

## Performance Improvement of Single-Flash Geothermal Power Plant Applying Three Cases Development Scenarios Using Thermodynamic Methods

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**Keywords:** geothermal, power plant, single-flash, double-flash, Dieng Indonesia, thermodynamic, exergy analysis, second law efficiency.

### ABSTRACT

The performance of an existing single-flash geothermal power plant was improved by applying three cases of expansion design, including double-flash, single-flash combined with binary and double-flash combined with binary, which have been carried out using the thermodynamic method. Engineering Equation Solver (EES) was employed to solve the mathematical equations for this thermodynamic design. The existing single-flash geothermal plant produces 24,300 kW with first and second law efficiency at 11.75% and 36.7%, respectively. The result shows that double-flash combined with binary produces the highest net power output with 30,466 kW. The first and second law efficiencies for this system are 14.73% and 46.02% respectively.

### 1. INTRODUCTION

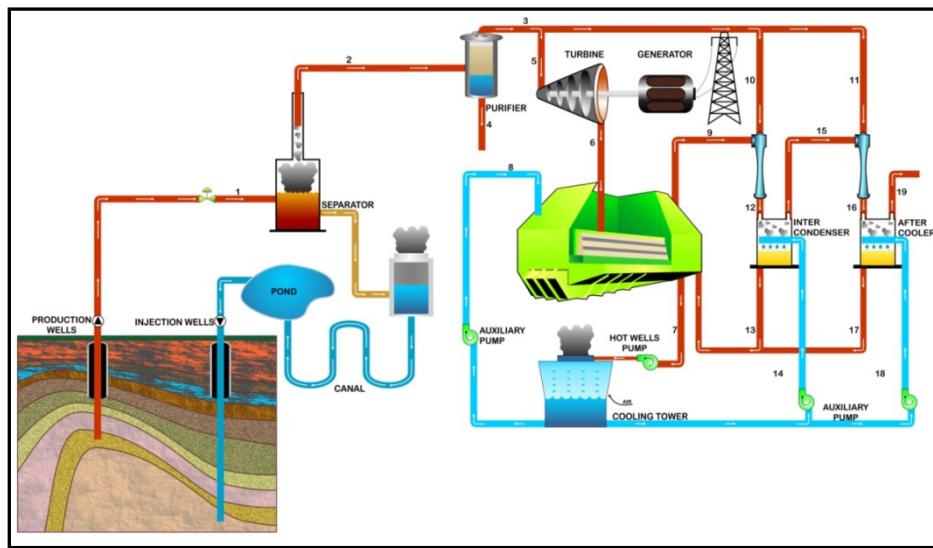
The improvement of performance in the existing geothermal power plant is significantly important. It does not only involve optimizing the resource available but also reducing the waste of disposed energy. An existing single-flash Dieng geothermal power plant is used as an example in this research by the development of scenarios exploring several designs of the power plant.

A Dieng has a reservoir temperature and enthalpy at around 310 °C and 1380 kJ/kg, respectively. The installed capacity is 60MW and is supplied by steam from ten production wells at five locations (Pambudi et al., 2014). The process of electricity production employs a single-flash plant with collects a huge quantity of hot water (the brine from the wells). This brine would be injected back to the reservoir through the precipitation system. During the injection process, the brine releases heat. The pressure and temperature also drop. A huge quantity of energy and exergy is released and this is less favorable for the process thermodynamically. In order to utilize this brine, the development of an energy conversion system that can handle the heat, pressure and temperature is an opportunity to gain more power output and increase the efficiency of the existing plant system.

In this work, we observed several designs, which applied optimization of the operating condition to the existing single-flash plant. The expansions of the design which are proposed are double-flash, single-flash combined with binary and double-flash combined with binary. The performance of this system, furthermore, was evaluated using the Second Law of Thermodynamics based on energy and exergy analysis. Engineering Equation Solver (EES) was employed to solve the mathematical equations.

### 2. EXISTING SINGLE-FLASH GEOTHERMAL POWER PLANT

The existing single-flash geothermal power plant is modeled using a simplified design that assumes a single production well and one separator as shown in Figure 1. Geothermal fluid is produced from the reservoir through the well and is separated into steam and brine in the separator. The separator pressure in each wellpad is different since the fluid enthalpy from different well productions is also different. However in our model, we use 10.5 bars for the separator pressure and the enthalpy fluid is set to 1379 kJ/kg, which is based on tracer flow testing (TFT). In the separation process, steam and liquid are separated.



**Figure 1. Schematic diagram of single-flash geothermal power plant.**

The separated steam flows into the power house, while the brine flows to the flasher. The brine then flows into the canal, and is finally trapped in the pond for several hours before being pumped into the reinjection wells. The steam flows into the turbine and generates electricity. The exhaust steam from the turbine flows to the condenser at a pressure of 0.07 bar and temperature of 38°C.

