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EXERGY ANALYSIS AND OPTIMIZATION OF KAMOJANG GEOTHERMAL POWER PLANT DRY STEAM TYPE CAPACITY 55 MW

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ABSTRACT

This study aims to analyze the exergy efficiency and irreversibility of the Kamojang Unit 2 Geothermal Power Plant (GPP) in Indonesia using an exergy analysis method. The results reveal that the turbine exhibits the highest exergy loss of 11,512 kW with an exergy efficiency of 82.78%. The condenser records the second-largest exergy loss of 9,875 kW, while the inter condenser and after condenser show the lowest exergy efficiencies at 22.6% and 38.55%, respectively. The overall system exergy efficiency is 65.3%, producing 63,261 kW of electricity from an input exergy of 96,764 kW. Optimization was conducted by varying the turbine inlet pressure from 4.5 to 6.5 bar, with the optimal pressure determined to be 4.5 bar, resulting in the highest exergy efficiency and the lowest irreversibility. This research provides valuable insights for enhancing geothermal power plant efficiency through thermodynamic parameter optimization.

KEYWORDS *exergy, geothermal power plant, irreversibility, optimization*

INTRODUCTION

The world's increasing energy needs amid the limitations of fossil resources and their environmental impact encourage the search for sustainable and environmentally friendly alternative energy sources. Renewable energy such as geothermal offers great potential to meet the ever-increasing energy needs while contributing to climate change mitigation. Sustainability of energy supply is one of the advantages of geothermal energy compared to other renewable energy sources (Piipponen et al., 2022; Rink et al., 2022). In addition, the amount of unwanted gases produced in these power plants is very small (Dashti & Gholami Korzani, 2021).

Indonesia has the second largest geothermal potential in the world, which is around 40% of the global geothermal potential (Pambudi & Ulfa, 2024). This is due to its location in the Ring of Fire, part of a series of volcanoes and seismic activity.

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Based on data from the Ministry of Energy and Natural Resources (EMR), Indonesia's total geothermal energy potential is estimated to reach 23.7 GW. The government targets geothermal development for the next decade (2020-2030) to reach 8,007.7 MW. This means that, with the current capacity of 2,130.7 MW, around 177 geothermal development projects are still needed to reach a total of 5,877 MW by 2030 (Susilo, 2023).

One way to help this is the development of geothermal power plants through production optimization, because when compared to other thermal power plants such as coal, oil, nuclear and natural gas, geothermal power plants tend to have low efficiency. This can be achieved through the use of allergy analysis, which uses the 2nd law of thermodynamics to investigate irverability processes through the measurement of changes in energy quality. Allergy analysis can not only determine the size, location and cause of irreversibility in the generation system, but also determine the efficiency of the components of the generation system (Biasi et al., 2019).

Energy analysis and power plant allergy have been widely carried out by several researchers. Elwardany et al. conducted an energy analysis and eczygosity efficiency at a Gas and Steam Power Plant in Assiut, Egypt in 2023 (Elwardany et al., 2023). The study revealed that the overall energy efficiency was 34.6% and the echerence efficiency was 33.5%, emphasizing the need to optimize the combustion process and HRSG efficiency to improve performance and sustainability. Meanwhile, Qurrohman et al. conducted an energy and allergy analysis at the Dieng PLTP in 2021. The results show that the largest allergic loss is found in turbines of 50 Mw (Qurrahman et al., 2021).

In the production process, optimization techniques are required to achieve optimal electricity production. In the production process, thermodynamic variables such as temperature and pressure contribute to the optimization process. To improve the energy efficiency of geothermal power plants, researchers have optimized in this regard. Aloanis et al. conducted an analysis of the exterioration and optimization of the power generation by varying the separator pressure at the Lahendong PLTP Unit 2 (Aloanis et al., 2021). The optimum separator pressure is at 10.4025 bar with a power of 13,025.4804 kW. Meanwhile, Rudiyanto et al. optimized a single flash cycle geothermal power plant in Dieng (Rudiyanto et al., 2021)v. By varying the pressure entering the turbine, the optimal pressure is at 5.5 bar.

