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Production Decline and Reservoir Pressure Decline Evaluation on the Ulumbu Geothermal Field, Flores, East Nusa Tenggara, Indonesia

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ABSTRACT

This work undertakes an evaluation of the production decline and the reservoir pressure decline of the load-varying well, ULB-2, which is the only well supplying steam to the power plant. The generating units supply electricity directly to the 20 kV distribution line, which is coupled with a diesel power plant, and the plant operating scheme often have to follow the local load demand pattern. The plant cannot be operated in a constant load. Increase opening and throttling the well alternately at the peak load time, and vice versa, is part of the well operator daily routine job.

Two numerical methods, i.e. Decline-Lumped Parameter Model and Inflow Performance Relationship (IPR) Model have been used to analyze well productivity. The result of the work will be used to forecast the plant generation capacity until the steam from a make-up well is available. It will be approximately one year after the drilling campaign for the development of a new unit is commenced, considering the time requirement for FEED process and construction of steam pipelines.

Analysis from the production data suggests that from Decline-Lumped Parameter Model, the overall production decline rate is 5.4% and 3.8% per annum, assuming an exponential and harmonic decline, respectively. Some analysis distinguishing the decline on the field when only two units were in operation (July 2012 – September 2014) versus four units (September 2014-afterwards), were also performed resulting lower decline rate for fewer plant units in operation, i.e. 2.04% versus 6.24% (exponential decline) and 2.78% versus 7.15% (harmonic decline). In addition, the forecasted plant generation capacity by the time a make-up well is ready in January 2022, is approximately between 4.5-6.5 MWe, depending on the operation scenario. The IPR model results maximum flow rate and reservoir pressure decline rate of 3.24 kg/s and 0.47 bar per annum, respectively. Furthermore, by using IPR model, it can be observed that between 2004 and 2011 productivity index (PI) decreases due to formation damage (wellbore skin), while between 2011 and 2016 PI deteriorates mainly as a result of reservoir pressure decline. It can be observed that Decline-Lumped Parameter and IPR model pressure decline results are in good agreement, thus confirm the applicability of both methods.

1. INTRODUCTION

Currently, PLN has been operating four geothermal units in Ulumbu, which consist of two condensing units generating electricity since July 2012 and two back-pressure units started operation since September 2014. During the period, only one well, ULB-2, supplies steam to the power plant. The operating wellhead pressure has been declining gradually, so does the wellhead pressure on the ULB-1 acting as a monitoring well and in a shut-in condition since 1996.

This work is intended to evaluate the well production decline and the reservoir pressure decline by compiling and analyzing operation data in July 2012 to December 2017.

2. SUBSURFACE GEOLOGY AND THE CONCEPTUAL MODEL OF ULUMBU

The Ulumbu geothermal field has fumarolic thermal manifestation and no chloride spring within the complex. The up-flow zone is likely to be beneath the Poco Rii-Poco Leok caldera (Kasbani, 1996), whereas the outflow zone is suspected to the southwest of the Poco Rii-Poco Leok area, to the direction of the existing well pad location. The Tertiary-age rock consists of sandstone, limestone, mudstone and lava rock units act as the basement of the geothermal system. Whereas, the Quaternary-age rock, which comprises three rock units, i.e. Quaternary Volcanic Lower (QVL), Quaternary Volcanic Middle (QVM), and Quaternary Volcanic Upper (QVU) act as a reservoir, caprock, and surface formation respectively (Figure 1). This inference was made based on the analysis of alteration intensity, the circulation losses indicated by physical drilling data, and cuttings as well as cores analysis (Kasbani, 1996). Figure 2 shows the subsurface geology beneath the Ulumbu area and the conceptual model.