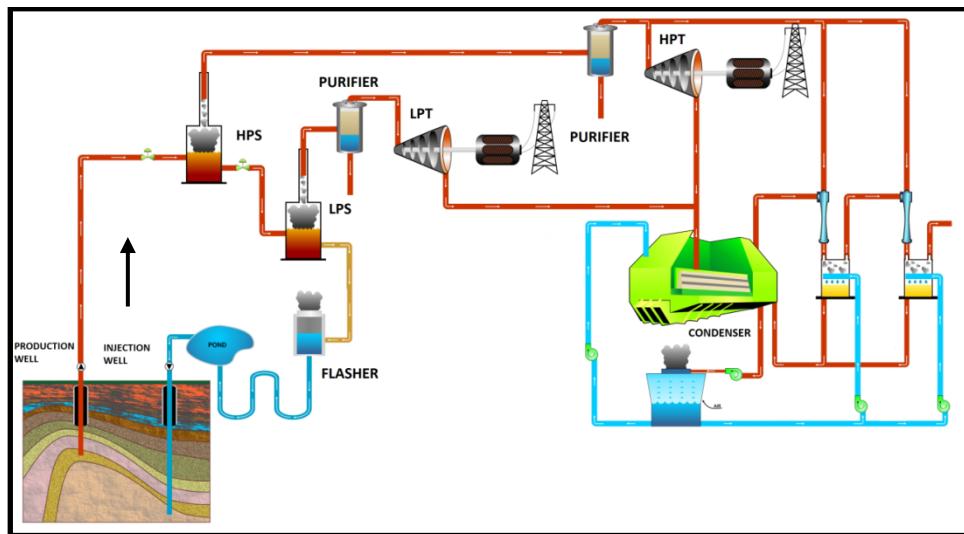
### 3. IMPROVEMENT DESIGN

#### 3.1 Operating Condition Optimization

The geothermal power plant can be optimized by controlling the separator pressure. In the initial condition when the plant was constructed, the separator pressure worked at its optimized value. However over time, the enthalpy of geothermal fluid changed and affected the dryness fraction. This influenced the mass flow rate of steam sent to the turbine.

#### 3.2 The double-flash system designed

Modifying the power plant into double-flash adds the low pressure separator (LPS). In the existing single-flash plant, brine flows to the flasher from the separator/High pressure separator (HPS) and continues to the precipitation system of canal and pond. However, in the new system with double-flash, brine flows to the LPS where it is flashed for a second time. Steam will be delivered to another low pressure turbine (LPT) and brine flows into the condenser and precipitation system.



**Figure 2. A proposed design of bottoming double-flash system**

#### 3.3 Combine single-flash and binary power plant model

The single-flash combined with a binary system that was proposed in this study uses the brine discharged from the separator. The simplified model of wellpad and binary can be seen in Figure 3. In the existing of plant in

Figure , after the brine leaves the separator, it flows to a flasher and terminates in ponds. In the binary model, the flasher has been removed and the brine flows directly to a heat exchanger system. The silica precipitation system is also removed from this model since the thermodynamic calculation is not included.

The process of the binary cycle starts from the discharged brine that heats and evaporates the pressurized working fluid in the pre-heater and evaporator. The saturated vapor of working fluid then flows to the turbine and produces electricity. The working fluid is then condensed in a condenser and flows back to the pre-heater using specific pressure controlling by the pump.

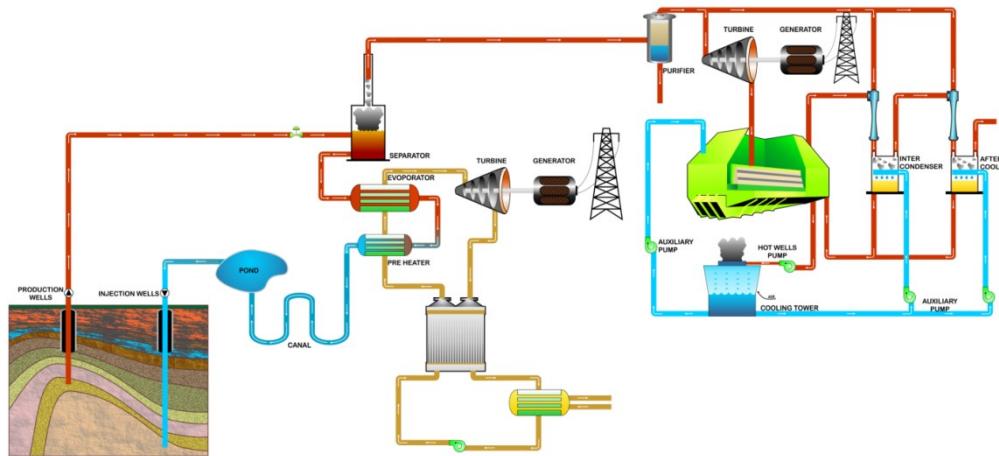
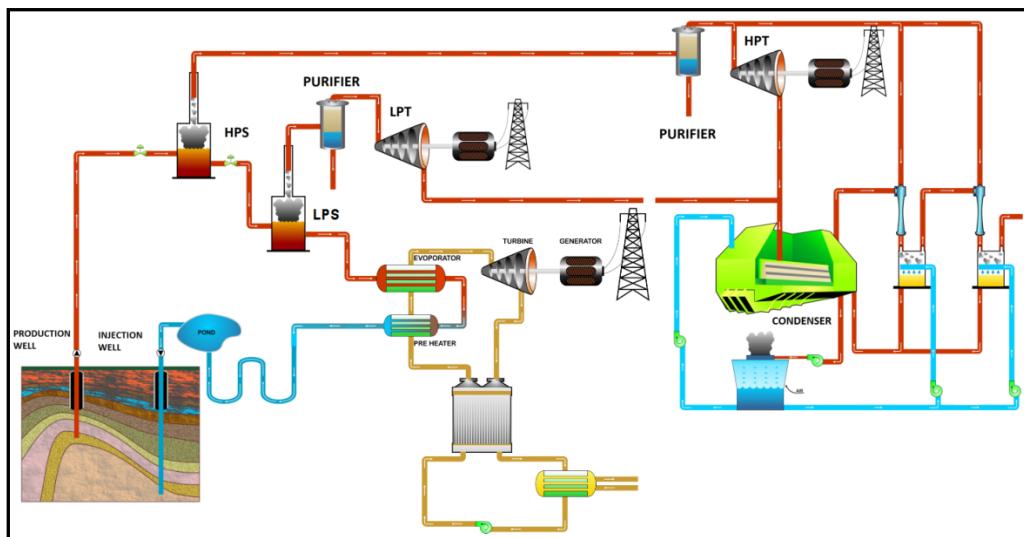


