Opportunity and Barriers to Develop a Bottoming Unit by Utilizing Separated Hot Brine in Ulubelu, Indonesia

Mawardi Agani, Salvius Patangke, Drajat B Hartanto, Marihot Silaban

PT Pertamina Geothermal Energy, Jakarta, Indonesia

E-mail: mawardi.agani@pertamina.com, s.patangke@pertamina.com, drajat@pertamina.com, Marihot@pertamina.com

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ABSTRACT

Two units of geothermal power plant, 2 x 55 MW were already commissioned in Ulubelu geothermal field on September 16th and October 24th, 2012 consecutively. PT Pertamina geothermal Energy (PGE) supplies 836 tons/hr (TPH) steam at pressure of about 9.0 bar abs to this 110 MW power station which is owned and operated by PT Perusahaan Listrik Negara (PLN).

Ulubelu is a liquid dominated geothermal system with enthalpy of about 1100 kJ/kg and a total separated brine of approximately 2,780 TPH being disposed to reinjection wells at temperature of 175 °C. Thermodynamically, this amount of brine is equivalent to 25 – 30 MW net additional capacity if utilized in bottoming technologies such as second flash, sub-critical and super-critical binary systems. This additional capacity will increase utilization efficiency of Ulubelu geothermal resources from 39.4 % to 51.4 %.

However, bottoming technology has some risks that could be barriers for development. Measures to mitigate silica scaling potential, risk of cold brine influx to productive reservoir and lack of reservoir understanding among others, needed to be identified and assessed to determine the feasibility of adopting the chosen technology. On the other hand, second flash and binary cycle are mature and proven technologies used worldwide. Technology is also available to overcome silica scaling by means of acid or base injection. PGE is currently conducting tracer test to monitor connections between production and injection wells. Moving injection wells further south will be an option to reduce risk of cooling the reservoir by injected cold brine.

1. INTRODUCTION

Ulubelu geothermal field is located about 100 km west of Bandar Lampung in South Part of Sumatra Island. It is associated with the volcanic depression surrounded by the quaternary volcanic of Mt. Sula, Rindingan and Tanggamus (Figure 1). Between 1993 and 1996, three exploration slim holes were drilled by Pertamina at the Ulubelu Field. The well encountered a steam cap overlying a liquid-dominated resource with temperatures from 210°C to 230°C (Surya Darma *at al*, 2010). Since 2006 until recently, Pertamina Geothermal Energy (PGE) already drilled 34 exploration and development wells in Ulubelu geothermal field to support 2 x 55 MW capacity power plants namely unit-1 and 2 built by PLN and also for 2 x 55 MW capacity total project development namely Unit-3 and Unit-4. The existing wells suggest that Ulubelu reservoir covers an area of around 20 km^2 with reservoir thickness between 600 m to 2000 m at temperature of about 270°C. Resources assessment conducted by PGE, shows that Ulubelu has proven reserve of about 330 MW which is enough to sustain operation of 4x 55 MW power plant for 30 years.

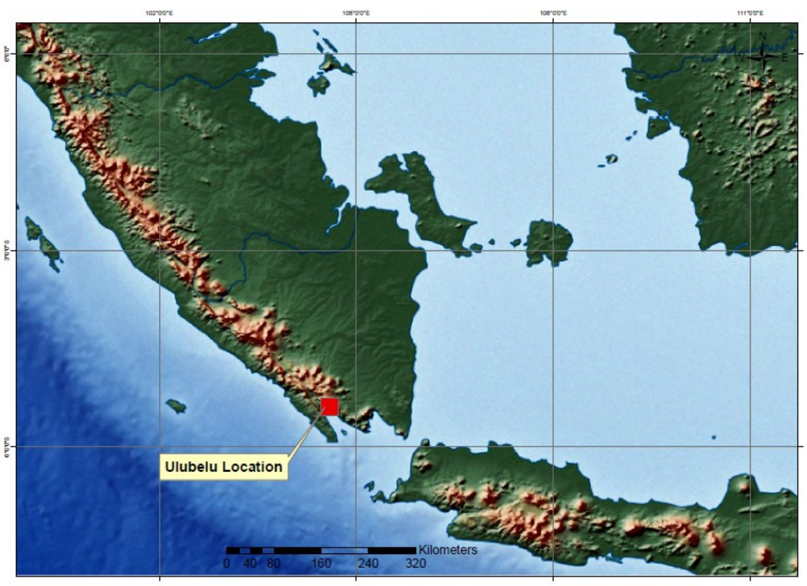

Figure 1: Location of Ulubelu Geothermal Field

Power plant Unit-1 commenced commercial operation on September 16th 2012 and followed by Unit-2 on October 24th the same year. This 110 MW total capacity power plant is operated and owned by PT PLN while steam is delivered by PGE. There are 23 wells dedicated for the power plant; consisting of 12 production wells, 6 reinjection wells and 5 monitoring wells. These wells are located in 6 clusters namely cluster A to F. Production wells are situated in 3 clusters namely cluster-B, C & D, injection wells located in 2 clusters namely cluster A & F while monitoring wells are located in cluster F as indicated in Figure-2

This paper discusses the prospect of utilizing the huge amount of hot brine produced from the separators to increase power production in Ulebelu Geothermal Field. Several barriers and risks are also addressed in order to find the best alternative and solution to utilize the waste heat to generate electricity.

