2510 m which provides an opportunity to monitor the reservoir behavior, changes in thermodynamic conditions during exploitation, and to identify impact of recharge (e.g.: injection, marginal recharge) to the production wells. Currently, the steam requirements for the two units are being supplied by 30 production wells, located mainly in the north and central parts of the field, while brine and condensate are currently being disposed of separately through two injection wells in the south.

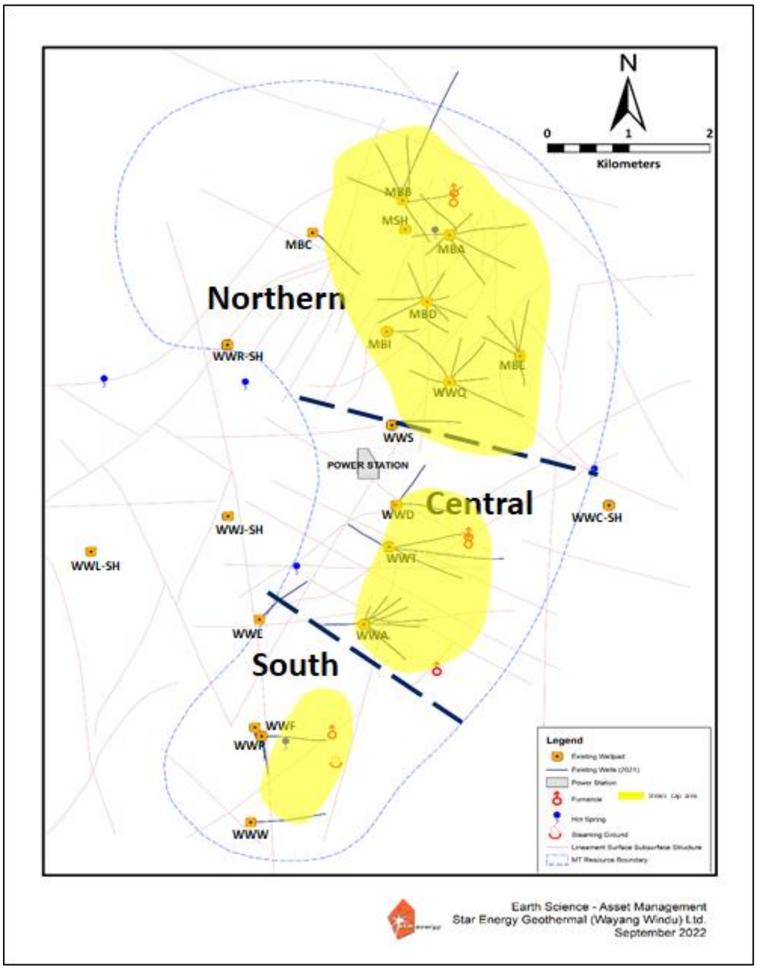


Figure 2: Locations of wells drilled in Wayang Windu along with the three main development areas. The production wells are all located in the northern and central areas, while all injection wells are located in the south.

2. RESERVOIR CONDITION PRE-EXPLOITATION

The Wayang Windu geothermal system is a high temperature transitional reservoir between vapor and liquid dominated with a benign chemistry and low-to-moderate NCG. The reservoir has a conductive layer associated with relatively impermeable argillic caprock, overlying the isothermal section down to around 1200 mASL in the north dipping to 500 mASL in the south. During the pre-exploitation stage, the main steam cap area in the north is estimated to have a pressure of 40-45 bar (equivalent to a temperature of 250-260°C), while average temperature of the brine reservoir was around 280-290°C. The brine reservoir pressure varied from the north toward the south (Figure 3). Moreover, the steam cap thickness varied from around 800 m in the north (located at elevation from 1200 to 400 mASL) and got thinner towards the central and the southern areas at around 400 to 250 m. As a result, the thicker and wider isothermal area in the north making it much more favorable to produce.