Figure 3. A simplified diagram of single-flash combined with binary power plant.

### 3.4 Combine double-flash and binary power plant model

If we take a look at the double-flash system in Figure 2, there is some waste brine that is disposed of to the reinjection system. Here, energy from the brine will be transformed into power using the binary system similar to Figure 3 above. The heat exchangers receive brine from the low pressure separator and heat the working fluid in the binary cycle.



**Figure 0.** A simplified diagram of double-flash combined with binary power plant.

## 4. METHOD

There are two methods for this calculation using thermodynamic and exergy analysis. The thermodynamic analyzing includes all the process from single-flash, double-flash, and combined binary.

#### 4.1 Thermodynamic calculation in the power plant

There are several main processes in the power plant that were investigated. For single-flash and double-flash the separation process in separator, expansion in the turbine, and condensation in the condenser are presented as follows (Dipippo, 2005):

$$X = \frac{h_1 - h_3}{h_2 - h_3} \quad (1)$$

$$\dot{W}_t = \dot{m}_5(h_5 - h_6)\eta_t \quad (2)$$

$$\eta_t = \frac{(h_5 - h_6)}{h_5 - h_{6s}} \quad (3)$$

$$\dot{m}_{o,ct} = \dot{m}_{o,t} \left( \frac{h_{out,t} - h_{out,con}}{cp(T_{in,ct} - T_{out,ct})} \right) \quad (4)$$

where  $X$  is the dryness fraction,  $h_1$  is the fluid enthalpy at inlet separator,  $h_2$  is the enthalpy of steam at the exit separator,  $h_3$  is the enthalpy of brine.  $\dot{W}_t$  is the work output,  $h_5$  is the enthalpy of the turbine inlet and  $h_6$  is enthalpy of the turbine outlet. Since the enthalpy of turbine outlet,  $h_6$ , is unknown, isentropic condition at Eq.(3) is used for calculating  $h_6$ .

The condenser employs equation 4 where  $\dot{m}_{o,ct}$  is the mass flow rate of cooling water needed to condense the steam in the cooling tower,  $\dot{m}_{o,t}$  is the mass flow rate of steam flowing to the condenser from the turbine outlet,  $h_{o,t}$  is the enthalpy of steam flowing to the condenser from the turbine outlet,  $h_{o,con}$  is the enthalpy of condensate water from the condenser outlet flowing to the cooling tower,  $cp$  is the specific heat of water,  $T_{in,ct}$  is the temperature of condensate water flowing to the cooling tower inlet from the condenser outlet,  $T_{out,ct}$  is the temperature of cooling water from the cooling tower outlet

The thermodynamic process in a binary power plant such as those in the evaporator, preheater, turbine and recuperator are presented in Equation 4-11 as follows. The turbine has similar calculation to Eq. 2.

$$\dot{m}_{wf} (h_{in,wf,ev} - h_{out,wf,ev}) = \dot{m}_b (C_b (T_{in,b,ev} - T_{out,b,ev})) \quad (5)$$

$$\dot{m}_{wf} (h_{out,wf,ev} - h_{in,wf,ev}) = \dot{m}_{brine} (C_b (T_{out,b,ev} - T_{out,b,ph})) \quad (6)$$

Where  $\dot{m}_{wf}$  is the mass flow rate of the working fluid,  $\dot{m}_{brine}$  is the mass flow rate of brine,  $h_{out,wf,ev}$  is the enthalpy of the working fluid at the evaporator outlet,  $h_{in,wf,ev}$  is the enthalpy of the working fluid at the evaporator inlet,  $C_b$  is the brine specific heat,  $T_{in,b,ev}$  is the temperature of the brine at the separator outlet/evaporator inlet,  $T_{out,b,ev}$  is the temperature of the brine at the evaporator outlet.  $h_{in,wf,ev}$  is the enthalpy of the working fluid at the evaporator inlet and  $h_{out,wf,ev}$  is the temperature of brine at the evaporator outlet.