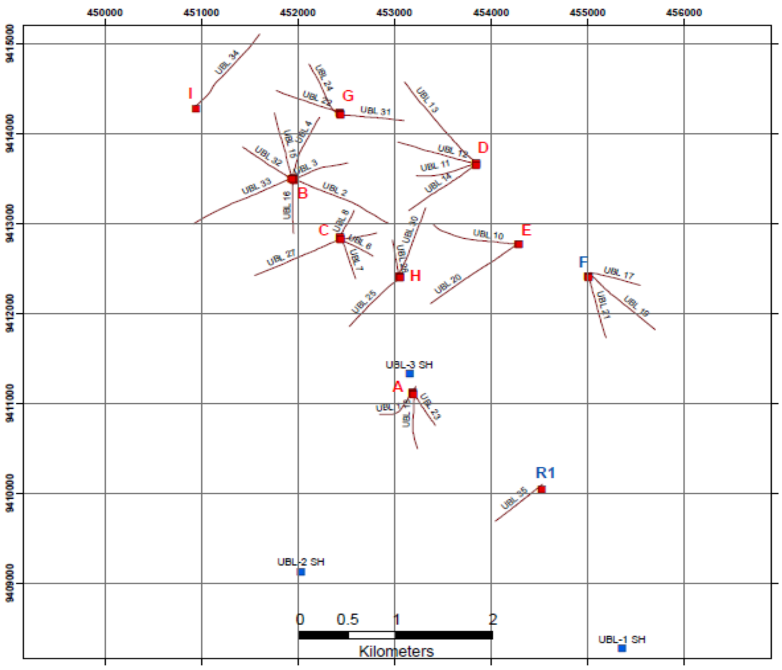

Figure 2: Well cluster, well location and well status in Ulubelu Geothermal Field

2. STEAM AND BRINE PRODUCTION

Ulubelu geothermal field produces two phase fluid with dryness from 9% to 17%, enthalpy ranging from 1000 to 1125 kJ/kg and average Non Condensable Gasses (NCG) content of about 0.6%. The lowest wellhead pressure is about 11 bar g. and the highest is 18 bar g. Two phase fluids from production wells Cluster B and C are delivered to two separators namely SPR-01A and SPR-01B located in Cluster C while two phase fluids from production wells in Cluster D are delivered to SPR-02 which is located on the same Cluster. Separated steam from each separator is delivered to a common header which is split via two streams to feed Unit-1 & Unit 2. Separated brines from SPR-1A and SPR-01B are injected into 2 reinjection wells located in Cluster-A while brines from SPR-2 are injected into 3 reinjection wells located in Cluster-F. Condensate from power plants are returned to PGE and injected into well UBL-23 in Cluster-A. Flow diagram of Steam field above Ground System (SAGS) in presented in Figure-3.

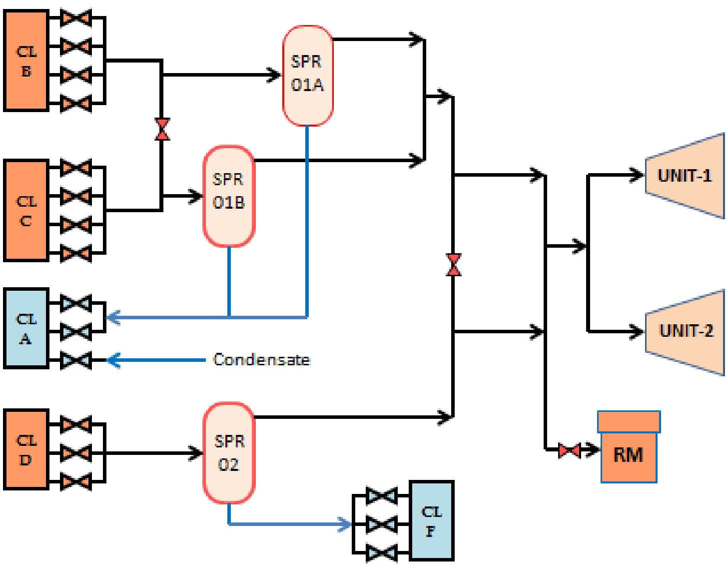

Figure 3: Flow diagram of Ulubelu Unit 1 & 2 Steamfield above Ground System (SAGS)

Normally, 836 TPH of steam at 9 bar abs are delivered to the power plants to generate 110 MW of electric power. Consequently, approximately 2780 TPH of hot brine with a temperature of 175°C are re-injected back to the reservoir. By utilizing other power plant technologies like second flash or Organic Rankine Cycle (ORC), significant amount of energy can still be extracted from these waste fluids. Finally, 200 TPH of condensates at temperature of 25°C is disposed at re-injection well UBL-23.

3. ALTERNATIVES TO INCREASE POWER PRODUCTION BY UTILIZING THE HOT BRINE

Single flash power plant is the most common type of geothermal power plant installation worldwide. It is often the first power plant installed at a newly-developed liquid-dominated geothermal field. Nowadays, installed capacity in Indonesia is 1343.5 MW, where 873.5 MW and 470 MW are generated from single flash and dry steam power plants, respectively. Therefore, there is an opportunity to further optimize the single flash units before injecting the brines to the reservoir by using bottoming technologies like ORC or binary cycle and second flash cycle, where low pressure steam can be fed to a low pressure turbine. However, despite the availability of these proven technologies, not a single binary cycle or a second flash cycle power plant has been installed in Indonesia until recently. Uncertainties on the long term availability of brines especially on high enthalpy reservoirs as well as risks on silica scaling and adverse cooling effects of reinjection returns to the production wells discourage application of these optimization technologies.

For Ulubelu case, to utilize huge amount of brine from separators, two well-proven bottoming technologies were considered. The first is second flash steam cycle and the second is ORC/binary cycle. To address different types of working fluid, three types of Binary cycles will be assessed namely sub-critical binary cycle using iso-pentane and super-critical binary cycle using iso-butane and R134a refrigerant. The bottoming cycle is estimated to generate up to 30% additional electricity without drilling additional production wells. Another bottoming technology namely Kalina cycle is not examined because this cycle is not common and more complex than a basic binary plant. So far only a few Kalina power plants are operating worldwide (Kjartansson, 2010).

3.1 Second Flash Cycle

Second flash cycle power plant is actually similar to double flash system; the difference is that the second flash system uses another low pressure turbine rather than using a single turbine with high and low steam inlet pressures. The second flash cycle usually utilizes brine from existing single flash units that operate as a first development stage of a geothermal field. If temperature of brine from steam separator in the single flash unit is high enough, the brine can be utilized further to produce more electricity. The second flash cycle uses geothermal brine by producing low pressure steam in a second flashing stage. The second or double flash cycle has been shown to be able to produce up to 20 – 25% more power than that of the single flash cycle alone (Karlsdottir *et al*, 2010). Figure 4 shows a schematic diagram of a typical second flash cycle as a second stage development to existing single flash power plants.