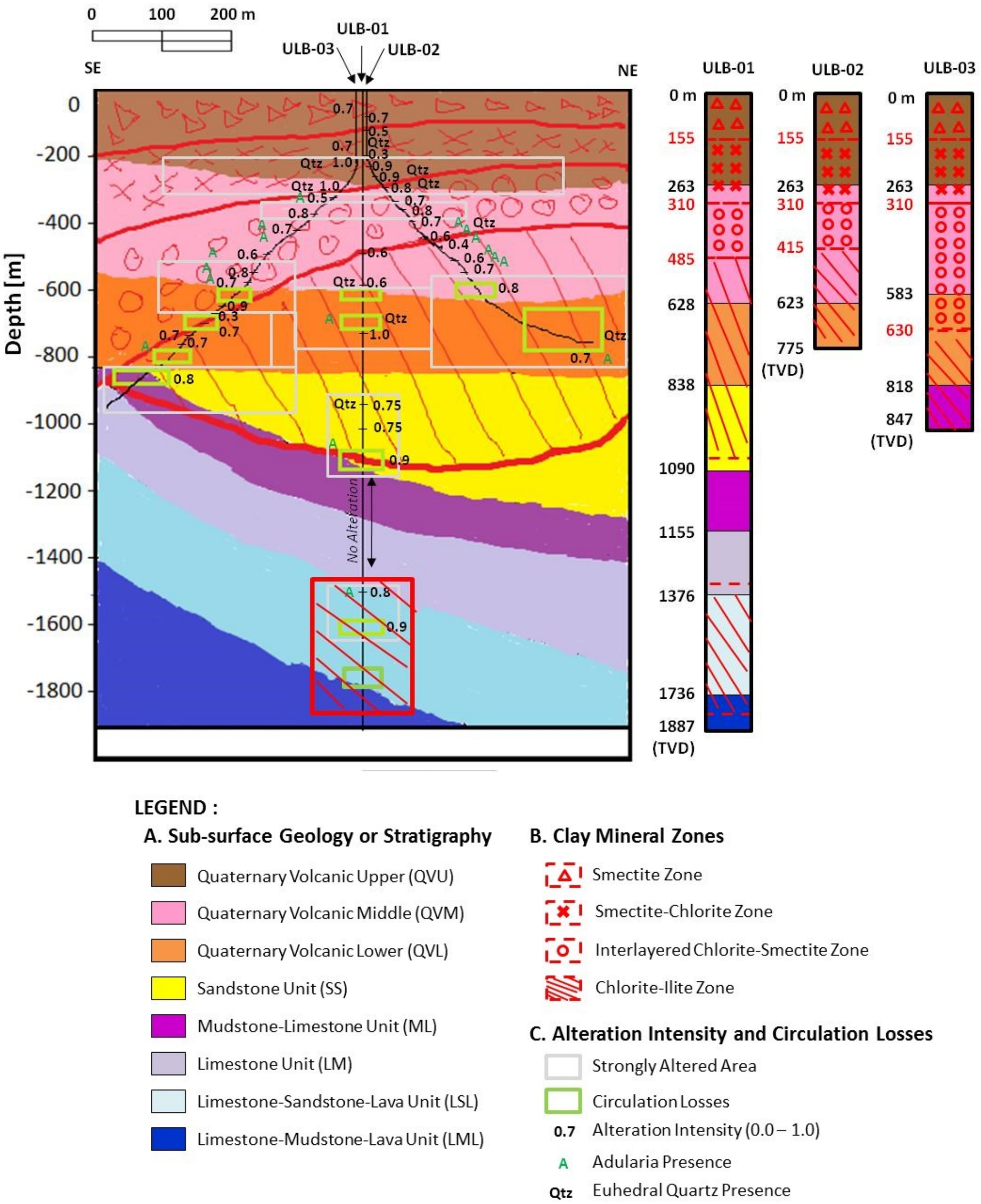

Figure 1: Summary of the drilling data used in the inference of reservoir structure, compiled from Kasbani (1996)

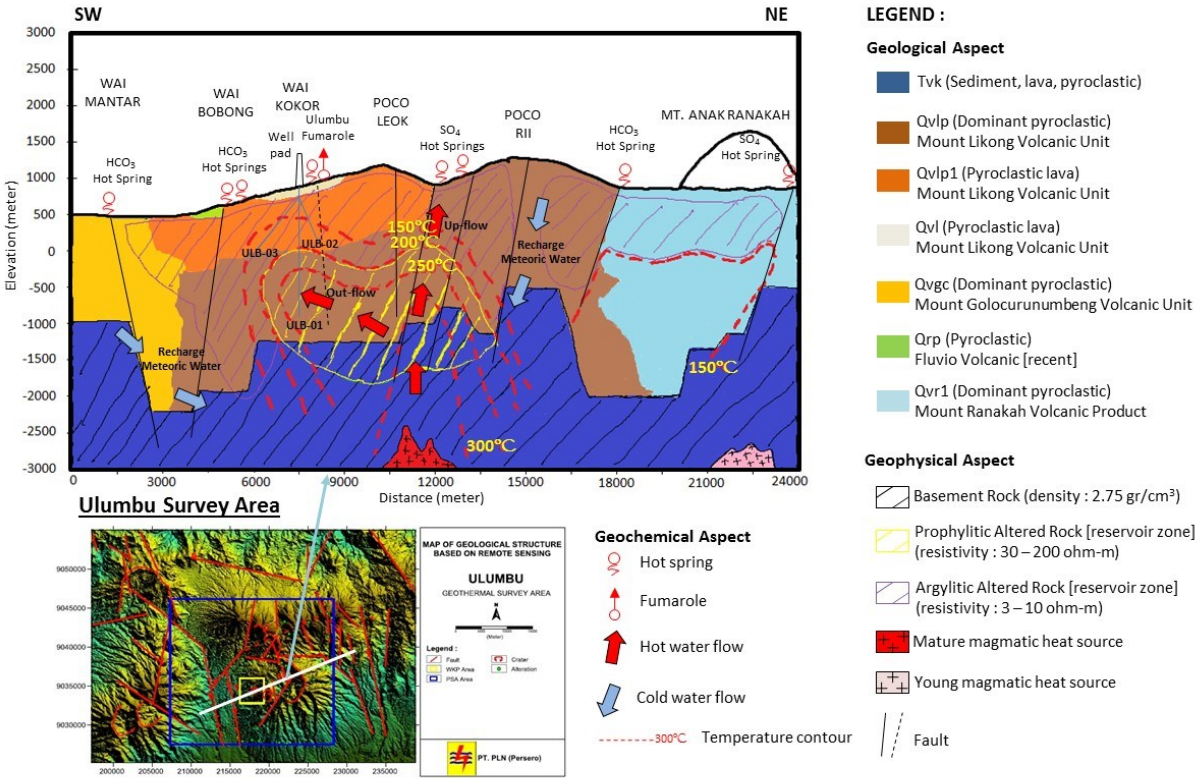

Figure 2: Conceptual Model of Ulumbu Geothermal Field summarized from Kasbani (1996) and PLN (2015)

3. WELL STATUS OF ULUMBU AND DATA MONITORING

Extensive drilling exploration in Ulumbu was conducted in July 1994 to October 1995, where three wells (ULB-1, ULB-2, and ULB-3) were drilled by GENZL of New Zealand from one well pad. Following the drilling, several downhole measurements was performed prior to shutting-in the wells in 1995. Pressure transient tests and flow test on the three wells were carried out in 1996. The result of flow test was promising for ULB-2, but not for the other two. Afterward, ULB-1 and ULB-3 were kept in shut-in condition until the commercial operation of the first and second power plant was begun in 2012, then ULB-3 was kept in bleeding and the ULB-1 have still been being closed since then. ULB-2 had opportunity to be tested two times in 2004 and 2011. The 2004 and 2011 long-term flow tests in ULB-2 were performed in order to understand steam supply characteristics and obtaining proper design parameter for the steam gathering system facility and the power plant facility.