Another research conducted by Rudiyanto et al. in different locations, in Kamojang Unit 4, Indonesia, by conducting an allergic analysis and optimizing the pressure of the well head and turbine. The optimal wellhead pressure is at 11.98 bar and 10.023 bar at the turbine with an overall efficiency of 51.22% (Rudiyanto et al., 2023). In the same area, in Kamojang, precisely in Unit 3, Wicaksono et al. optimized the vacuum pressure of the main condenser using an allergy analysis. The optimum vacuum pressure is at 0.1 bar with an ecclesiastical efficiency of 57.42% and an output power of 54,738 kW (Wicaksono et al., 2020).

With this background, this study aims to analyze the allergy and irreversibility of the Kamojang Unit 2 Geothermal Power Plant in Indonesia. In this study, the efficiency and magnitude as well as the location of irreversibility in the overall system are determined. The results obtained are used to optimize the system, which can improve the efficiency of the excision. Actual data is collected during plant operation. This data is then used in mathematical models and simulations, which are carried out using Engineering Equation Solver (EES).

Kamojang Geothermal Power Plant

Kamojang is one of the geothermal power plants located in Ds. Laksana, Kec. Ibun, Bandung Regency, West Java which is + 17 km Northwest of Garut or + 42 km Southeast of Bandung, and is located at an altitude of 1640 to 1750 m above sea level. The Kamojang Unit 2 Geothermal Power Plant is managed by PT. PLN Indonesia Power UBP Kamojang which is engaged in electric power generation and power plant operation and maintenance services. The Kamojang Unit 2 geothermal power plant operated in early 1987 with an installed capacity of 55 MW.

In Figure 1. showing a schematic diagram of the Kamojang Geothermal Power Plant. To prevent steam fluctuations, which directly affect electricity production, the generating unit is equipped with Steam Receiver Headers (SRH). The SRH is connected to a vent valve system, which discharges excess steam that enters the plant. The steam then enters the separator, which uses centrifugal force to remove debris and other substances from the vapor. This function is different from the single flash technology used to separate brine from steam.

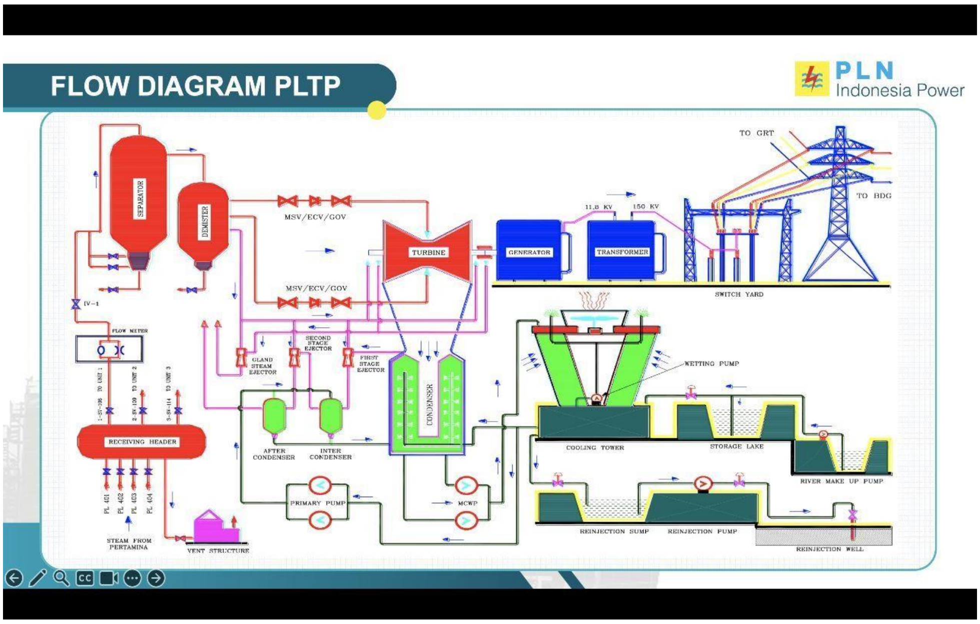


Figure 1. Diagram Scheme of PLTP Kamojang

After that, the steam goes to the demister to make sure the steam is dry. Then the moisture content will be discharged into the flash tank and the steam will proceed to the system. The steam is then divided into main steam stream and auxiliary steam. The main steam flows to the turbine through the Left-Hand (LH) pipe and the Right-Hand (RH) pipe. Each of these pipes is equipped with a Main