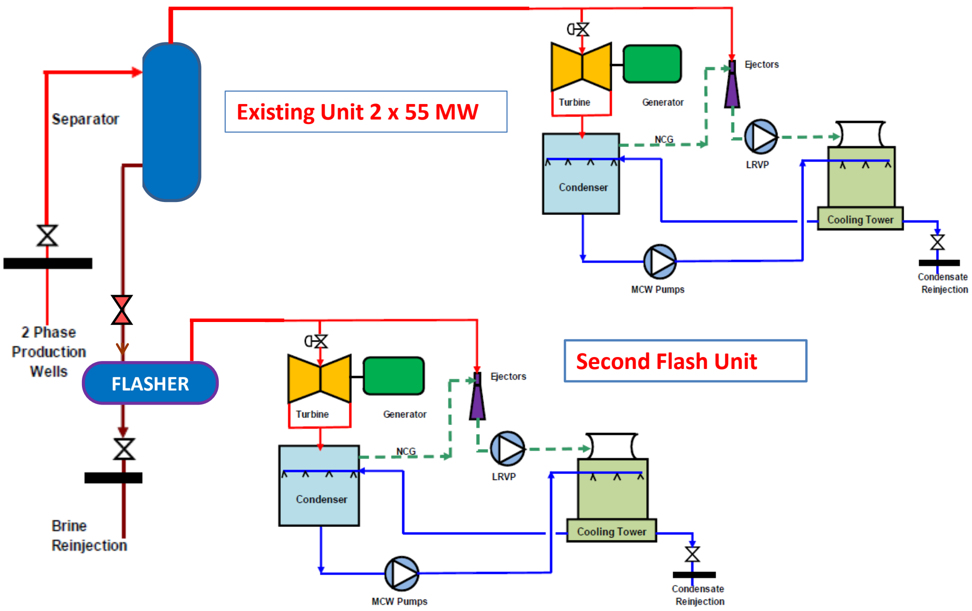

Figure 4: Simplified schematic diagram of a combined single and second flash plant

The process of second flash cycle is similar to single flash cycle. After geothermal fluid has been separated in the high pressure steam separator, the brine is fed through a low pressure separator/flasher for the second stage separation. The brine is then disposed to reinjection wells. The low pressure steam from the separator is then delivered to low pressure turbine to generate electricity.

This kind of development has been successfully accomplished at Hellisheidi Geothermal Field, Iceland in 2007. It uses 600 kg/s (2160 TPH) of brine at temperature of 175°C and pressure of 9 bar abs to be flashed at pressure of 2 bar abs and temperature of 120°C to produce 65 kg/s (234 TPH) of low pressure steam to generate 24.4 MW of electric power. Presently, numerous geothermal LP-turbines are in operation worldwide, generating 20 – 30 MW at 1 – 3 bar abs inlet pressure, each unit (Kjartansson, 2010).

Resource condition of Ulubelu is quite similar to that of Hellisheidi Geothermal Field. It produces geothermal fluid at enthalpy of 1100 kJ/kg and pressure of about 9 bar abs at separator. The following table 1 show heat source parameters used in calculating power output for a second flash cycle in Ulubelu:

Tabel 1: Heat source parameters and ambient condition used in calculation for second flash cycle

Total Fluid Flow (ton/hour)	3616
Fluid Enthalpy (kJ/kg)	1100
Separator Pressure (bar abs)	9.0
Brine Flow (ton/hour)	2780
Second flash pressure (bar abs)	2.0
Condenser Pressure (0.1 bar abs)	0.1
Avg. Dry Bulb Temperature (°C)	22.9
Avg. Wet Bulb Temperature (°C)	21.0
Avg. Humidity (%)	96.0
Atmospheic Pressure (bar abs)	0.93

3.2 Binary Cycle

Adding a binary cycle as bottoming unit to existing single flash plant is another alternative optimization method to the second flash cycle. Binary cycle is a well-known technology and has been widely used type of geothermal power plant with 162 units in operation in May 2007, generating 373 MW of power in 17 countries. However, despite the larger number of units in operation, they contribute only 4% of total global power generation. Thus, the average power rating per unit is small, only 2.3 MW/unit. (Di Pippo, 2007). The binary cycle coupled to the single flash cycle has shown an increased power production of about 13 – 28% compared to the conventional single flash cycle (Karlsdottir *et al*, 2010).

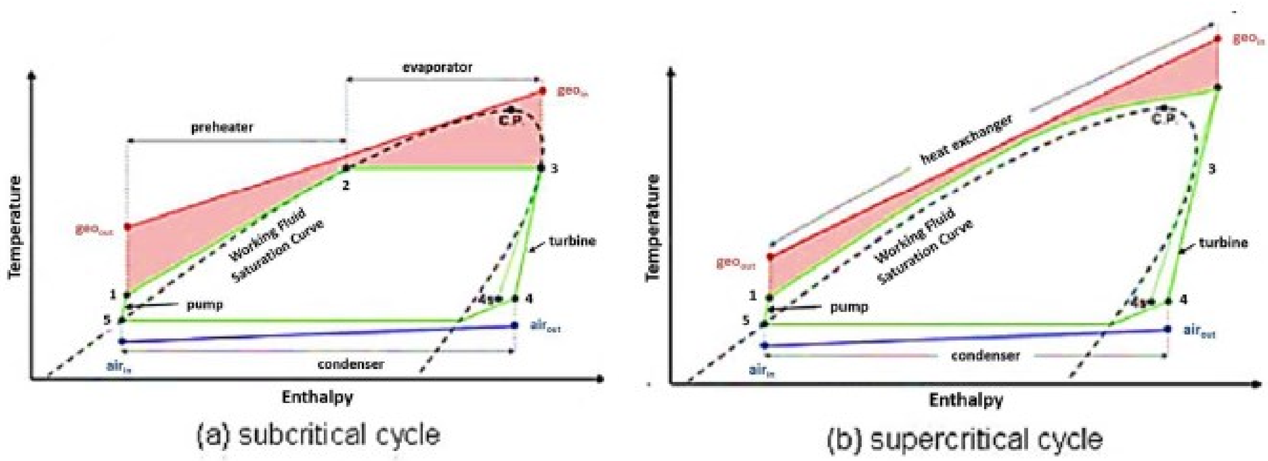

Figure 5: Temperature-entropy diagram for subcritical cycle and supercritical cycle