The well pad location and generalized wells trajectory depiction are shown in Figure 3, whereas the wells status since the commercial operation of first plant unit is reported in Table 1. ULB-2 well was in shut-in condition for a few days two times due to some requirement from power plant side, i.e. April 2015 and November 2017. Shut-in wellhead pressure were 30.1 barg and 27.1 barg, respectively.

Table 1: Well Status of Ulumbu Since the Commercial Operation of First Plant

<table>
<tr><th>TIME</th><th>ULB-1</th><th>ULB-2</th><th>ULB-3</th></tr>
<tr><td>Jul 2012-5Apr 2015</td><td rowspan="6">Shut-in</td><td>Operation</td><td rowspan="5">Bleeding</td></tr>
<tr><td>6-7 Apr 2015</td><td>Shut-in</td></tr>
<tr><td>8 Apr 2015-29 Oct 2017</td><td>Operation</td></tr>
<tr><td>30 Oct-1 Nov 2017</td><td>Shut-in</td></tr>
<tr><td>2 Nov 2017-29 Aug 2018</td><td rowspan="5">Operation</td></tr>
<tr><td>30 Aug-23 Oct 2018</td><td>Shut-in</td></tr>
<tr><td>24 Oct-2 Nov 2018</td><td>Shut-in</td><td>Flow test</td></tr>
<tr><td>3 -12 Nov 2018</td><td>Flow test</td><td rowspan="2">Shut-in</td></tr>
<tr><td>13 Nov 2018 – now</td><td>Shut-in</td></tr>
</table>

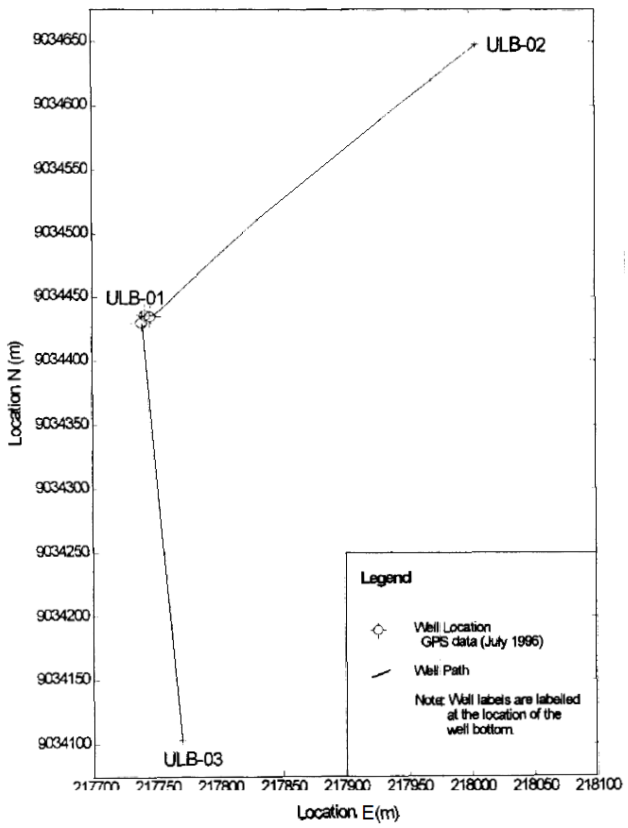

Figure 3: Generalized Wells Trajectory

Starting from the commencement of first two generating units, wellhead pressure and temperature of the three wells are continually monitored, including the production rate from ULB-2. The availability of such data is then used for evaluating the ULB-2 production decline and the reservoir pressure decline.

Since, during the entire evaluation period (July 2012 – December 2017), the ULB-1 is:

i. in a shut-in condition;
ii. having the feedzone vertical depth that is same as ULB-2 (Figure 1 – see the circulation losses) and hydraulically connected (Figure 4);
iii. showing water level depth at the same feedzone vertical depth as ULB-2 (Figure 5 – 750 to 850 mVD), and;
iv. in a boiling condition at corresponding depth (Figure 5);

even without installing downhole pressure chamber, wellhead pressure monitoring data of ULB-1 could be very usefull to analyze the reservoir pressure decline.