In addition, the initial pressure gradient at pre-exploitation stage shown in Figure 3 also indicates the steam-brine contact in the reservoir, where initially the steam-brine contact was at around 400 mASL in the north and deeper to around 100 mASL in the central the south. This steam-brine contact was then followed by the boiling zone underneath with an average thickness of ~300 m before it reaches the compressed liquid/brine reservoir. According to Figure 3, the brine pressure seemingly connected from the north toward the south without having any compartment, while the temperature extents to more than 300 °C where it comes within the upflow regions. Figure 4 shows the Wayang Windu conceptual model along with the three major upflows spreading along the field, associated with Mt. Gambung (north), Mt. Wayang (central), and Mt. Windu (south).

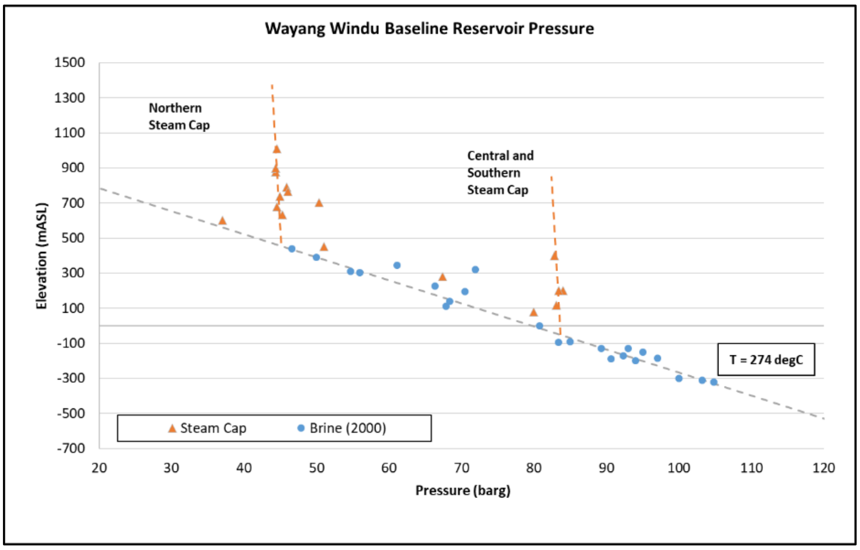


Figure 3: Pre-exploitation steam cap and liquid pressures at Wayang Windu.

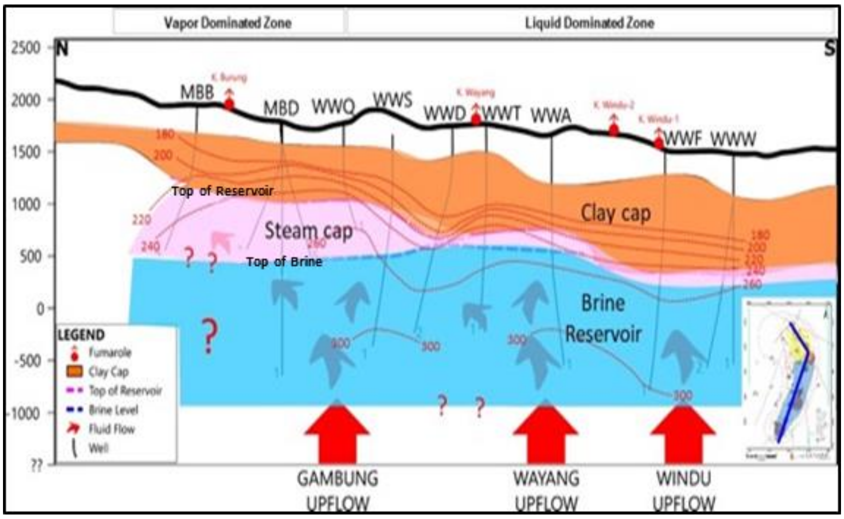


Figure 4: The conceptual model of Wayang Windu.

3. FIELD PERFORMANCE

3.1 Production History

At the beginning of the exploitation, the steam that was produced to generate the electricity were obtained nearly in equal proportion between steam cap and two-phase wells. However, since the development of Unit-2 in 2009 the exploitation of the field was focused on the northern steam cap area due to its productivity and sustainability. This development option was also due to challenges faced in completing wells deep in the brine reservoir and in having a sustainable production from the two-phase wells. Currently, about 95% of the total steam production in the Wayang Windu field is from the northern area, while the remaining 5% is from the central area. Out of the 95% of steam from the north, 95% is from the steam cap wells with the remaining 5% is from the two-phase wells. Figure 5 shows the mass production at Wayang Windu to date. Presently, steam production is still predominantly coming from the steam cap wells followed by the two-phase wells with a proportion of 85 to 15%, respectively.