An ORC is a binary cycle using an organic working fluid such as iso-pentane, iso-butene or other refrigerant for example R134a. The organic fluids have an advantage over water as a working fluid due to the shape of saturation curve as seen in Figure 5. The shape of the curve has a negative slope or retrograde shape that allows expansion from saturated vapor line into the superheated region, avoiding any moisture during the turbine expansion process. The organic working fluids typically have lower boiling temperatures than water, making them suitable for utilizing lower temperature geothermal brine for power production. Moreover, the critical temperatures and pressures are significantly lower than water that makes them more applicable to supercritical cycle for hydrocarbons. In order to make comparison among available hydrocarbon fluids, three working fluids will be assessed for Ulubelu case; they are iso-pentane ($i\text{-}C_5H_{12}$), iso-butane ($i\text{-}C_4H_{10}$) and R134a (CH_2CF_4).

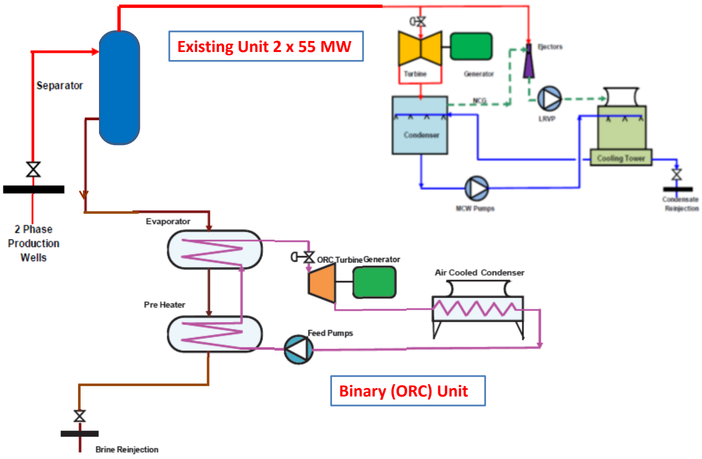

Figure 6: A simplified schematic diagram of a binary cycle as a second stage development to existing single flash plants

Figure 6 shows a schematic diagram of a binary cycle coupled in parallel to the existing single flash cycle. The brine from steam separator is led through heat exchangers namely pre-heater and evaporator that transfer heat to the working fluid, causing it to boil. The saturated vapor of the working fluid is then led the turbine that turn the generator to generate electricity. Leaving the tubine, the low pressure vapor of working fluid is cooled and condensed in an air cooled condenser and finally pumped to appropriate working pressure to the heat exchangers to complete the cycle. Table 2 shows parameters used to calculate output power for binary cycle power plant.

Tabel 2: Heat source parameters and ambient condition used in calculation for binary cycle

Brine Flow rate (ton/hour)	2780
Brine Temperature in (°C)	175
Brine Temperature out (°C)	100
Avg. Dry Bulb Temperature (°C)	22.9
Avg. Wet Bulb Temperature (°C)	21.0
Avg. Humidity (%)	96.0

3.3 Working Fluid Selection

One of the most important tasks undertaken when designing a binary cycle plant is the choice of the working fluid. This design decision has great implications for the performance of a binary plant. Various factors should be taken into account, among others are thermodynamic properties, toxicity, explosive properties and flammability, environmental impact such as Ozone Depletion Potential (ODP) and Global Warming Potential (GWP), cost, availability in the market, extent of knowledge about its properties, etc. (Nikolskiy *et al*, 2010).

For Ulubelu case, to make a comparison between binary cycle power output for the same input of heat source, three potential working fluids have been selected, that satisfy general criteria such as: thermally stable in the range of operating temperature, readily available in the market in order to minimize plant down time in case working fluid leakage and other emergencies, available at a reasonable price, toxicity of none to low and having thermodynamic properties for an acceptable cycle performance, having thermodynamic properties to make good design of component possible, having minimal to no environmental impacts and has to fulfill all local/international environmental regulations (Agahi and Behrooz, 2010). Moreover, these three working fluids are widely used.by binary plant original equipment manufacturers (OEM) worldwide. Ormat Technologies Inc. and Exergy for example utilize iso-pentane as the working fluid, Ben Holt – Rotoflow uses iso-butane while Turbine Air System (TAS) uses R134a. Table 3 shows critical temperature and pressure of the selected working fluids included in calculation. Since the brine temperature is about 175°C and assume 5°C pinch point temperature, then iso-pentane will work in sub-critical area while iso-butane and R134a will work in supercritical area.

Tabel 3: Critical temperature and pressure of three most common working fluids for binary cycle

Fluid	Formula	T_c (°C)	P_c (bar abs)
i-Butane	i-C_4H_{10}	135.92	36.85
i-Pentane	i-C_5H_{12}	187.8	34.09
R134a	CH_2CF_4	101.0	40.6

3.4 Calculation Result and Discussion

The result of calculation for four alternative bottoming cycles is presented on table 4. Microsoft excel macros is used to calculate power produced from second flash cycle while HYSYS software is used to calculate power produced from binary cycle for different working fluids.

It can be seen that under the same heat source and ambient condition, all binary cycles produce higher gross output compared to second flash cycle. Binary cycle with iso-butane working fluid is superior compared to second flash and other binary cycles. Unfortunately, binary cycles also consume much higher power for house load compared to single flash cycle. Iso-butane and R134a binary cycles for example, consume about 21% and 21.7% of generator output respectively while iso-pentane binary cycle consumes about 14.8% and second flash cycle consumes only about 3.5%. Super critical binary cycle (Iso-butane and R134a) consume more power for feed pumps compared to that of iso-pentane binary cycle since they work at higher pressure and temperature.