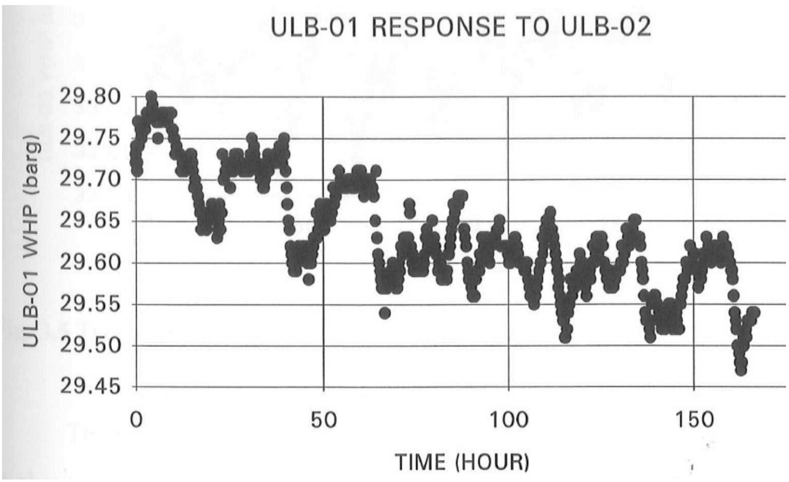

Figure 4: Wellhead Pressure response of ULB-1 to ULB-2 discharge

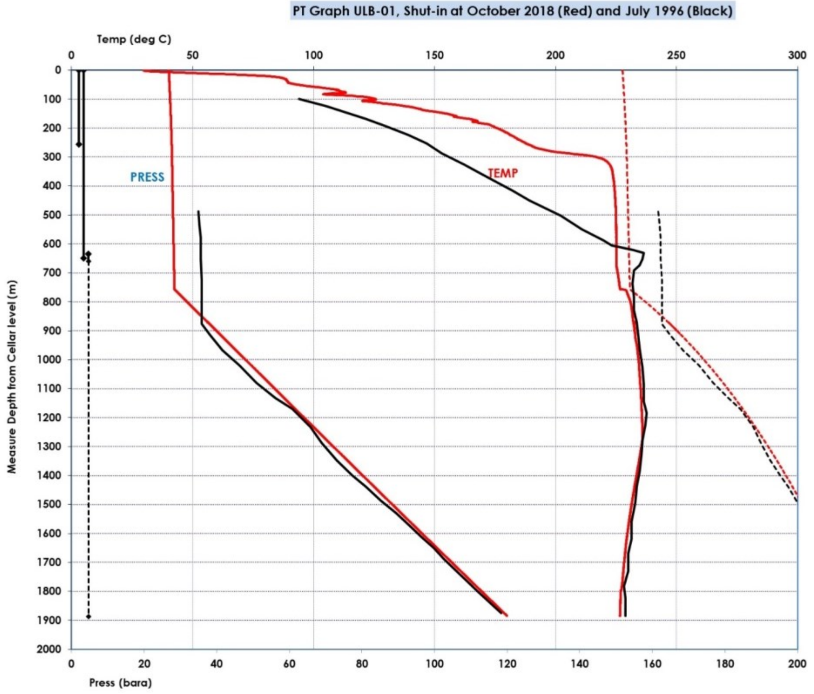

Figure 5: Shut-in PT Logging Graph of ULB-1 (Red = July 1996; Black = October 2018; Dashed line = Saturation Temperature)

4. THE POWER PLANT OPERATION MODE

The generating units supply electricity directly to the 20 kV distribution line which is coupled with a Diesel Power Plant, the plant operating scheme often have to follow the local load demand pattern. The plant cannot be operated in a constant load. Increase opening and throttling the well alternately at the peak load time, and vice versa, is part of the well operator daily routine job. Figure 6 shows the typical daily load profile.

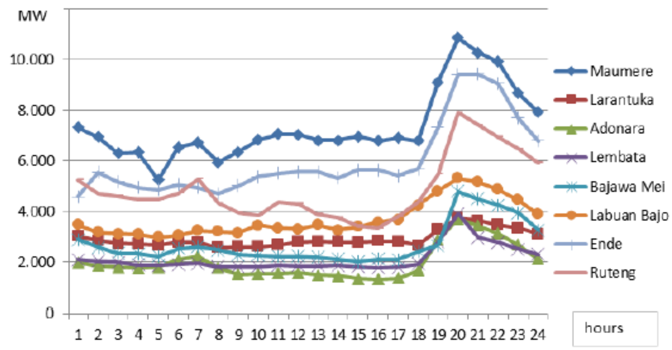

Figure 6: Typical Daily Load Curves in the Eight Main Local Grids of Flores (Ulumbu is connected to Ruteng – the third biggest load)

5. PRODUCTION DECLINE ANALYSIS

Two numerical methods, i.e. Decline-Lumped Parameter Model and Inflow Performance Relationship (IPR) Model are used to analyze well productivity. The result of the work will be used to forecast the plant generation capacity until the steam from a make-up well is ready.

5.1 Decline-Lumped Parameter Model

The decline model and lumped parameter model are basically trend-fitting of well performance technique to establish a simple model for estimating future well performance. They are usefull for short-term extrapolation since establishing a trend or pattern of well performance, that could be immediately detected (and subsequently checked) when some deviation on the trend is observed. It relies on the assumption that the process affecting the well is significantly unchanged. Any deviation usually indicates some new process on the well and/or reservoir.

The decline model uses mathematical expressions introduced by Arps, J.J (1945) and is currently used for decline analysis widely. It is established the following types of production decline: Exponential, hyperbolic and harmonic. Whereas, the lumped parameter model consists of two model: an open and a closed model, which are distinguished by the assumed recharge condition. Pressure historical data is plotted then fitted to the certain pattern to estimate the future value.