Stop Valve (MSV) that functions as a safety valve in the event of a problematic or shut-off unit and a regulating valve that controls the rate of steam flow to maintain the speed of the turbine. This turbine produces steam at an inlet pressure of 5.8 bar abs and an outlet pressure of 0.12 bar abs on average for all three units. The turbine is coupled with a generator and the speed is set to 3,000 rpm for synchronization purposes to the frequency of the Java-Bali interconnection network 50 Hz. The generator produces 11.8 kV and 3,000 A; Through a step-up transformer, this voltage will be raised to a grid voltage of 150 kV.

The exhaust steam is condensed inside the condenser with cooling water from the cooling tower. The condenser has a pressure that is regulated in vacuum conditions due to the Gas Removing System (GRS), cooling water temperature and flow rate. The condensate in the condenser hot well will be pumped by the Main Cooling Water Pump (MCWP) to the cooling tower. The condensate that has been cooled inside the cooling tower flows back by gravity and vacuum pressure to the condenser as cooling water.

In the case of unit termination, the cooling tower gets its water supply from a river water pump that stores water temporarily in the storage lake. A portion of the cooling water from the cooling tower flows into the reinjection tank which in time will be sent to the reinjection well by the reinjection pump. Since 2008, PT. PLN Indonesia Power no longer uses the reinjection pump mechanism because the pressure can be replaced by gravity

RESEARCH METHOD

System Description

In Figure 2. There are 20 states that indicate the flow of steam from the plant. State 1 is the vapor containing water (2 phases) from the SRH towards the separator. State 2 is a separate steam generated from the separator to the demister with a decrease in the moisture content in the vapor. States 3 and 4 (i.e. dry steam from the waterless demister) will enter the steam turbine. State 5 is the steam produced from the expansion of the turbine towards the condenser, which is converted into a liquid phase. State 6 is condensed water in the condenser towards the MCWP. State 7 water pumped by MCWP to the cooling tower to lower the temperature. State 8 is the result of cooling in the cooling tower that flows to the condenser and primary pump. In state 9, that is, the cooling water flows into the condenser. State 10 is the non-condensable gas (NCG) towards the 1st ejector which will pump condensation through the main condenser. States 11 and 12 are the parts of the vapor that come from the demister going into the 1st ejector and 2nd ejector. In state 13 it is a mixture of steam and NCG enters the inter condenser. State 14 is the result of condensation in the inter condenser flowing into the condenser.