It is obvious that only iso-butane binary cycle can surpass the net power produced by second flash cycle. It produces net power output 7.3% higher than second flash, while the other two binary cycles produce net power 3% less than second flash cycle. Finally, the exercise demonstrates that the bottoming cycle is able to produce additional net power capacity from 27.5% to 30.0% relative to the existing 110 MW single flash plants,

Besides the power output given by each alternative cycle, there are many others factors that should also be addressed. Cost for example, will play a very important factor when selecting a technology to be adopted. In contrast to binary cycle superiority in power output, second flash cycle costs less than binary cycle.

Tabel 4: Calculation result

Description	Second Flash Cycle	Binary Cylce (Iso-pentane)	Binary Cycle (Iso-butane)	Binary Cycle (R134a)
Generator Output (kW)	31,360	34,501	41,155	37,569
Pump Power Consumption (kW)	420	1,245	4,915	4,460
Fan Power Consumption (kW)	430	3,588	3,412	3,412
Other Aux.plant Load (kW)	234	276	329	300
Total House Load (kW)	1,084	5,109	8,656	8,172
Net Power Output (kW)	30,276	29,392	32,499	29,397
Turbine Inlet Pressure (bar abs)	2	11	41	50
Turbine Inlet Temperature (°C)	120	121	152	159
Relative Power Increase (%)	28.4	27.5	30.0	27.6

The average capital cost of a binary cycle was about US$ 2,259 per kW installed capacity (2004 basis). The average capital cost of a single flash cycle was US$ 1,236 per kW installed capacity and the average capital cost of a double flash cycle was US$ 1,294 per kW installed capacity (Swandaru and Pallson, 2010). The capital cost of a binary plant is higher than that of the flash plant due to the complexity of the equipment, the need of low boiling point working fluid and much larger land needed for air cooling system. This complexity likewise leads to higher Operation and Maintenance (O&M) cost compared to that of flash plant. Swandaru and Pallson (2010) suggest that O&M cost for flash plant is US cent 1.5/kWh while for binary plant is US cent 2.0/kWh.

Furthermore, at present, commercial binary units has not been manufactured lager than 8 MW (Kjartansson, 2010). Therefore, in case of Ulubelu, at least three such units would be needed to utilize the brine. On the other hand, a single second flash unit shall be enough to utilize all the brine and convert it to electricity. This is a major advantage of the second flash cycle power plant. Another advantage is its flexibility to use low pressure steam from idle low pressure production wells if brine production declines in the future. Worldwide experience on rising enthalpy of fluids after long years of exploitation provides ample supply of HP steam that can be used to augment LP steam turbines (Kjartansson, 2010).

Finally, both second flash and binary cycle processes lead to lower brine temperature at the outlet of flasher or heat exchanger. This low temperature can induce silica scaling in the flasher, heat exchanger, injection pipelines and also re-injection well. Moreover, additional flash process that occurs in second flash cycle may cause the waste brine becomes more highly concentrated that can exaggerate the silica precipitation. The silica scaling effect of utilizing brine in Ulubelu will be discussed further in section 4.2.

3.5 Utilization Efficiency Improvement

The performance of the existing plants and the bottoming plants in Ulubelu can be assessed using the second law of thermodynamics by comparing the actual net power output to the maximum theoretical power that could be produced from a given geothermal fluid. Utilization efficiency, η_u, is defined as the ratio of the actual net plant power to the maximum theoretical power obtainable from a given geothermal fluid in the reservoir state:

$$\eta_u = W_{net}/E_{res}, \text{ and } E_{res} = m_{total}[(h_{res} - h_0) - T_0(s_{res} - s_0)]$$

Where W_{net} is the net plant power, E_{res}, h_{res} and s_{res} are exergetic power, enthalpy and entropy at reservoir temperature respectively, m_{total} is total mass flow rate of geothermal fluid, T_0 is the dead-state temperature (ambient dry-bulb temperature), and h_0 and s_0 are the enthalpy and entropy values for the geothermal fluid evaluated at the dead-state pressure and temperature (DiPippo, 2007). DiPippo suggests that utilization efficiency for single flash cycle is 30 – 35%, for double flash cycle is 35 – 45% while for basic binary is 25 – 45%.

Exergy analysis conducted by Taghaddosi and Moghachi (2010) and Jalilinasrabady et al. (2010) indicate that the largest exergy loss in geothermal power plant occurs in brine fluid. Therefore, utilizing the waste brine to produce more power will reduce the exergy loss and thus increase the utilization efficiency of the heat source.

Table 5 shows utilization efficiency of Ulubelu geothermal field for various power plant cycles under consideration. The following variables are used in calculation: reservoir enthalpy is 1100 kJ/kg, total mass flow of geothermal fluid is 3616 TPH, and average ambient dry bulb temperature is 22.9 ^{0} C.

Table 5: Utilization efficiency for various power plant cycles in Ulubelu

Description	Single Flash Cycle	Single + Second Flash Cycle	Single Flash + Binary (i-Pentane)	Single Flash + Binary (i-Butane)	Single flash + Binary (R134a)
Gross Power (MW)	110	139.3	144.5	151.2	147.6
Net Power (MW)	106.7	134.1	135.3	138.4	135.3
Utilization Eff. (%)	39.4	50.5	50.2	51.4	50.2

Calculation results in table 5 suggest that by developing bottoming cycle, the utilization efficiency of Ulubelu Geothermal Field increases from 39.4% using only single flash plant to 50.5% if it is combines with a second flash cycle. The highest efficiency is provided by a combination of single flash plant and Iso-butane binary cycle that is 51.4%, while combination with the two other binary cycles provides utilization efficiency of about 50.2%.

4. BARRIERS TO DEVELOP BOTTOMING CYCLES IN ULUBELU GEOTHERMAL FIELD

Utilizing brine through bottoming technologies leads to decline in brine temperature. This would be the source of barriers that hamper the development of the technology especially for the high-temperature geothermal system such as Ulubelu. At least there are two main obstacles why efficient use of high temperature geothermal fluids cannot be achieved. The first is the threat of cold brine influx to the productive reservoir and the second is silica scaling potential. These two contentious issues have been the subject of many deliberations among PGE engineers and scientists causing the delays in the optimization of the Ulubelu resource.