In the recuperator Eq. 7,8, there are two sides of stream flow: hot and cold. In the hot-side stream, working fluid flows from the turbine outlet to the inlet of the condenser, while the cold-side stream, working fluid flows from the pump outlet into the preheater inlet. The effectiveness variable is assumed to be 0.7 and there is also no pressure drop in the recuperator. Therefore, the pressure inlet and outlet of the recuperator is equal in any side stream.

$$\epsilon_{rec} = \frac{\dot{m}_{wf} C b_{wf} (T_{out,t} - T_{out,rec})}{\dot{Q}_{max}} \quad (7)$$

$$\epsilon_{rec} = \frac{\dot{m}_{wf} C b_{wf} (T_{in,con} - T_{out,pu})}{\dot{Q}_{max}} \quad (8)$$

where  $T_{out,t}$  is the turbine outlet temperature,  $T_{out,rec}$  is the recuperator outlet temperature,  $T_{in,con}$  is the condenser inlet temperature/recuperator outlet and  $\dot{Q}_{max}$  is the maximum amount of heat the recuperator can transfer. Then, it can be calculated in Equation 9.

$$\dot{Q}_{max} = \dot{m}_{wf} C b_{wf} (T_{out,t} - T_{out,pu}) \quad (9)$$

The working fluid is then condensed in the condenser. There are assumptions in the condenser, such as the pinch point at 10 °C and the delta of the cooling water supplied is at 10 °C. The temperature of the working fluid at the condenser outlet is:

$$T_{out,con} = T_{amb} + \delta_{pinch} + \delta_{cw} \quad (10)$$

where  $T_{out,con}$  is the condenser outlet temperature,  $T_{amb}$  is the ambient temperature in Dieng location,  $\delta_{pinch}$  is the pinch point temperature difference and  $\delta_{cw}$  is the temperature difference of the inlet and outlet cooling water from the cooling system.

After the condensation process has occurred, the working fluid is compressed with specific pressure by the pump. The parasitic load of the pump can be calculated using Equation 14, as follows:

$$\dot{W}_{pu} = h_{out,pu} - h_{in,pu} \quad (11)$$

where  $h_{in,pu}$  is the enthalpy of the working fluid in the pump inlet and  $h_{out,pu}$  is the enthalpy of the working fluid in the pump outlet.

#### 4.2 Exergy analysis

The exergy and energy is based on the first and second law of thermodynamics. Jorgensen stated that the exergy is the maximum amount of entropy-free energy or maximum work, which can be produced upon establishment of equilibrium with the surroundings of the system (Jørgensen and Mejer, 1977). The exergy ( $\dot{E}_i$ ) is expressed in Equation 13, while specific exergy ( $\dot{e}_i$ ) is expressed in Equation 14.

$$\dot{E}_i = \dot{m}_i [(h_i - h_0)T_0(s_i - s_0)] \quad (15)$$

$$\dot{e}_i = (h_i - h_0)T_0(s_i - s_0) \quad (16)$$

where  $\dot{E}_i$  is exergy,  $\dot{m}_i$  is mass flow rate,  $h$  is enthalpy,  $h_0$  is the enthalpy of the dead state,  $T_0$  is the temperature of dead state,  $s$  is entropy and  $s_0$  is the entropy of the dead state. Subscript i denotes stream i.

## 5. RESULT AND DISCUSSION

### 5.1 Single-Flash

Table 1 presents the important parameters of the states of the power plant: the enthalpy, pressure, entropy, mass flow rate, energy, and exergy. The quality of the steam at state 1 is calculated to be 0.317. The reference conditions used for exergy analysis are state 0, with 18°C and 0.78 bar for the atmospheric temperature and pressure, respectively. The cooling tower employs air in state 20 to decrease its temperature. This table is used to create a Grassmann diagram of the overall exergy flow. The mass flow rate of discharge fluid from reservoir at point 1 is calculated based on mass flow rate of steam inlet the turbine. This mass flow rate of steam is provided from the data plant.

**Table 1 Important parameters for the major stages of a single-flash power plant**

State i	Enthalpy	Entropy	Pressure	Temp.	Mass flow	Energy	Exergy
	(kJ/kg)	s(kJ/kg K)	P(bar)	(°C)	Kg/s	kW	kW
0	75.54	0.78	0.2676			18	
1	1380	3.313	10.5	187	158.6	206869	66204
2	2780	6.569	10.5	182	48	129792	41727
3	768.4	2.151	10.29	181.2	0.01798	12.46	2.60
4	2779	6.576	10.29	181.2	47.98	129707	41578
5	2779	6.576	10.29	181.2	44.48	120237	38542
6	2174	7.000	0.07	38	44.48	93337	6150
7	134	0.464		32	4599	269052	5938
8	113.2	0.395	1.42	27	4321	162921	2740
9	1429	4.670			1	1497	85.16
10	2779	6.576	10.29	181.2	1	4000	1282
11	2779	6.576	10.29	181.2	2	5470	1754
12	2201	5.761			3	5496	1367
13	167.5	0.572		40	97.44	8961	315.7
14	113.3	0.395	2.1	27	96.31	3640	149.7
15	1709	5.463	1		1	2376	182.2
16	2332	6.111			3	7846	1936
17	167.5	0.572		40	140.8	12951	456.3
18	135.5	0.468	2.26	27	137.8	8264	216.5
19	1473	4.747	0.7806	40	0.4893	683.8	112.1