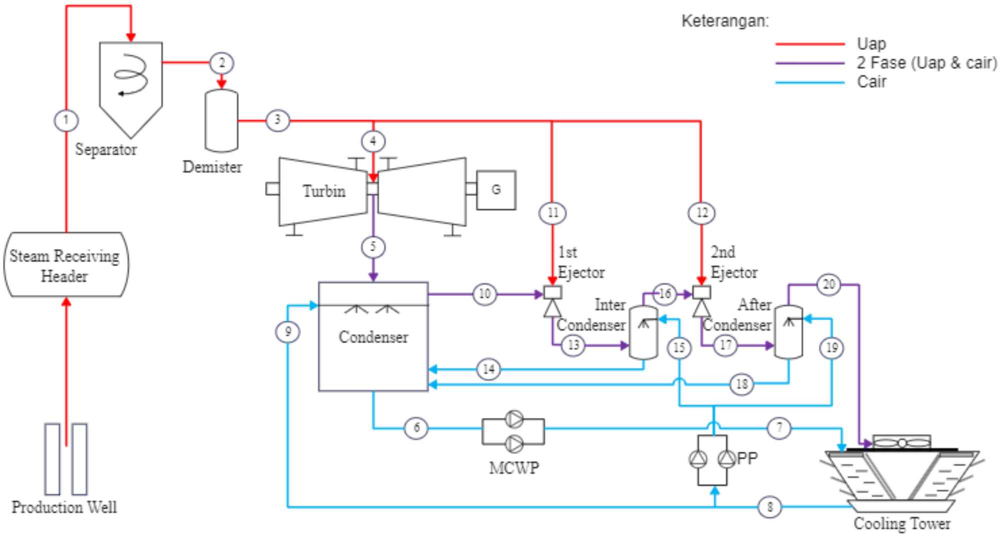


Figure 2. Kamojang PLTP Unit 2 Scheme

State 15 is the result of the cooling process in the cooling tower, which flows into the inter-condenser to help the condensation process. State 16 is the remains of non-condensable gases resulting from condensation in the main condenser and inter condenser that will be sucked in by the 2nd ejector. State 17 is a mixture of steam and NCG enters the after condenser. State 18 is the result of condensation in the after condenser flows into the condenser, while state 19 cools the water from the cooling tower to the after condenser. State 20 is a portion of the vapor that cannot be condensed in a condenser discharged into the atmosphere through a cooling tower.

Allergy Analysis

Allergy analysis is a method that can reveal both the quality and amount of heat loss as well as the location of energy degradation (measuring and identifying the causes of energy degradation) (Moran et al., 2010).

$$\dot{E}_i = \dot{m}_i\big((h_i - h_0) - T_0(s_i - s_0)\big) \quad (1)$$

Where:

$\dot{E}$ = Laju eksergi (kW)
$\dot{m}$ = Mass flow rate (kg/s)
h = Entalpi (kJ/kg)
T = Temperatur (K)
s = Entropi (kJ/kg. K)
i = Menunjukkan titik keadaan
0 = Keadaan lingkungan

To perform an allergy analysis on a system, it is important to understand the equilibrium of the exterior, which indicates that the change in the eczema in the system during the process is equal to the total amount of eczema sent through the system boundary and the eczema destroyed due to the irreversibility of the system (Bejan, 2016).

$$\Delta\dot{E}_{sistem} = \dot{E}_{input} - \dot{E}_{output} - \dot{E}_{destroyed} \quad (2)$$

After that, to calculate the value of the exergiation loss of each component using the following equation:

$$\dot{E}_{loss} = \dot{E}_{input} - \dot{E}_{output} \quad (3)$$

Then to evaluate the performance of power plant components using an allergy analysis, the formula based on the efficiency of the allergy is expressed in equation (4). It can be applied across systems or component efficiencies.

$$\eta = \frac{\dot{E}_{out}}{\dot{E}_{in}} \quad (4)$$

Where is the total inlet ecrosity from the components of the geothermal power plant system and E ̇_out is the total ecstasy that comes out. $\dot{E}_{in}$

As for the calculation of the overall allergy efficiency, it can be obtained by the equation:

$$\eta_{overall} = \frac{W_{net}}{\dot{E}_{in}} \quad (5)$$

where is the total excess that enters the plant and is the production power by the plant.$\dot{E}_{in} W_{net}$

Allergy to Separators

Based on the analysis of the allergy, the magnitude of the allergy loss or irveriability of the separator can be determined by the difference between the incoming and outgoing allergies, namely:

$$\dot{E}_1 = \dot{E}_2 + I_{sep} \quad (6)$$

Where:

$\dot{E}_1$ = Eksergi pada inlet separator (kW)

$\dot{E}_2$ = Eksergi outlet separator (kW)

I_{sep} = Eksergi *loss* separator (kW)

Separator ecrology efficiency is the comparison of the steam exfaction exiting the separator with the fluid ecraction entering the separator.

$$\eta_{sep} = \frac{\dot{E}_2}{\dot{E}_1} \times 100\% \quad (7)$$

Where:

η_{sep} = Efisiensi eksergi separator (%)

Allergy to Demister

There are two main paths for steam output, namely the main steam that is flowed to the turbine, and the auxiliary steam that acts as a drive for the ejector. The balance of allergy in demister can be determined by the equation:

$$\dot{E}_{in} = \dot{E}_{out} + I_{demister} \quad (8)$$

$$\dot{E}_2 = \dot{E}_3 + I_{demister} \quad (9)$$

Steam dryness at the outlet is a measurement of the performance of the demister, so it can be stated that the main function of the demister is to maximize the amount of dry steam coming out of the outlet.