5.1.1 Decline Model

The decline model requires a continuous history of static wellhead pressure and/or flow rate at a constant flowing wellhead pressure. As the power plant cannot be operated in a constant load, achieving constant flowing wellhead pressure is difficult. Thus, it is also difficult to elaborate the true decline trend in the well productivity without normalizing the production rate to a certain flowing wellhead pressure. In addition, the static wellhead pressure is often not readily available and could be only measured occasionally, typically during the power plant outage. Sanyal, et.al (1989) established an equation to relate the steam production rate as a function of static wellhead pressure and the flowing wellhead pressure of a steam well. It also introduces an approach to estimate the static wellhead pressure that allowing continuous monitoring of producing wells as well as normalizing the production rate to the certain flowing wellhead pressure.

In this work, 13 bara was chosen as the standard flowing wellhead pressure of ULB-2 to normalize the production rate. Whereas, the saturation pressure at corresponding reservoir temperature (33.46 bara; 240 °C) was used to estimate a representative value C_i statistically based on the first week of well production. Since the production data is available hourly, it was decided to normalize all the production rate values, then averaging the normalized values daily (See the working flowchart on Figure 7).

As suggested by Arps, J.J (1945), exponential decline is expressed by equation :

$$q=q_i e^{-Dt}$$

where q is the production rate, q_i is the initial production rate, D is the decline rate and t is time. By plotting the historical production rate data versus time in a semi-log graph, where the production rate data plotted in the natural logaritmic axis, linear curve could be obtained. The gradient of this linear curve then represents the decline rate, D_i. See the following equations.

$$\ln q = \ln\left(q_i e^{-Dt}\right)$$

$$\ln q = \ln\left(q_i\right) + \ln\left(e^{-Dt}\right)$$

$$\ln q = -D\,t + \ln\left(q_i\right)$$

Harmonic decline type proposed by Arps, J.J (1945) is governed by equation:

$$N_p = \frac{q_i}{D}\left(\log q_i - \log q\right)$$

where N_p is the cummulative production. Similar to the exponential decline expression, it is then possible to represent the equation above by a straight line in a semi log scale and by knowing the initial production rate, the decline rate could be easily calculated from the constant on the second term of the linear equation.

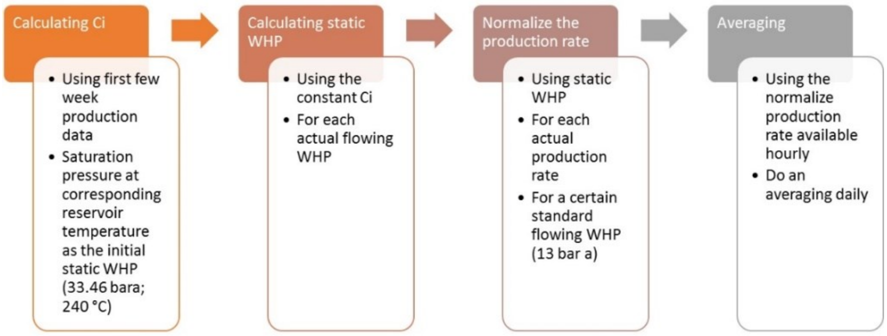

Figure 7: Working Flowchart in Implementing Systemic Approach

Analysis distinguishes the decline on the field when only two units were in operation (July 2012 – September 2014; green circle and blue circle shown in Figure 8 and 9, respectively) versus four units (September 2014-afterwards; red circle and orange circle shown in Figure 8 and 9, respectively). Figure 8 and 9 represent two different type of decline trending: exponential and harmonic .

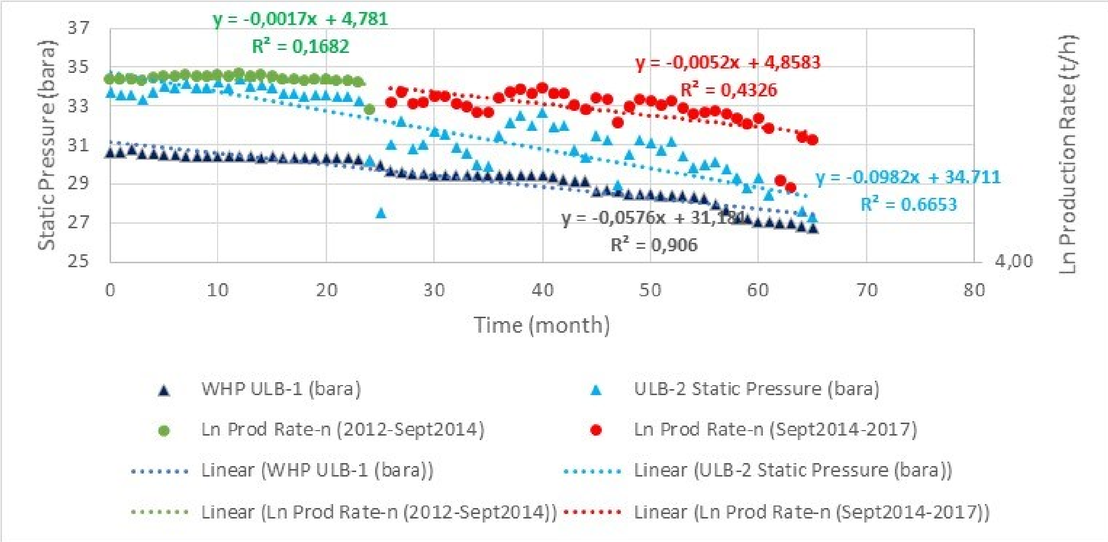

Figure 8: Production Rate (green and red circle), Monitoring Well WHP (dark blue triangle), and Calculated Static Pressure (light blue triangle) Historical Data Plot