20	75.54	0.268	0.7806	18	2	0	0
21	117.6	0.410	0.7806	37.04	0.042	1.75	0.030
22	772.3	2.159	10.5	182	110.6	77077	16143
23	2664	7.442	0.7806	92.85	18.64	286372	9316
24	388.9	1.225	0.7806	92.85	91.98	34668	3174

The Grassmann diagram the can be constructed based on Table 1 as shown in Figure 5. The total exergy input to the system is estimated to be 66,204 kW, which arrives from the reservoir in the form of a steam-water mixture, and produces a power output of 24,300 kW.

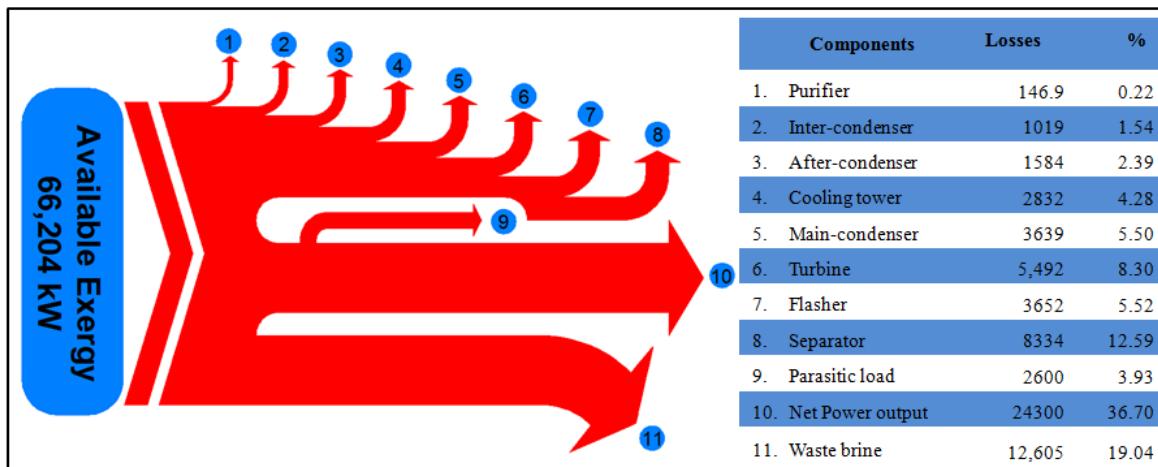


Figure 5. Grassmann diagram for exergy flow and losses in power plant system.

## 5.2 Improvement by operating condition optimization

The power plant produces 24,300 kW of electricity with a separator pressure of 10.5 bars. To maximize the generated power output, the separator pressure is an excellent candidate for a parameter that can be adjusted in sensitivity analyses.

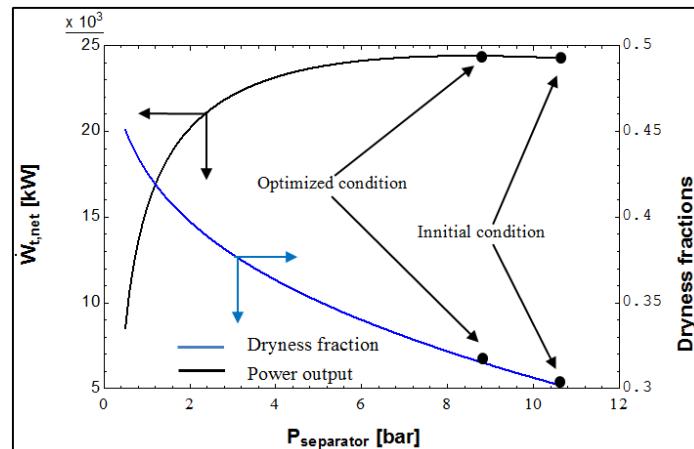
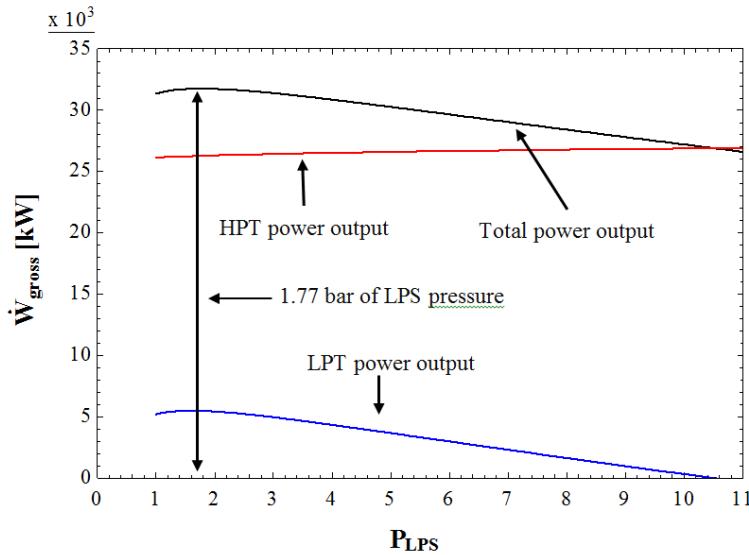