$$\eta_{demister} = \frac{\dot{E}_3}{\dot{E}_2} \times 100\% \quad (10)$$

Allergy to Turbines

Assuming the process in the turbine is adiabatic and the change in kinetic energy and potential energy is ignored. The maximum possible work will be produced if the turbine operates in an adiabatic and reversible manner, i.e. on isentropics. The efficiency of an isentropic turbine, η_t, is the ratio of actual work to isentropic work, which is as follows (DiPippo, 2012):

$$\eta_t = \frac{h_4 - h_5}{h_4 - h_{5s}} \quad (11)$$

Where:
η_t = Efisiensi isentropik turbin (%)
h_4 = Entalpi masuk turbin (kj/kg)
h_5 = Entalpi keluar turbin (kj/kg)
h_{5s} = Entalpi ideal keluar turbin (kj/kg)

So that the turbine power produced is as follows:

$$W_t = \dot{m}_4(h_4 - h_5) \quad (12)$$

Where:
W_t = kerja turbin (kW)
$\dot{m}_4$ = laju aliran massa uap turbin (kg/s)

The equation of the balance of allergy in the turbine process is:

$$\dot{E}_4 = \dot{E}_5 + W_t + I_t \quad (13)$$

Where:
$\dot{E}_4$ = Eksergi masuk turbin (kW)
$\dot{E}_5$ = Eksergi uap buang turbin (kW)
I_t = Eksergi losses turbin (kj/s)
So the losses are as follows:

$$I_t = \dot{E}_4 - \dot{E}_5 - W_t \quad (14)$$

The goal of this process is to convert as much steam as possible into the turbine into electrical energy. Turbine eczema efficiency is the ratio of the gross power output (electrical energy produced) to the steam eczema used to produce the work (the difference between the steam ecclesiastical inlet and the steam ecclesiastical effervescent at the outlet). Then the efficiency of turbine allergy will be provided by:

$$\eta_{turbin} = \frac{W_t}{\dot{E}_5 - \dot{E}_6} \times 100\% \quad (15)$$

Allergy in Condenser

The ectopic balance of the process in a condenser can be determined by the equation:

$$\dot{E}_{in} = \dot{E}_{out} + I_{cond} \quad (16)$$

$$\dot{E}_5 + \dot{E}_9 + \dot{E}_{14} + \dot{E}_{18} = \dot{E}_6 + \dot{E}_{10} + I_{cond} \quad (17)$$

Where:
$\dot{E}_5$ = Turbine exhaust steam allergy (kW)

$\dot{E}_9$ = Ecstasy of refrigerant water entering the condenser (kW)
$\dot{E}_{14}$ = Condensate exfraction from inter condenser (kW)
$\dot{E}_{18}$ = Condensate ex-contamination from after condenser (kW)
$\dot{E}_6$ = Condensate exfiltration out of the condenser (kW)
$\dot{E}_{10}$ = Allergy from NCG (kW)
I_{cond} = Allergies *Loss* kondensor (kW)

The main function of the condenser is to maximize the exection of the exhaust steam and condense the steam into condensate by using cooling water. So that the efficiency of the exhalation is the ratio of the exhalation obtained by the cooling water to the excise lost by the exhaust steam.

$$\eta_{cond} = \frac{\dot{m}_9(e_6 - e_9)}{\dot{m}_5(e_5 - e_6)} \times 100\% \qquad (18)$$

Where:
η_{cond} = Condenser ecclesiastical efficiency (%)
$\dot{m}_9$ = Cooling water mass flow rate (kW)
e_6 = Ecorge per unit mass of condensate (kW)
e_9 = Eclysis per unit of cooling water mass (kW)
$\dot{m}_5$ = Flow rate of turbine exhaust steam mass (kW)
e_5 = Ecclesiastical per unit mass of turbine exhaust steam (kW)