4.1 Threat of Cold Brine Influx

After operating more than a year, Ulubelu geothermal field already suffered 5 – 7% decline in wellhead pressures and fluids flow rate. This decline corresponds to decrease in power production from 111 MW during commissioning to about 96 MW recently. Moreover, two production wells namely UBL-6 and UBL-12 ceased discharging because of cooling inside the wellbore. It was confirmed after conducting PTS surveys that surface cold water influx occur at 258 m and 767 m depth through a leak in the production casing.

With continuous mass extraction, the reservoir pressure is expected to decline, and with increasing pressure from the reinjection sector, the speed by which fluids will return to the more depleted production zone will be faster, causing premature thermal breakthrough. An internal report also indicates decline in enthalpy and NCG content of individual wells. This decline is shown in Figure 7.

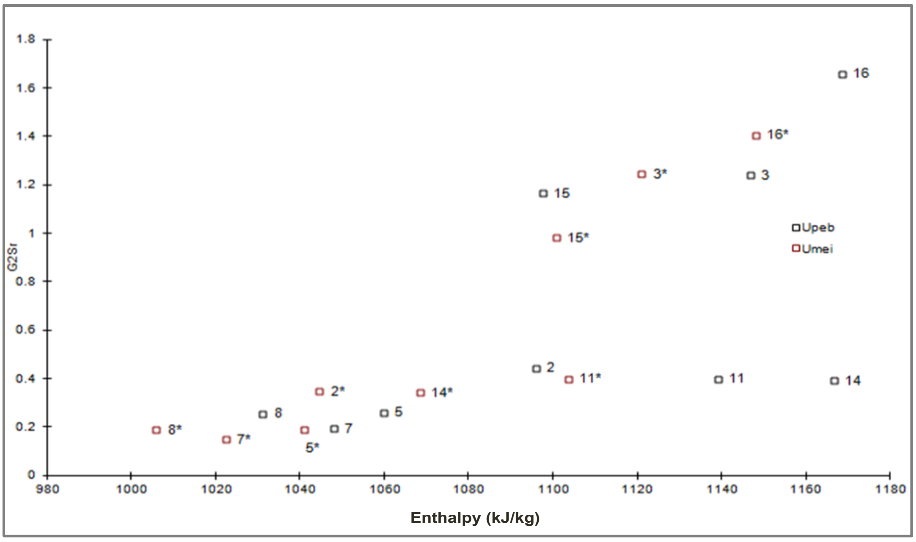

Figure 7: Plot of Enthalpy – NCG content (%) for Ulubelu wells

The well data were taken on February and May 2013 using Tracer Flow Test (TFT). Most of wells shows decline in reservoir fluid enthalpy and NCG. Well UBL-16, for instance shows decrease in enthalpy from 1170 kJ/kg on February to about 1150 kJ/kg on May, as well as decrease in NCG content from 1.5% on February to 1.4% on May.

It is recognized that brine re-injection impacts positively in maintaining reservoir pressure by acting as an artificial recharge to the system. However, adverse effects also usually observed when reinjection fluids communicate rapidly with the production wells causing reduction in temperature and production. In some cases, the effects are irreversible. The concern in Ulubelu optimization is when the much relatively cooler fluids from second flash or binary plants also reach the production sector rapidly, causing further degradation in reservoir temperatures. Thermal breakthrough has occurred in cases where the spacing between injection and production wells is small or when direct flow-paths exist between the wells (Axelsson *et al*, 2005).

In Ulubelu, separated hot brine at 175 °C from separator is directly injected into re-injection wells which are located in cluster A and F. These are about 2 km from production well locations as shown in Figure-8. The effects of brine injection and its temperature to reservoir and fluids production are currently under observation. To evaluate the impact of brine injection, tracer tests were conducted in December 2013.

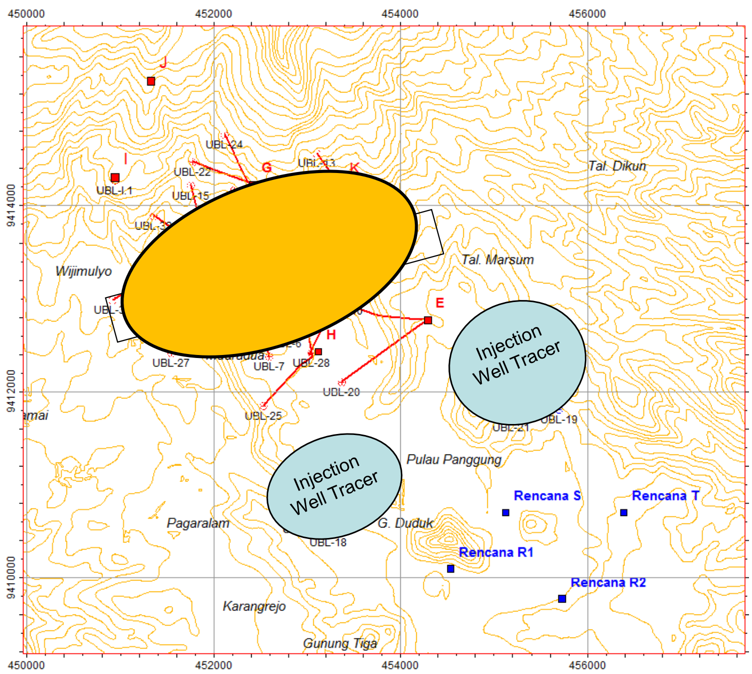

Figure 8: Location of tracer injection wells and monitoring/sampling wells

Three types of tracer agent were injected into 5 injection wells located in two clusters (Figure 8). Tracer 1,6-NDSA and 1,5-NDSA were injected into two hot brine injection wells namely UBL-1and UBL-18 respectively located in cluster A. Tracer 2-NSA was injected into a condensate injection well namely UBL-23 located in the same cluster. Tracer 2,6 NDSA and 2,7-NDSA were injected into other two hot brine injection well namely UBL-19 and UBL-21 respectively located in cluster F. The recovery of the tracer was monitored in 10 production wells for 50 days. The monitoring wells, comprises 4 wells in cluster B (UBL-02, 03, 15, 16), 4 wells in cluster C (UBL-05, 07, 08, 27) and 3 wells in cluster D (UBL-11, 14).