3.2 Steam cap reservoir performance

Over the last 20 years of production, the Wayang Windu geothermal field has been performing well. The natural decline of fieldwide steam production has been steady at an average rate of around 5%/year. Throughout 2010-2020, the average total mass production from the Wayang Windu field was 461 kg/s with the steam and brine production were at 419 kg/s and 42 kg/s, respectively.

Wellbore scaling, particularly silica, has been an issue at the Wayang Windu field but its significant impact to the fieldwide steam production performance is only limited to five steam cap wells. Nevertheless, this issue has been successfully managed by conducting biannual workovers using mechanical cleanouts, combined with a more frequent well broaching every six months. The scaling has caused these five wells to experience a steam production decline in the range of 12-23%/year; however, the workovers so far are able to restore the well productivity and bring back the steam decline at the natural rate of 5%/year.

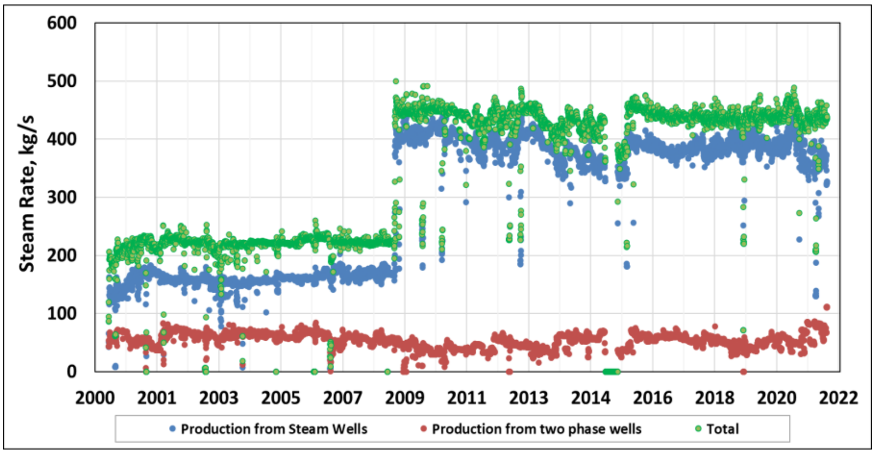


Figure 5: Steam production profile from steam and two-phase wells at Wayang Windu.

The wells producing from the steam cap are mostly from MBA, MBB, MBD, MBE, MBI, and WWQ pads in the north with an estimated production area of 10 km^2. Figure 6 shows the extent of the northern steam cap along with cumulative mass extractions and pressure decline rates in the past five years. On average, the northern steam cap pressure is declining at a rate of around 0.5 bar/year in the past five years, which is very moderate. In the meantime, Figure 7 shows the evolution of the steam cap pressure observed in wells from MBA and MBD pads, contributing about 60% of the fieldwide steam production at Wayang Windu. The higher steam cap pressure declines in 2000-2002 and 2009-2014 were associated with the transient following the start-up of Unit-1 and Unit-2, respectively. Post the transient periods, the steam cap pressure was averaging at around 0.5 bar/year. The moderate pressure decline in the steam cap reservoir around MBA and MBD pads shows that the underlying performance of the northern steam cap at Wayang Windu is strong and the recharge to the steam cap appears to be robust, despite the on-going 85% steam extraction to date.