Allergies in *the Inter Condenser* and *After Condenser*

The equilibrium of the exterioration is expressed in the equation below:

$$\dot{E}_{in} = \dot{E}_{out} + I_{inter\text{-}after} \qquad (19)$$

The inter *condenser input allergy* is the sum of the mixture of the motive vapor and NCG (13) and the cooling water (15). The ectopic output is the amount of condensate excise that will be flowed back into the condenser (14) and the NCG vapor mixture that will be extracted by *the 2nd ejector* (16). Meanwhile, the input ecrosity of the *after condenser* is the sum of the mixture of motive vapor and NCG (17) and cooling water (19). The ectopic output is the amount of condensate that will be flowed back into the condenser (18) and the NCG that will be discharged into the atmosphere through *the cooling tower* (20).

The efficiency of the *inter-after condenser* ectopic is equal to the ratio of ectopic obtained by the cooling water to the ectopic loss of NCG.

$$\eta = \frac{\dot{m}_{CW}\left(e_{inter-after} - e_{CW}\right)}{\dot{m}_{NCG}\left(e_{NCG} - e_{inter-after}\right)} \qquad (20)$$

RESULT AND DISCUSSION

Allergy Analysis

The calculation of the exclusivity value in PLTP is carried out for each component and state defined in figure 2. The data used comes from the logsheet of PT. PLN Indonesia Power UBP Kamojang Unit 2, which includes data on pressure, temperature, and mass flow rate in each state, with a generation capacity of 55 MW. The environment of the Kamojang Unit 2 PLTP is considered to be a very large simple compressible system modeled as a thermal reservoir with constant temperature ("T" _"0") and pressure ("P" _"0").

Table 1. Operational Data of Each State

State	***Stream***		**P**	**T**	**ṁ**	**h**	**s**	**Exexhibition**
	From	*to*	bar	℃	kg/s	kJ/kg	kJ/kg.K	Kw
0	*Environment*		0,85	18		75,62	0,267	96764
1	*Steam Header*	*Separator*	6,5	166,24	2770	6,756	95537	95537
2	*Separator*	*Demister*	6	164,09	2769	6,786	94764	94764
3	*Demister*	*Turbines and Ejectors*	5,7	162	2766	6,799	92395	92395
4	*Demister*	*Turbine*	5,7	162	2766	6,799	25531	25531
5	*Turbine*	*Condenser*	0,129	55,67	2283	7,104	22904	22904
6	*Kondensor*	*MCWP*	0,129	51,25	213	0,715	24356	24356
7	*MCWP*	*Cooling Tower*	2,9	51,3	215	0,720	3715	3715
8	*Cooling Tower*	*Condenser and Primary Pump*	1	30,8	129,2	0,447	3529	3529
9	*Cooling Tower*	*Kondensor*	1	30,8	129,2	0,447	56,95	56,95
10	*Kondensor*	*1st Ejector*	0,129	30	2593	8,06	1431	1431
11	*Demister*	*1st Ejector*	5,65	156,56	2754	6,779	1280	1280
12	*Demister*	*2nd Ejector*	5,7	157,47	2755	6,771	1494	1494
13	*1st Ejector*	*Inter Condenser*	3,81	141,9	2736	6,912	821,4	821,4
14	*Inter Condenser*	*Kondensor*	0,382	54,83	313	1,013	2875	2875
15	*Primary Pump*	*Inter Condenser*	2,9	30,181	556,5	1,66	26,82	26,82
16	*Inter Condenser*	*2nd Ejector*	0,382	48,4	2634	7,685	1289	1289
17	*2nd Ejector*	*After Condenser*	4,837	150,59	2747	6,832	1340	1340
18	*After Condenser*	*Kondensor*	0,754	48,33	385	1,215	2875	2875
19	*Primary Pump*	*After Condenser*	2,9	30,181	556,5	1,66	2875	25,29
20	*After Condenser*	*Cooling Tower*	0,754	58,28	2663	7,454	7,454	95537

Table 1 displays the resulting data from the summary of parameters and the calculation of the rate of allergy of each state or state. These parameters include mass flow rate, pressure, temperature, enthalpy, entropy, and ectopic rate in each state using equation 1. The environmental conditions (0) are a temperature of 18°C and an air pressure of 0.85 bar at an altitude of 850 meters above sea level and enthalpy and entropy values of 75.62 kJ/kg and 0.267 kJ/kg°C, respectively.