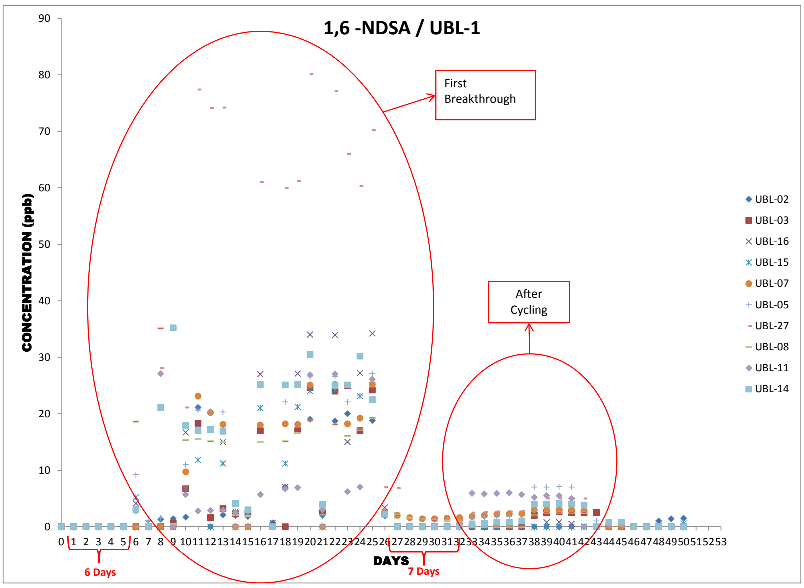

Figure 9: Tracer 1,6-NDSA monitoring results collected from production wells.

The tracer test result reveal that there are strong connections between injection wells and production wells. Figure 9 shows first breakthrough of tracer 1,6 NDSA occurring 6 days after tracer injection in 7 production wells. Breakthrough occurred from 8 - 9 days in three other wells. The peak breakthroughs occurred after 8 to 11 days in 4 wells, 20 to 23 days in 2 wells and 25 days in 4 wells. Other tracer tests also indicate relatively similar result where the first breakthrough occurs at 7 to 10 days after tracer injection. However, tracer 2-NSA which is injected in a condensate injection well (UBL-23) shows its first breakthrough after 21 to 28 days.

This injection breakthrough will be more threatening when brine temperature is much cooler such as brine from bottoming cycles which is usually at temperature about 80 to 120°C. In this case, injection wells should be located far away from production wells to prevent cold brine influx to productive reservoir. Currently PGE already drilled a new injection well in cluster R1, more south of Ulubelu Geothermal Field (see Figure 8). With both the positive and negative effects of reinjection already known, an appropriate strategy to strike a balance between these two effects should be drawn. The use of tracers in determining flowpath, transit times and in determining temperature cooling plays a significant role in the planning and evaluation. Continuous monitoring in Ulubelu is thus being followed with the objective of being able to come up with more reliable prediction of the reservoir performance using numerical modelling.

4.2 Silica Scaling Potential

Potential problem with silica scaling in high temperature geothermal system such as Ulubelu is very high. Silica is in equilibrium with quartz when the hot water is underground. However, when the two-phase mixtures are brought to the surface, a considerable drop in temperature due to flashing occurs, and the difference in the solubility of quartz and amorphous silica allows the latter to be supersaturated in the solution. Hence the form of silica that normally precipitates at the surface is amorphous silica (Brown, 2011).

The potential for silica to precipitate is dependent on the degree of silica saturation in brine in respect to amorphous silica. Silica Saturation Index (SSI) is often used to indicate the potential for silica scale deposition. It is defined as the ratio of silica concentration in the solution to the equilibrium solubility of amorphous silica. Silica scaling will occur when the SSI is greater than 1. It means that the brine is already supersaturated with silica.

Tabel 7: Silica concentration of Ulubelu brine and result of SSI calculation

Separator	Cl_{surf} (ppm)	$SiO2_{surf}$ (ppm)	pH	Temp. (°C)	SSI
SEP 1A	1137.00	673.00	7.76	173.5	0.96
SEP 1B	995.00	610.00	8.60	175.7	1.27
SEP D	1092.00	727.00	8.84	178.3	1,38
FLASH 1A+1B	1196.08	720.12	8.20	120.0	1.93
FLASH D	1219.92	825.34	8.48	120.0	2.59
BINARY 1A+1B	1057.62	638.03	8.20	100.0	1.98
BINARY D	1092.00	727.00	8.84	100.0	2.92

The SSI calculation shown in Table 7 suggests that there is potential silica scaling in separator, flasher and downstream facilities such as heat exchanger, pumps and piping, except in separator 1A where the SSI is less than 1. Note that even though binary plant disposes brine at lower temperature; the SSI of binary plant is about the same with that of second flash plant. In the second flash, the brine is flashed to a lower temperature and hence increases silica concentration at the separated brine. In the binary plant, the brine is not flashed but only cooled, thus there is no increase in the silica concentration as the fluid pass through the plant.

Many works were already conducted in order to overcome the silica scaling problem. Silica precipitation on surface facility and possibly in reservoir could happen if geothermal fluid is not properly handled before reinjection. Brown (2011) suggests several treatments to cope with silica scaling. Among them, pH modification could be the most widely use now in geothermal industry. It reported that at pH about 5, the silica polymerization has been delayed, while at the normal pH, silica polymerization is very rapid. In the same way, raising the pH to 9 also prevent the silica scaling without any problem with corrosion of steel. However, the major disadvantage is the cost of alkali.

Horie *et al*, (2010) reported successful application of pH modification by dosing the HP brine with sulfuric acid (H_2SO_4) in the double flash plant in Kawerau, New Zealand. The acid injection rate is precisely adjusted by variable speed dosing pump to target the LP brine to the reinjection system at pH 5.0. Gray (2010) also reported the same application in the triple flash plant Nga Awa Purua power plant, in Rotokawa, New Zealand. However, extremely corrosive nature of sulfuric acid should be considered when selecting material for mixing.