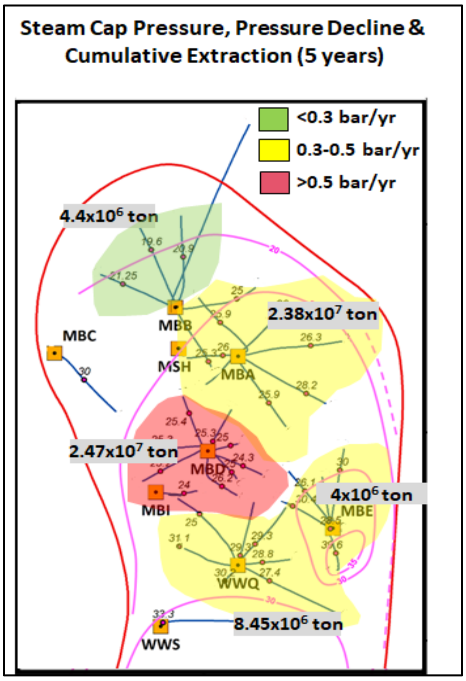


Figure 6: The northern steam cap pressure regimes of MBA, MBB, MBD, MBE, and WWQ pads alongside with the last five years of the cumulative mass extraction.

Downhole superheat is observed in the northern steam cap of Wayang Windu as shown in Figure 8. The superheat is determined by calculating the difference between the measured and saturation temperature of the flowing pressure, and it is ranging from as low as <5°C to anywhere between 5-10°C. Higher superheats of 5-10°C are mostly observed in the MBB area, suspected due to its proximity to the boundary with limited recharge. In the meantime, the lower superheats are mostly observed in the eastern area, covering wells in MBA, MBD, and MBE pads.

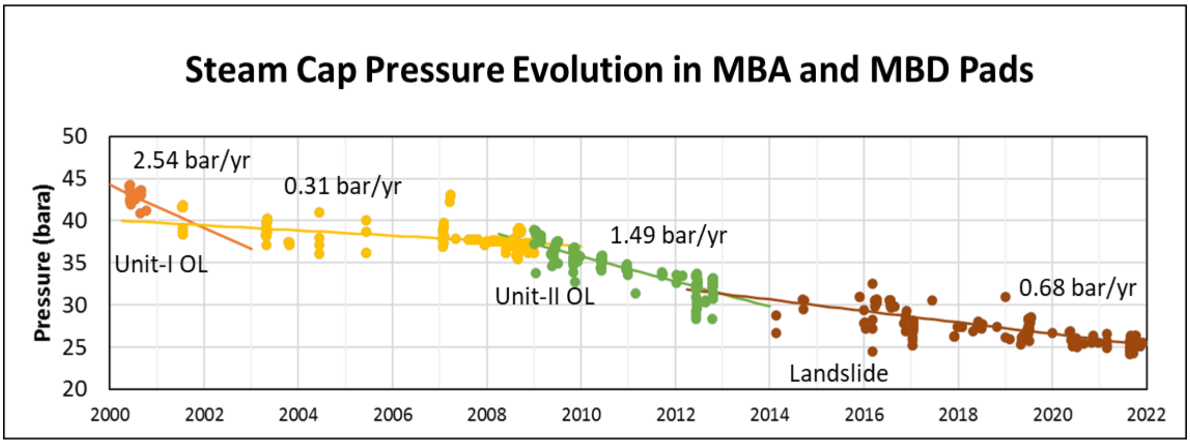


Figure 7: Pressure decline observed in steam wells at MBA and MBD wellpads.