Based on the results of the calculation of table 1, the enthalpy, entropy, and rate of exhalpy values are used for the analysis of exhalpy loss or irreversibility and exhalation efficiency in each component. The results of the calculation of allergy loss and efficiency of allergy can be summarized in table 2.

Table 2. Calculation of Allergy Loss and Allergy Efficiency of Each Component

Component	Inlet Allergy Rate (kW)	Exit Excess Rate (kW)	Eksergi *Castle* (kW)	Excess Efficiency (%)
Separator	96764	95537	1227	98,73
Demister	95537	94764	772,8	99,19
Turbine	92239	80883	11512	82,78
Condenser	31221,4	22960,95	9875	70,45
Inter Condenser	4369	848,22	5765	22,6
After Condenser	5677	1365,29	4351	38,55

In Table 2, it can be seen that the largest value of allergic loss is found in the turbine, which is 11,512 kW with an ecclesiastical efficiency of 82.78%, with an exfoliation rate of 92,239 kW and an ecclesiastical rate of 80,883 kW from the reverse turbine, where the power generated by the turbine ("W" _"gross") is 55,352 kW or 55.35 MW. The presence of silica in steam increases the irreversibility of the turbine, which reduces the efficiency of the turbine and reduces the capacity of the generator to generate electricity (Sundari et al., 2022). The condenser experienced the second largest eskergi loss after the turbine, which was 9,875 kW. The condenser itself is divided into 3 components, namely the condenser itself or the main condenser, inter condenser, and after condenser. The inter condenser and after condenser are the components that have the smallest exeration efficiency compared to the other components, namely 22.6% for the inter condenser and 38.55% for the after condenser.

Energy Conversion Process

The energy conversion process at the Kamojang Unit 2 PLTP is shown through the T-s diagram in figure 3. Point 1 explains that steam enters the turbine at a pressure of 5.77 bar and at a temperature of 162 ° C. Steam expansion occurs in the turbine to produce work and the pressure drops to 0.129 bar at the turbine outlet (point 2). The process from point 1 to point 2 also saw an increase in entropy from 2766 kJ/kg.° C to 2283 kJ/kg.° C. The process from point 2 to 3 shows the process of vapor condensation, which is to change the fluid from the vapor phase to the liquid phase, which occurs in the condenser.

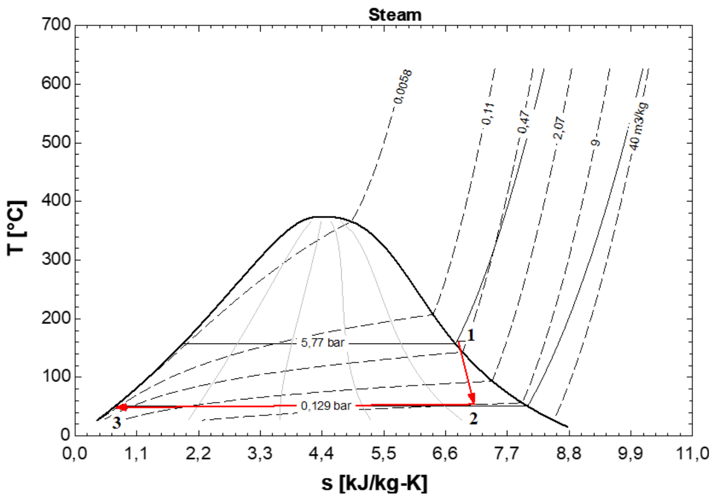


Figure 3. Diagram T-s

Diagram Grassman

Figure 4. is a grassman diagram that provides a detailed description of the flow of aggression in the Kamojang Unit 2 PLTP. The number of eczerates available and entering the system is 96,764 kW. Not all available allergies can be converted into electrical energy due to the irreversibility of each component. The value of the efficiency of the entire system is 65.3% and as much as 63,261 kW can be converted into electricity.