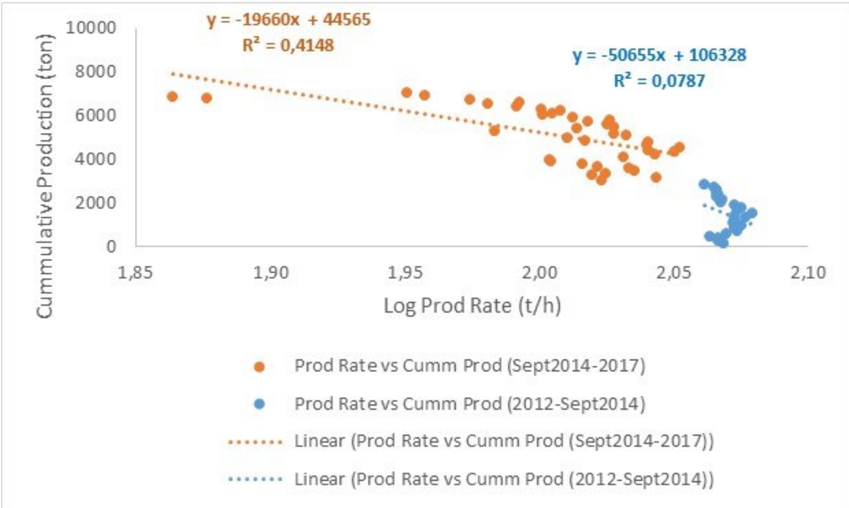

Figure 9: Cummulative Production versus Logarithmic Scale of Production Rate Data Plot

The result of analysis from the production data suggests that the overall production decline rate is 5.4% and 3.8% per annum, assuming an exponential and harmonic decline, respectively. Whereas, when only fewer units were in operation (July 2012 – September 2014) compared to four units (September 2014-afterwards) resulting lower decline rate for fewer plant units in operation, i.e. 2.04% versus 6.24% (exponential decline) and 2.78% versus 7.15% (harmonic decline). See Table below.

Table 2: Result of Decline Model Analysis

Decline Mode	2012-Sept2014		Sept2014-2017	
Exponential	0,17%	p.month	0,52%	p.month
	2,04%	**p.annum**	**6,24%**	**p.annum**
Harmonic	0,23%	p.month	0,54%	p.month
	2,74%	**p.annum**	**6,53%**	**p.annum**

The result of decline model analysis is subsequently used to predict the future well performance as well as the plant capacity. As the four generating units consist of two different plant types, i.e. condensing and back-pressure units, this work also distinguishes the corresponding plant capacity: condensing units prioritized, back-pressure units prioritized, and equally combined. The condensing units prioritized prediction assumes that the available steam is given priority to fulfill the two condensing units generation, then the remaining available steam for the other units, and vice versa for the back-pressure units. Figure 10 shows the prediction of plant capacity for the 30 years plant operation (until July 2032) based on the result of decline model analysis. On the other hand, Figure 11 indicates the forecasted plant capacity at the time when the steam from a make-up well is readily available. The drilling campaign for this unit will be simultaneously with the drilling campaign for the development of a new unit (January 2021). Considering the time requirement for FEED process and construction of steam pipelines, one year duration is then added (January 2022).

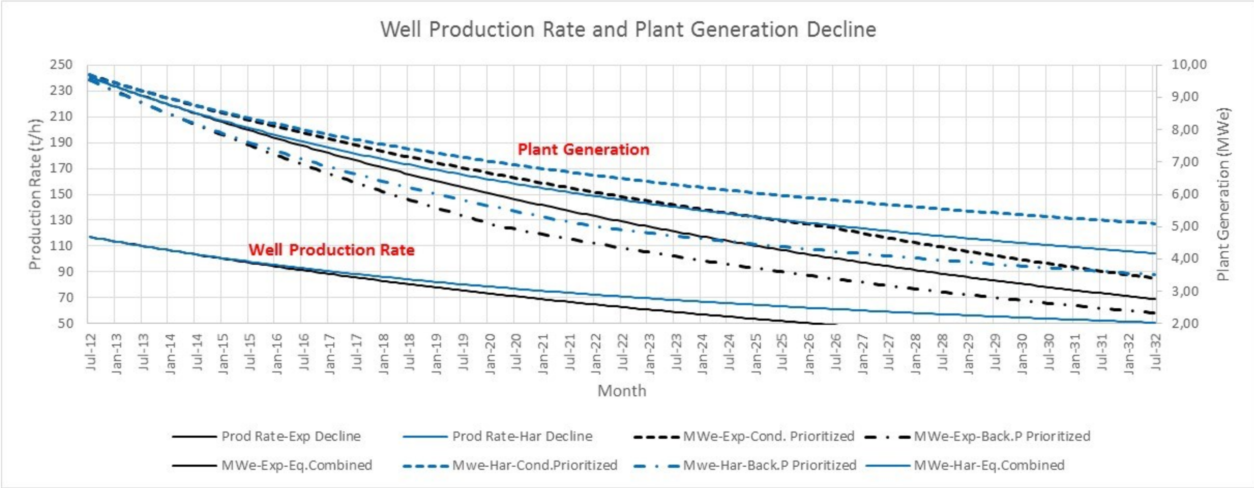

Figure 10: Forecasted Well Production Rate and Plant Generation until July 2032 (Blue = Harmonic; Black = Exponential; Dashed = Condensing Units Prioritized; Solid = Equally Combined; Dashed Dot = Back-prssure Units Prioritized)