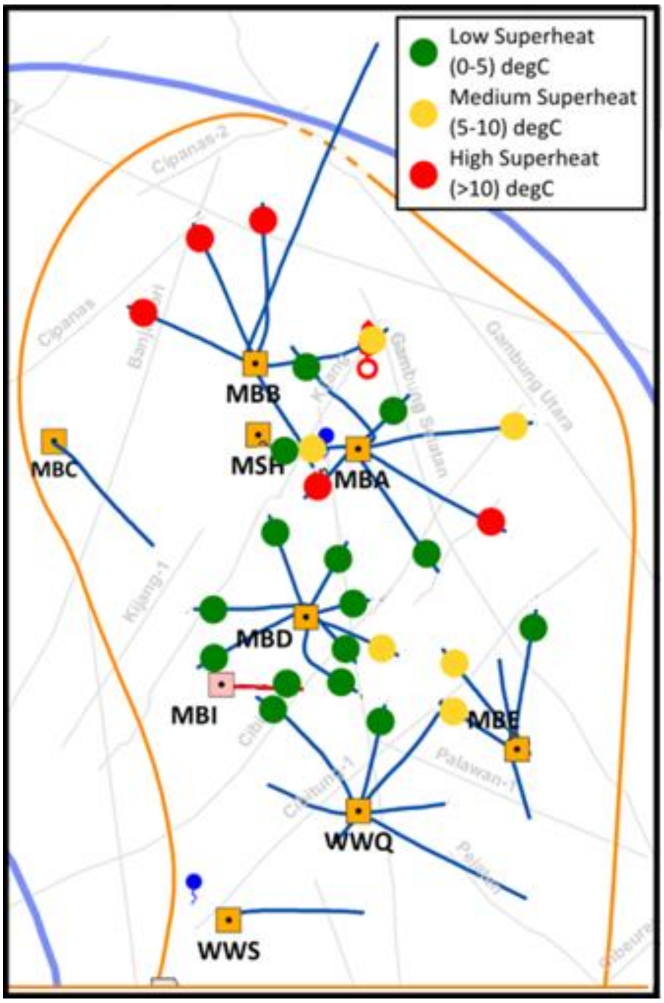


Figure 8: Map of downhole superheat at Wayang Windu.

NCG in the northern steam cap is in the range of 0.2 to 1.4 wt% while the average fieldwide NCG is 0.2 to 2.5 wt%. The highest NCG is in MBB wells at up to 1.4 wt% and the lowest NCG is in MBD wells drilled to the east. In the long run, NCG in the northern steam cap is expected to not undergo a significant change given extensive boiling has already occurred following the start-up of Units-1&2. The high NCG in MBB pad is associated with steam condensation in the steam cap, as indicated by the high CO_2/H_2S ratio. The CO_2/H_2S ratio is observed to be lower in production wells drilled in the southern part of the field. The recharge mechanism to the steam cap is mainly from the matrix of the reservoir rock; however, Cl-Si-B data collected in steam wells in MBA and MBD pads indicates that part of the steam cap is also getting support from the deep liquid reservoir, albeit minor. The Cl-Si-B data from production wells in those pads is higher, compared to that from the steam cap wells further to the north.

3.3 Liquid reservoir performance

The deeper two-phase wells able to produce brine are scattered across the field, from the north toward the south almost in every pad, except in MBA and MBB pads. Up to date, no wells in MBA and MBB pads were drilled deep enough to reach the brine reservoir due to uncertainties in getting good permeability. Downhole pressure-temperature-spinner (PTS) surveys and geochemistry surveys have been conducted regularly in order to monitor changes in fluid characteristics and reservoir behaviors.

In the early production period, the deep brine reservoir in the north, especially in wells in WWQ and MBE pads, showed a large pressure drop of as high as 25 bar in the first 3 years of exploitation where it peaked in 2003 as shown in Figure 9. In 2003-2010, large amount of brine production from the area decreased and the liquid pressure was observed to recover. Currently, the pressure in the area has been steady where only 0.5 bar/year of pressure drop is observed. The initial liquid pressure dropped during the first three years was due to a combination of high brine extraction and localized low transmissivity in the area. The deep pressure in the central area (i.e.: WWA pad) appears to be relatively stable since the beginning of the exploitation, likely due to low brine production and good recharge.