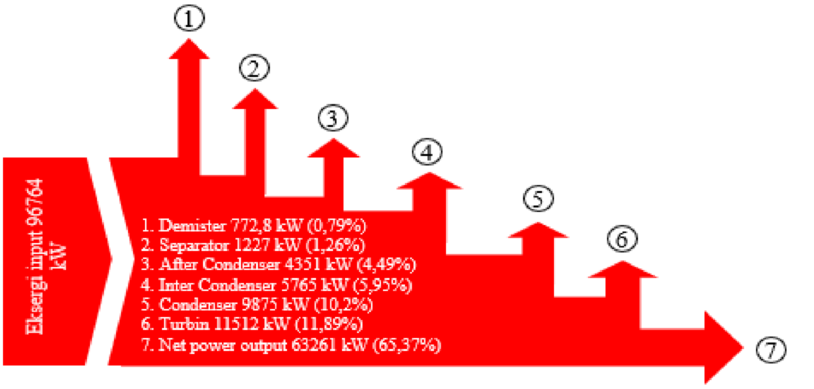


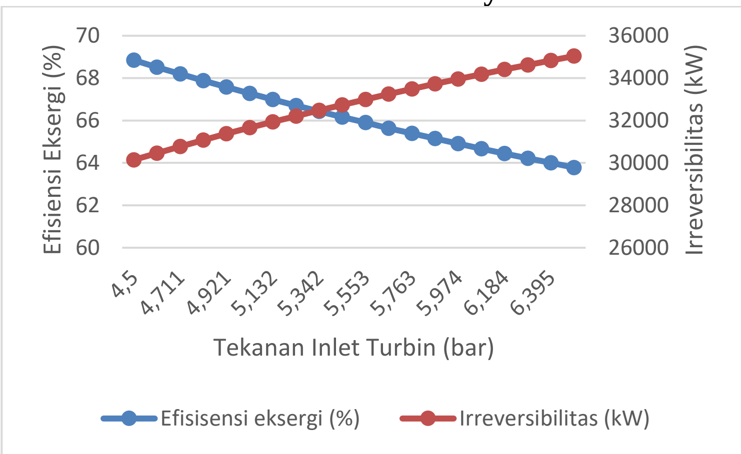
Figure 4. Grassman Diagram of the Eruption Flow of PLTP Kamojang Unit 2

Allergy Optimization of PLTP Kamojang Unit 2

Optimization is carried out with the intention of increasing the efficiency of the entire allergy. Optimization efforts on turbines need to be carried out as components with the greatest allergic loss or irreversibility. Optimization is carried out by varying the pressure entering the turbine, which is 4.5-6.5 bar based on the design data.

It can be seen in figure 5. It is a graph of the relationship between turbine inlet pressure and overall irreversibility and ectopic efficiency. The results showed that at a pressure of 4.5 bar it resulted in the highest efficiency of the exergation and the lowest irreversibility. The graph also shows that the higher the pressure that enters the turbine, the greater the efficiency of the excursion decreases and the irreversibility increases.

Figure 5. Graph of the Effect of Turbine Inlet Pressure on Excess Efficiency and Irreversibility



CONCLUSION

This study analyzed the exergy efficiency and irreversibility of the Kamojang Unit 2 Geothermal Power Plant (GPP) in Indonesia using an exergy analysis approach. The results show that the turbine is the component with the highest exergy loss, amounting to 11,512 kW, with an exergy efficiency of 82.78%. The condenser has the second-largest exergy loss at 9,875 kW. The inter condenser and after condenser have the lowest exergy efficiencies among all components, at 22.6% and 38.55%, respectively. The overall system exergy efficiency is 65.3%, with 63,261 kW of electricity generated from a total input exergy of 96,764 kW. Optimization was performed by varying the turbine inlet pressure between 4.5 and 6.5 bar. The results indicate that a turbine inlet pressure of 4.5 bar achieved the highest exergy efficiency and the lowest irreversibility. This research significantly contributes to improving the operational efficiency of geothermal power plants by optimizing thermodynamic parameters.

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