Figure 6. Sensitivity analysis of separator pressure to net power output and dryness fractions.

The results of this analysis are shown in Figure 6. It is found that if the separator pressure decreases, the power output increases a little, though the improvement can be neglected because it significantly small. It is found that a separator pressure of 8.6 bars produces the maximum net electricity of 24,409 kW. Therefore, setting this parameter to that pressure produces 109 kW of additional electricity. The blue curve that represents how the dryness fraction increases as separator pressure is decreased, indicating that more steam can be delivered to the turbine. At 8.6 bars of separator pressure, when the power plant has its highest power output, the dryness fraction appears at 31.69%.

### 5.3 Double-flash

In double-flash, prior to calculating the proposed system, the pressure of LPS should be determined in order to maximize the output power. The sensitivity analyses of this pressure parameter indicates the suitable pressure producing the highest power generation as shown in Figure 7.

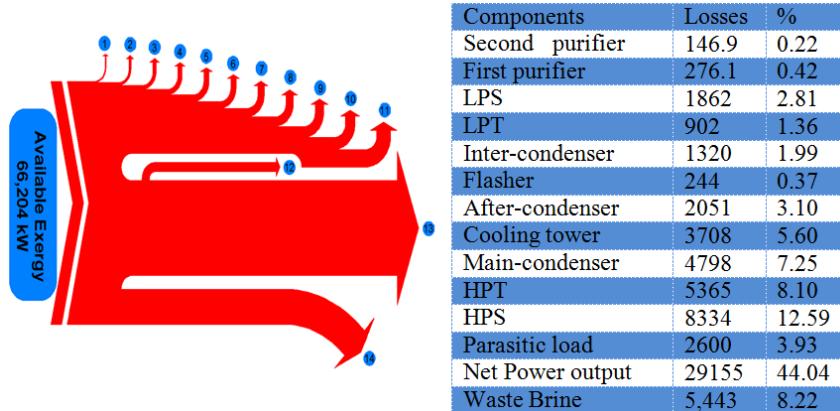


**Figure 7. Adjusting LPS pressure to maximize power generation**

The gross work output of the HPT is 26,275 kW with 10.5 bar pressure as shown in the red line. It is a slight decrease because the ejectors needed more mass flow to extract more NCG. The gross work output of the LPT changes once the pressure of LPS is adjusted. Once the LPS pressure is increased, the gross work output of the LPT also increases. However, after specific pressure of 1.77 bar, it starts to decline. The value of 1.77 bar is the optimum pressure for LPS to gain the highest power output from the LPT at 5,480 kW. The total gross output that appears in the blue line has a similar trend with the gross output of the LPT.

The work output is calculated based on the mass flow rate of steam and the change in enthalpy of steam in the turbine. Once the pressure of LPS is changed, the mass flow rate and delta enthalpy also changes. Increasing the LPS pressure changes the enthalpy of steam and brine flowing out from the separator. This change influences the dryness fraction, which controls the mass flow rate of both steam and brine.

After the LPS pressure is determined, the evaluation of a double-flash power plant is calculated using a thermodynamic analysis and the result can be seen on the Grassman diagram in Figure 8.