Another method of silica scale prevention is aging of the brine, allows the silica to become polymerized then suspended in a retention tank. Kiyota and Uchiyama (2011) reported that Hatchobaru geothermal water which was alkaline and contained supersaturated silica that only needs one hour to reduce monomeric silica concentration to amorphous silica solubility. Additionally, Klein (1995) suggests the use of gas and condensate mixing to suppress silica scale development.

Silica scaling mechanisms are fairly complex and poorly quantified; therefore it has been common to manage scale on the basis of local experiments. A rig test experiment such as constructed for Kawarau and Rotokawa geothermal field is very effective to simulate the response of the brine to different power cycle process conditions (Brown and Rock 2010). The testing result then can be used to design and develop a new plant with a system that can minimize the silica scaling problem.

5. CONCLUSIONS

Two power plant cycles were studied in order to evaluate the power output produced at a given amount of heat source. The second flash cycle utilizes low pressure steam obtained from LP flasher at 2 bar abs and condenses it at 0.1 bar abs in condenser. For binary cycle, three working fluids were evaluated to compare net power output produced by each working fluid. The calculation indicates that iso-butane binary cycle produces 32.5 MW net, the highest among the group. It is followed by second flash cycle at 30.3 MW net, then R134a and iso-pentane binary cycle at 29.4 MW net. Relative to the existing 110 MW power plant, the bottoming cycle generates 27.5% to 30.0% more power from utilizing the hot brine. For Ulubelu geothermal field, the bottoming cycle contributes to more efficient use of its resources, because the utilization efficiency increases from 39.4% to 50.2 - 51.4%.

Second flash cycle is less expensive compared to binary cycle, but on the other hand, iso-butane binary plant produces about 7.3% more power than second flash plant. Aside from the potential increase in output of each bottoming technology, financial aspects, environmental issues, land requirement, compactness, ease of operation and simplicity should be considered before making a final decision.

Concerns on the impact of reinjection of cooler fluid such as cold brine influx, silica scaling in the surface facilities, reinjection wells and reservoir should be thoroughly studied. Tracer test can be applied to analyze a proper injection strategy in order to prevent the cooling water breakthrough in reservoir, while pH modification is widely used to eliminate or to delay silica precipitation. Sulfuric acid (H_2SO_4) injection to maintain pH at 5 is already common practice in geothermal power plant worldwide. If pH modification does not work, the brine can be simply disposed to retaining tank for a while to settle down the silica then pumped into reinjection wells.

Since Ulubelu geothermal field is only about 2.5 years in operation, there is a need to gather and analyze more data. A numerical reservoir model is being set up to aid in forecasting the performance of the reservoir and addresses the impact of injecting brine at higher and cooler temperature. A test rig experiment is a good practice to evaluate heat source characteristics related to how should the resource be utilized efficiently. This experiment also provides the best method to overcome silica scaling problem when multi-flash or binary cycles are employed.

REFERENCES

Agahi, R., Behrooz, E.: Power Cycle for Low Temperature Heat Recovery and Geothermal applications. ANIMP – ATI, Milan, Italy (2010).

Axelsson, G., Bjornsson, G., Montalvo, F.: Quantitative Interpretation of Tracer Test Data. *Proceedings* World Geothermal Congress 2005, Antalya, Turkey (2005)

Brown, K.: Thermodynamics and Kinetics of Silica Scaling. Test rig Experiments for Silica Scaling Inhibition. *Proceedings,* International Workshop on Mineral Scaling 2011, Manila,Philippines, Indonesia (2011).

Brown, K., Rock, M.: Test rig Experiments for Silica Scaling Inhibition. *Proceedings,* World Geothermal Congress 2010, Bali, Indonesia, (2010).

DiPippo, R.: Geothemal Power Plants – Principles, Applications, Case Studies and Environmental Impact, Second Edition, Elsevier, Burlington, USA (2007).

Gray, T.: Power Plant Selection in Mighty River Power Development Project. *Proceedings,* International Workshop on Mineral Scaling 2011, Manila, Philippines (2011).

Horie, T., Muto, T., Gray, T.: Technical Features of Kawerau Geothermal Power Station, New Zealand, *Proceedings* World Geothermal Congress 2010, Bali, Indonesia (2010).

Kiyota, Y., Uchiyama, N.: Silica Scale Prevention Effects of Brine pH Modification at Hatchobaru Power Station, Japan. *Proceedings,* World Geothermal Congress 2010, Bali, Indonesia (2010).

Kjartansson, G.: Low Pressure Flash-Steam Cycle at Hellisheidi – Selection Based on Comparison Study of Power Cycles, Utilizing Geothermal Brine, *Proceedings,* World Geothermal Congress 2010, Bali, Indonesia (2010).

Jalilinasrabadi, S., Itoi, R., Fujii, H., Tanaka, T.: Energy and Exergy Analysis of Sabalan Geothermal Power Plant, IRAN, *Proceedings* World Geothermal Congress 2010, Bali, Indonesia (2010).

Karlsdottir, M.R., Palsson, H., Palsson, O.P.: Comparison of Methods for Utilization of Geothermal Brine for Power Production, World Geothermal Congress 2010, Bali, Indonesia (2010).

Nikolskiy, A.I., Shipkov, A.A., Tomarov, G.V., Semenov, V.N.: Creation of Pilot Binary Geothermal Power Plant on Pauzhetsky (Kamchatka) Site, *Proceedings,* World Geothermal Congress 2010, Bali, Indonesia (2010).

Suryadarma, Purnomo, A., Pramono, A., Brahmantio, E.A., Kamah, Y., Suhermanto, G.: The Role of Pertamina Geothermal Energy (PGE) in Completing Geothermal Power Plants Achieving 10,000 MW in Indonesia, *Proceedings* World Geothermal Congress 2010, Bali, Indonesia (2010).

Swandaru, R., Pallson, H.: Modelling and Optimization of Possible Bottoming Units for General Single Flash Geothermal Power Plants, *Proceedings* World Geothermal Congress 2010, Bali, Indonesia (2010).

Taghaddosi, M., Moghacy, H.: Geothermal Power Plant in Meshkin-Shahr Iran, *Proceedings* World Geothermal Congress 2010, Bali, Indonesia (2010).