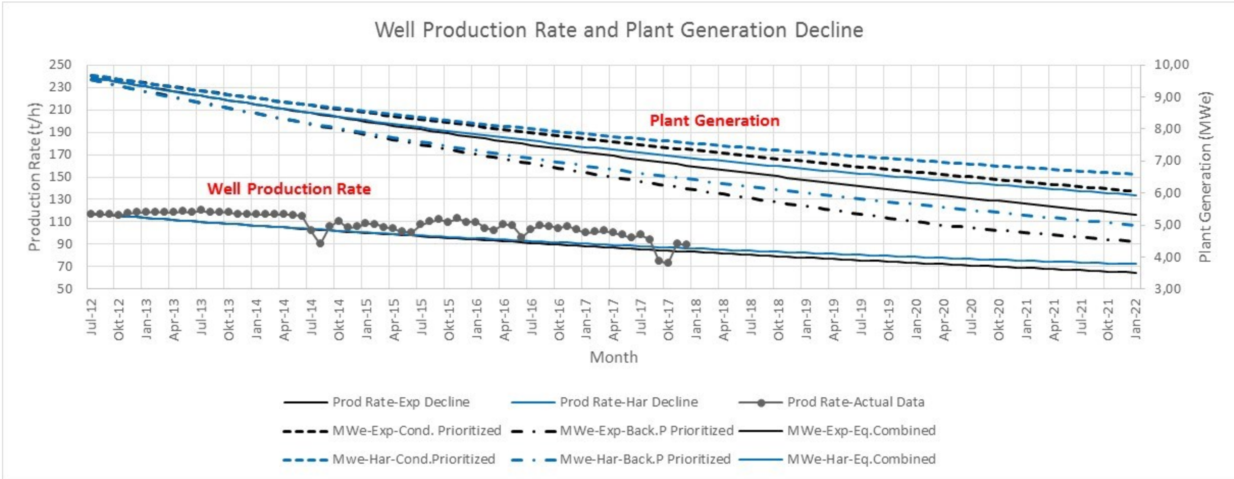

Figure 11: Forecasted Well Production Rate and Plant Generation until January 2022 (Blue = Harmonic; Black = Exponential; Dashed = Condensing Units Prioritized; Solid = Equally Combined; Dashed Dot = Back-prssure Units Prioritized)

The model predict that the at the time when the steam from make-up well is ready, the plant capacity will be approximately between 4.5-6.5 MWe, depending on the operation scenario. This number could be then very usefull for the power system planning in the preparation of power grid operation scenario. Decline model analysis performed seems reliably matched with the actual production rate data, resulted in slightly more conservative than the actual data.

5.1.2 Lumped Parameter Model

A simple model is considered in this work where parameter such as temperature and fluid chemistry are not included in the consideration. The model simply considers reservoir as a single box containing homogeneous rock and fluid, in which fluid withdrawal and recharge on the box follow conservation of mass equation for the box. In addition, the period of the available pressure data monitoring is perceived shorter than the system time or relaxation time, τ, therefore within this time the fluid recharge has negligible effect on the pressure, the model behaves as closed model with negligible recharge and the pressure drop falls linearly. Thus, over the period, the reservoir storage coefficient can be estimated based on the following equation.

$$P_o\text{-}P = {}^{W\,t}/_{S_M}$$

where P_o and P are the pressure drop component, W is the mass flow rate, t is time, and S_M is reservoir storage coefficient on a mass basis.

Examining the pressure drop according to the pressure data from ULB-1 and the cummulative withdrawal mass flow representing W t component, then S_M can be easily calculated. The reservoir storage coefficient is 1799 ton/bar. In addition, by taking an assumption of closed model as explained above, in which pressure will decrease linearly, the model predicts that the reservoir pressure decline is 0.058 bar monthly or 0.696 bar per annum. Considering the assumption of closed model, this value might be perceived as a conservative value, provided that no change on the fluid withdrawal and reservoir hosted rock condition.

5.2 Inflow Performance Relationship (IPR) Model

The WellboreKit was used to investigate bottomhole pressure from production data measured at the wellhead. The characteristic curves of the well (CC: W vs WHP) is from the production input data.

By using the input data, characteristic curve (W, WHP), and the geothermal fluid properties (assuming a ternary compound system), the maximum mass flow (W_{max}) of the wellbore is computed from a best polynomial regression equation, which are together used by wellbore simulator (WellboreKit) to determine the well production parameters (pressure and enthalpy) at bottom-hole conditions. From these parameters, inflow type curves, IPR (W, BHP) are predicted.

By using the best polynomial equation, which was inferred from the IPR curves (at bottom-hole conditions), the static reservoir pressure (p_e) and the productivity index (PI) are estimated. PI is defined as the $\Delta P/W$ ratios (for geothermal wells); whereas ΔP is the differential pressure between p_e and BHP at flowing conditions. The dimensionless mass flow and pressure parameters (W_D, P_D) are subsequently calculated by using the improved equations.