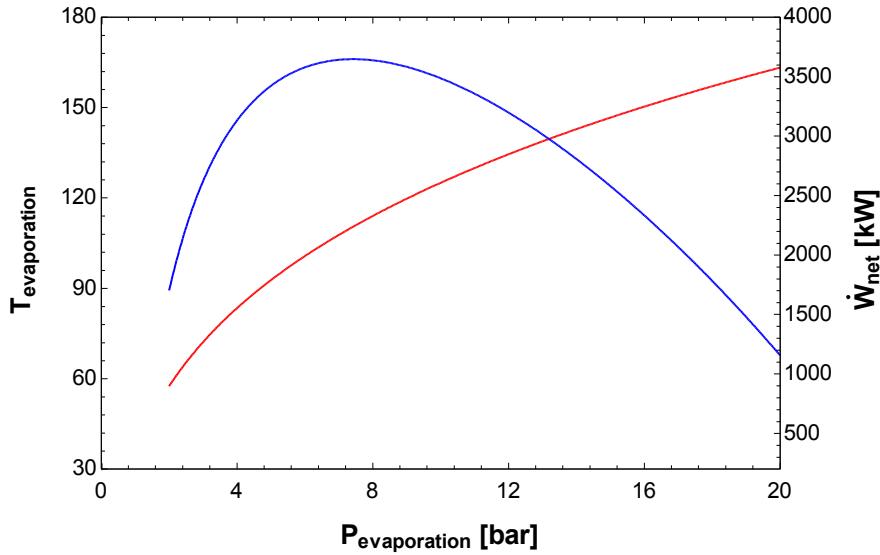


**Figure 8. Grassman diagram for exergy flow of the double-flash geothermal power plant proposed.**

In the double-flash Grassman diagram, additional components such as LPS, the second purifier and the HPT exist at the plant. The available exergy from resources is constant at 66,204 kW. We also assume that the parasitic load is the same as the existing single-flash power plant at 2,600 kW. The important point for the double-flash geothermal power plant is that the net power output is enhanced by 4,855 kW and the total net power output is now 29,155 kW, which means it occupies 44.04 % of total available exergy. In double-flash, the power output of the HPT decreases in the event that the pressure on HPS is kept at 10.5 bar. This is because the two steam ejectors need more steam to extract NCG gas from condenser. Therefore, the steam flows to the HPT decrease. Furthermore, the waste brine that flows to the precipitation system decreases to 8.22 % at 5443 kW. The total losses from all of the components such as the first purifier, second purifier, LPS, inter-condenser, after-condenser, flasher, LPS, condenser, cooling tower, HPT and HPS are 43.81% at 29,007 kW.

#### 5.4 Improvement at of single-flash combined with binary

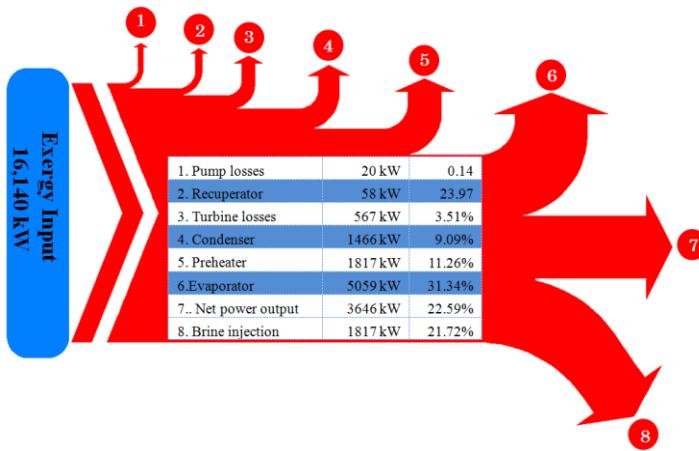
Figure 9 shows the pressure optimization of the pump for single-flash combined with the binary system. The evaporation temperature of the working fluid is shown to have increased once the pressure was altered. The optimized evaporation temperature was found for the maximum net power output. It can be seen that the evaporation temperature of 111.3°C produced the maximum power output of 3,645 kW. To reach that temperature, the pressure pump should be controlled at 7.56 bar.



**Figure 9.** The effect of the evaporation pressure on the net working output (blue color) and evaporation temperature of the working fluid (red color).

Information on properties such as enthalpy, entropy, pressure, temperature, exergy and energy is evaluated in each state for the binary cycle. The mass flow rate of n-pentane as working fluid was calculated based on the energy conservation equation for thermodynamic methods as previously presented, which amounted to 61.18 kg/s. The pressure employed in these states was divided by the highest and lowest pressures in the whole cycle. The high-pressure flow works starting from the pump inlet to the turbine outlet, employing 7.56 bar. Whereas, the low-pressure flow works from the turbine outlet to the inlet of the pump, employing 1.088 bar based on the condensation temperature.

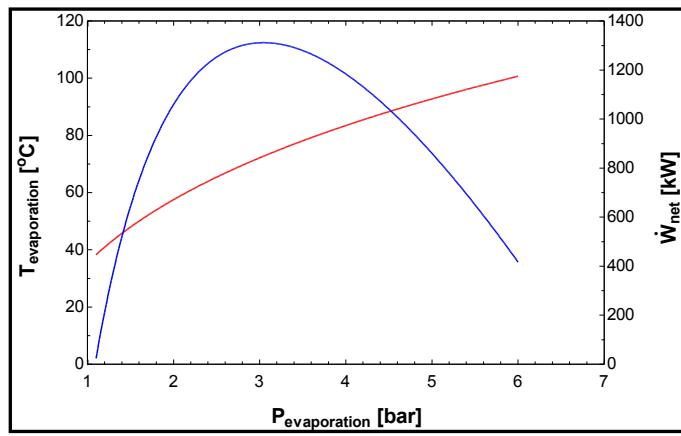
To recognize the stream of exergy in the components of a binary system, a Grassmann diagram was used to illustrate available exergy given to the system, losses, net power output and waste brine, as shown in Figure 10. The available exergy received by the binary system from the separator in the Wellpad was 16,140 kW. This amount of available exergy generated 3,732 kW electricity, representing 21.46% of the total available exergy.