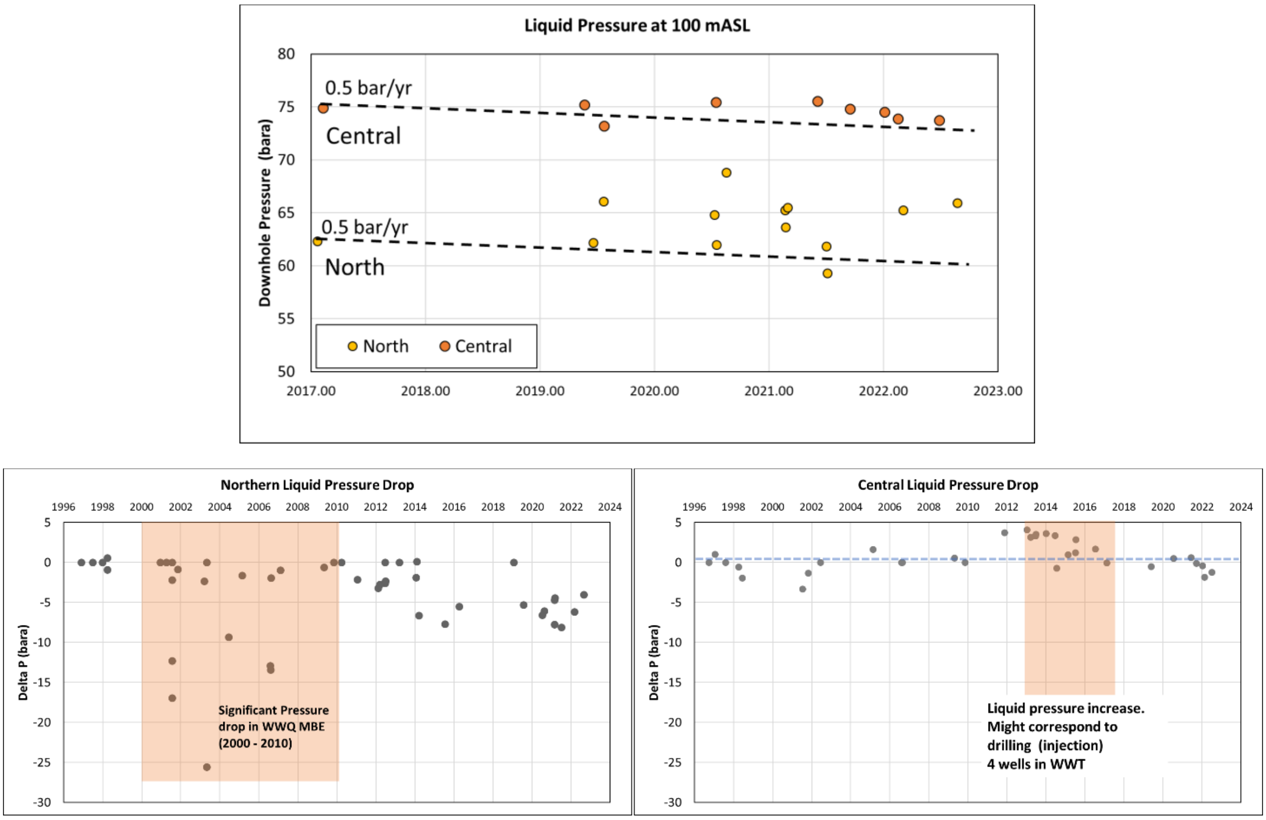


Figure 9: Downhole liquid pressure evolution in the northern and central areas (top). Evolution of total liquid pressure drop observed in the two-phase wells in the northern and central areas (bottom).

From the temperature point of view, no indications of thermal breakthrough to production wells, either from injection or from marginal recharge, are observed. This has been confirmed also from a regular fluid chemistry and discharge enthalpy monitoring. Despite the fact that there is a connection between injection wells in the south and production wells in the central based on a reservoir tracer test, the temperature of the compressed liquid section of the reservoir in the central wells are relatively steady. More of this will be discussed in the next section. Some temperature drops have been observed in several production wells, but all of them are related to pressure declines in the liquid reservoir due to boiling.