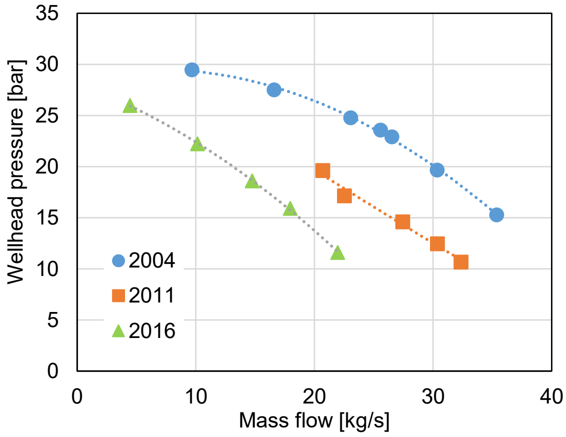

Figure 12: Characteristic curve of ULB-2 well derived from measurement of pressure, enthalpy and mass flow at the wellhead.

From the use of the dimensionless IPR curves (W_D, P_D), the damage effect (S) is finally determined from the 'best overlapping' process among the dimensionless IPR curves (obtained from the coordinates: W_D, P_D, and the pattern of IPR curves originally plotted in Figure 3.3).

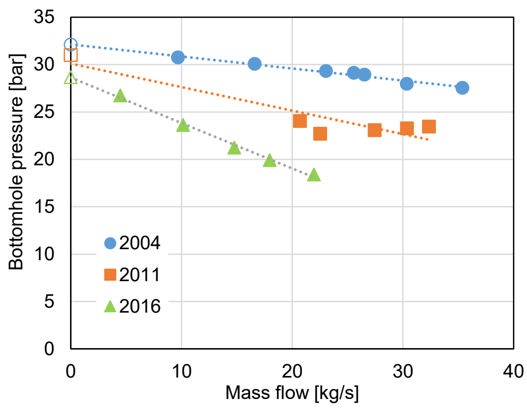

Figure 13: Inflow Performance Relationship (IPR) derived from wellhead pressure and mass flow data. The bottomhole pressure was calculated using the WellboreKit.

Table 3: Behavior of production parameters in wells of Ulumbu geothermal field.

	Period time [y]	p_e [bar]	W_{max} [kg/s]
2004	0	32.1	48.14
2011	7	31	47
2016	12	28.65	30.8

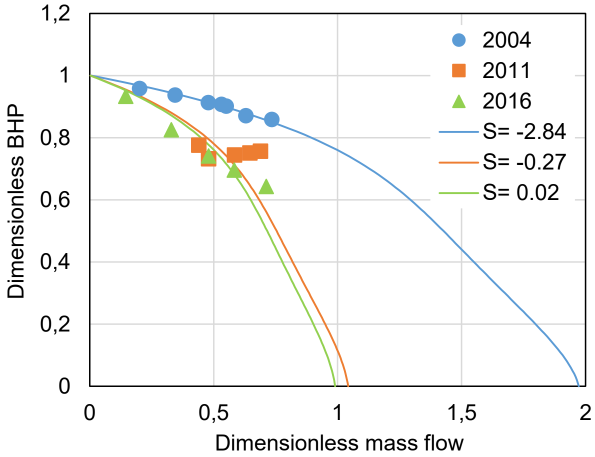

Figure 14: Dimensionless Inflow Performance Relationship (IPR) derived to "best fitting" the damage (skin) factor correspond to time.

Finally, an interpretation of the computing results for determining the most suitable well maintenance operations either to keep or improve its productivity efficiency is carried out. By using the dimensionless IPR curves with values obtained at different stages of the operative life cycle of the well, the history of the productivity with time ($\Delta p/\Delta t$, $\Delta S/\Delta t$, and $\Delta W_{max}/\Delta t$) is analyzed either for maintaining a stable and sustainable production or to identify an earlier declining trend of the wellbore (i.e., before to achieve minimum values of pressure and flow in the turbine admission section).

Table 4: Behavior of production parameters obtained in ulb-2 at year 2004, 2011, and 2016.

Year	Period time [y]	Δp/yr [bar/y]	ΔW/y [kg/s/y]	PI [kg/s/bar]	S	ΔS/y
2004	0			8.1	-2.84	
2011	7	0.16	0.16	3.48	-0.27	-0.37
2016	12	0.47	3.24	2.11	0.02	-0.06

The sudden significant change observed in the wellbore damage effect (S) determined after 7 years of idle, indicates a clear deterioration of the well ULB-2, and a deep strong problem in the reservoir rock-formation. In fact, the PI change observed in the production phase of 5 years shows strong reservoir pressure decline with relatively constant damage effect (S).

6. CONCLUSION

Analysis from the production data suggests that from Decline-Lumped Parameter Model, the overall production decline rate is 5.4% and 3.8% per annum, assuming an exponential and harmonic decline, respectively. Some analysis distinguishing the decline on the field when only two units were in operation (July 2012 – September 2014) versus four units (September 2014-afterwards), were also performed resulting lower decline rate for fewer plant units in operation, i.e. 2.04% versus 6.24% (exponential decline) and 2.78% versus 7.15% (harmonic decline). In addition, the forecasted plant generation capacity by the time a make-up well is ready in January 2022, is approximately between 4.5-6.5 MWe, depending on the operation scenario. The IPR model results in the maximum flow rate and reservoir pressure decline rate of 3.24 kg/s and 0.47 bar per annum, respectively. Furthermore, by using IPR model, it can be observed that between 2004 and 2011 productivity index (PI) decreases due to formation damage (wellbore skin), while between 2011 and 2016 PI deteriorates mainly as a result of reservoir pressure decline. It can be observed that Decline-Lumped Parameter and IPR model pressure decline results are in good agreement, thus confirm the applicability of both methods.

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