**Figure 10.** Grassmann diagram for binary power plant system

#### 5.5 Optimization of Double-flash combined with binary

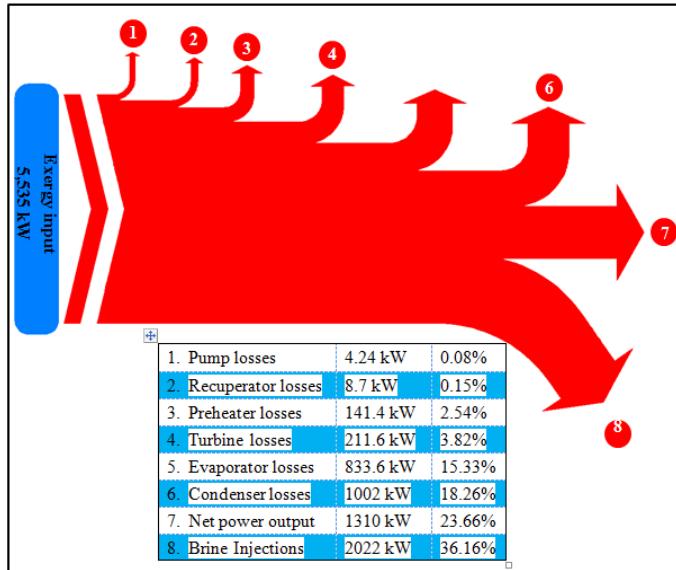
Similarly to a single-flash combined with binary system, in double-flash, first the potency of the system is calculated and the optimization of pump pressure is determined. It is also desirable to obtain the optimized condition in the highest working output of the system. As we have seen in Figure 11 the trend of net work output and evaporation temperature is similar to those for the single-flash combined with a binary system. However, the optimized point of a double-flash combined with a binary system has distinct differences. For working output, the optimized pressure with the highest working output is a pressure of 3 bars with 1,310 kW. The temperature of evaporation at the optimized condition is 72.97 °C.



**Figure 11.**The effect of the evaporation pressure on the net work output (blue color) and evaporation temperature of the working fluid (red color).

The Grassmann for double-flash combined with the binary described in Figure 12. The amount of available exergy received by the binary system from the separator in is 5,059 kW. This amount of available exergy generated 1,310 kW of net electricity, representing 23.66% of the total available exergy.

Another stream, waste brine, disposed 2,022 kW of exergy to the injection system. This was the largest exergy stream, representing 36.16% of the total available exergy. Other exergy streams found were made up of losses from the pump: 4.24 kW (0.08%), the recuperator: 8.7 kW (0.15%), the turbine: 211.6 kW (3.82%), the condenser: 1,002 kW (18.26%), the preheater: 141.4 kW (2.54%) and the evaporator losses: 833.6 kW (15.33%).



**Figure 12.** Grassmann diagram for a double flash system combined with a binary cycle.

##### 5.6 Performance improvement of all models

Three cases for unit expansion in the existing single-flash Dieng geothermal power plant have been evaluated using the thermodynamic method. The potential expansions of the unit, including double-flash; single-flash combined with binary; and double-flash combined with binary are presented with the plant's current performance.

The information from the binary system only is also presented in Table 2 to evaluate the plant's current performance.

**Table 2** Performance evaluation of three cases power plant

Parameter	Existing Single-flash	Double-flash	Single-flash Binary	Double-flash Binary
Net power output (kW)	24,300	29,155	27,947	30,466
First law efficiency (%)	11.75	14.09	13.51	14.73
Second law efficiency (%)	36.7	44.04	42.31	46.02

The net power output increases from 24,300 kW (in existing single-flash) to 29,155 kW for the double-flash, 27,947 kW for the single-flash combined with the binary and 30,466 kW for a double-flash combined with binary system.

## 6. CONCLUSIONS

Performance improvement of a single-flash geothermal power plant applying three cases of design has been evaluated using the thermodynamic method. The three cases include double-flash, single-flash combined with binary and double-flash combined with binary. An analysis has been carried out to identify the best system in terms of the thermodynamic method, and the conclusion can be summarized as follows:

1. The existing single-flash geothermal plant produces 24,300 kW with first and second law efficiency at 11.75% and 36.7%, respectively.
2. In the optimization by setting the separator pressure at 8.6 bars, it is found that the plant produces a net power output of 24,409 kW. Therefore, controlling this parameter with that pressure produces 109 kW of additional electricity.
3. The waste brine which flows out from the plant was calculated at 16,140 kW for 110.6 kg/s at a temperature of 182°C. This is a huge amount of energy, which can be utilized with other expansion units.
4. The first design employs the double-flash plant, and it produces 29,155 kW net power output. First and second law efficiency increase to be 14.09% and 44.04% respectively.
5. Using a binary cycle for the expansion system produced 27,947 kW. This is lower than the double-flash design. The first and second law efficiencies were 13.51% and 42.31% respectively.
6. After the double-flash there is 5,537 kW of available exergy from brine and the temperature was 116.4°C. If more expansion applied to this double-flash using a binary cycle, the new power output that can be reached is 30,466 kW. This is the highest net power output from all the expansion designs.

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