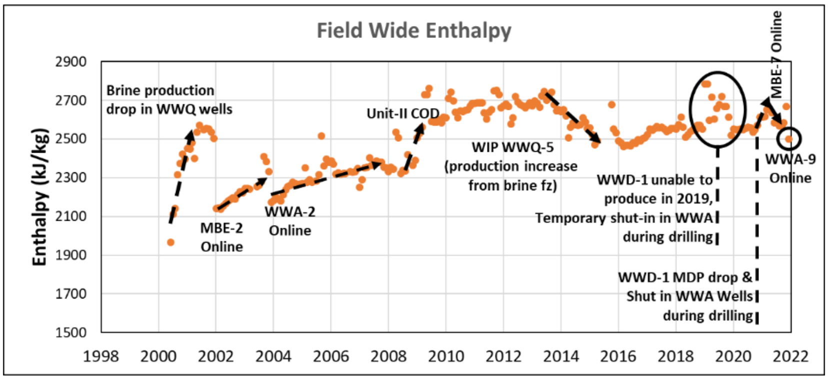
3.4 Enthalpy response

The declining brine production from the two-phase wells in the north has a significant impact to the fieldwide enthalpy as shown in Figure 10. In that figure, the fieldwide enthalpy increased rapidly in 2000-2002 due to declining production of two-phase wells in WWQ pad in the north. A similar condition occurred also in 2002-2004 and in 2004-2008 where production from two-phase wells of MBE-2 and WWA-2, respectively, were declining. In 2009, the fieldwide enthalpy showed a rapid increase after the start-up of Unit-2 with more steam wells started to produce. Following a workover on WWQ-5 in 2013, allowing more brine to produce from the reservoir, the fieldwide enthalpy was observed to drop slightly. In 2021, the enthalpy dropped slightly with the introduction of two more two-phase wells, MBE-7 and WWA-9, successfully drilled in the same year.

In summary, the fieldwide enthalpy at Wayang Windu has been performing well with no issue such as cooling in the reservoir. The dynamic condition of the fieldwide enthalpy has been mainly due to the source of mass production (e.g.: steam wells vs. two-phase wells). A good proxy of this can be seen in WWQ-5 as illustrated in the lower plot of Figure 10. WWQ-5 is one of the two-phase wells at Wayang Windu, having both steam and brine feedzones. WWQ-5 experienced enthalpy increase when the contribution from the brine feedzones was reduced due to scaling; and on the contrary, the enthalpy dropped when the brine feedzones started to produce again following a workover/WIP (Well Intervention Program) to clean-out the scale.

4. INJECTION STRATEGY

The main injectors at Wayang Windu are in WWF and WWW pads located in the southern part of the field. When needed, WWS-1 in the central part of the field is also used as a back-up injector. The Windu reservoir was chosen as an injection location due to several reasons, such as: low topography allowing gravity feed, high NCG system making it not suitable as a production area, and relative distance to the production area minimizing risk of rapid injection returns. Currently, no indication of thermal breakthrough to the production wells is observed. Over the 20 years of exploitation, the same injectors have been used to dispose of the separated brine and condensate, with only minor changes occurred during the period when the brine and condensate injectors were shifted. Initially, WWF pad was used for the condensate injection while WWW pad was used for the brine injection. Following tracer tests in 2008 and 2013 where the injected tracer was detected 18 days after the tracer injection in the nearest production well, WWA-2, it was decided to shift the condensate injection into the southernmost WWW pad and the hotter brine injection into WWF pad, which is relatively closer to the production area to minimize any risks of thermal breakthrough. To date, the performance of the injection wells at Wayang Windu has been sustainable and the plant has never experienced shortage in injection capacity. The injection wells do not experience scaling issue and do not pose thermal breakthrough risk to production wells.



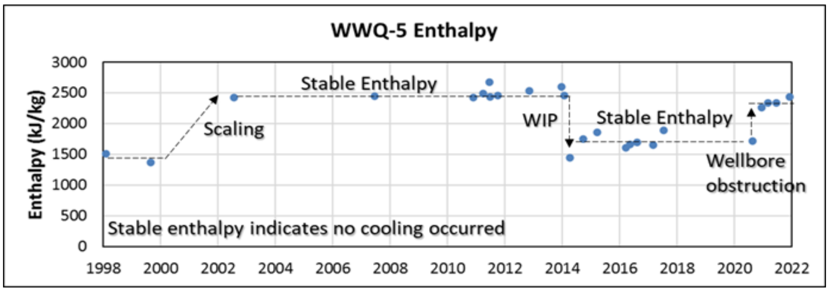


Figure 10: The Wayang Windu enthalpy profile of the field wide (top) and WWQ -5 (bottom) through years.

5. FUTURE OPPORTUNITIES AND INITIATIVES

Future opportunities for Wayang Windu include maximizing the value of the field by increasing the generation through retrofitting the existing plants and/or adding new power plants while mitigating any adverse risks from additional production from the reservoir at the same time. After 20 years of Wayang Windu field production, major risks have been comprehended and mitigations have been put in place, allowing the field to perform steadily. In the meantime, comprehensive and efficient surveillance program has been put in place to capture early signs of any potential long-term risks, such as encroachment of cooler fluid from marginal recharge.

The reservoir characterization and reservoir response from 20 years of field production have been captured in the latest reservoir simulation model of Wayang Windu. The latest model forecast shows that Wayang Windu has sufficient resource to support 280 MW of generation for the next 30 years. However, there are some areas that need to manage further at Wayang Windu, such as: scaling management in production wells (particularly in steam wells), reservoir permeability characterization for better well targeting, and balancing the extraction between steam cap and brine reservoir. Improvements in these areas will help managing the steam supply decline, reducing the need for make-up well, and extending the life of the field.

Below are the initiatives related to the three areas discussed above that have been planned and progressing to optimize the performance and maximize the value of the Wayang Windu resource.

5.1 Scaling Removal

Calcite and silica scaling which occurs in both steam and two-phase wells are currently being managed with mechanical cleanouts. The mechanical cleanouts are conducted through a routine well intervention every two years, combined with a more frequent well intervention using a low-cost broaching (quarterly). Results to date show that the mechanical cleanouts have been successful in removing the scale and restoring the well performance to its natural decline. Application of downhole scale inhibition has also been tested successfully in a two-phase well to maintain the brine production sustainability. However, given silica scaling in steam wells is currently the main scaling issue at Wayang Windu, a study is currently underway to obtain a more efficient and cost effective way of preventing and/or removing silica scaling in steam wells. Another assessment currently proceeding at Wayang Windu is to obtain a more effective way of removing calcite/silica scale in the formation by using acid stimulation.

5.2 Fracture Permeability Characterization

Permeability distribution in the brine reservoir of Wayang Windu, especially in the northern area, is still not fully comprehended given only a few wells which have been drilled deep enough penetrating the steam-brine interface. Within the area where a few deep two-phase wells were drilled in the north, there is an indication of heterogeneity in the permeability distribution. The permeability heterogeneity carries some uncertainties and risks when it comes to well targeting. Efforts are currently underway to better characterize the permeability distribution in Wayang Windu, especially in the deep brine reservoir in the northern area, by incorporating feedzone information from the existing wells, fracture drivers, and other information. Results from this study, along with other information, will be used as the basis for well targeting at Wayang Windu in the future.

5.3 Optimizing Brine Production and Balancing Steam-Brine Extraction

Brine production at Wayang Windu will be optimized by maintaining the sustainability of the production of the existing two-phase wells and by drilling more two-phase wells in the future. The existing two-phase wells at Wayang Windu are currently able to produce at least 80 kg/s of brine where the brine production will be maintained through well intervention when necessary and by ensuring the reliability of the brine injection capacity. Hereafter, more two-phase wells will be drilled in the central area due to its good recharge and good transmissivity in the brine reservoir. Meanwhile, results from the fracture permeability study will be used to carefully target two-phase wells in the northern area in the future to increase the chance of success. A success in drilling deep two-phase wells in the north not only will increase the brine production and allow the steam cap to expand from the lowering of the liquid level, but also will provide a valuable information with regard to the reservoir extension vertically. The ultimate goal for balancing the steam-brine extraction is to maintain the sustainability of the steam cap performance that will result in prolonging the steam supply plateau of the field and providing growth opportunities for the Wayang Windu geothermal field.

6. SUMMARY

The Wayang Windu geothermal field has been performing well where steam production from the reservoir has been able to maintain full generation for the 227 MW installed capacity with no loss generation for more than 20 years. Up until now, the fieldwide natural decline has been sustainable. Individual well and fieldwide enthalpy at Wayang Windu have been very steady, with no issue of cooling from marginal recharge or rapid injection breakthrough. The reservoir steam cap and liquid pressure in the reservoir is currently declining at a moderate rate of less than 1 bar/year. Furthermore, silica scaling has been limited to a few steam cap wells and successfully managed with workovers or well intervention. Simultaneously, efforts are currently underway to better characterize deep brine permeability to provide better targeting for future deeper two-phase wells and to allow more brine production for better steam cap development.

7. AKNOWLEDGEMENT

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