

Evaluation and Optimization Based on Exergy in Kamojang Geothermal Power Plant Unit 3

Bayu Rudiyanto ^{a,*}, Arief Wicaksono ^b, Miftah Hijriawan ^c

^a Energy Engineering Laboratory, Department of Renewable Energy Engineering, Politeknik Negeri Jember, Jember, 68121, Indonesia

^b Graduate Program of Department of Renewable Energy Engineering, Politeknik Negeri Jember, Jember, 68121, Indonesia

^c Graduate Program of Mechanical Engineering, Universitas Sebelas Maret, Jl. Ir. Sutami 36, Surakarta, 57126, Indonesia

Corresponding author: *bayu_rudiyanto@polije.ac.id

Abstract—The quality of production well from the Kamojang geothermal power plant unit 3 diminishes annually, whereas there has been a substantial rise in the demand for electrical energy in the region. This research focuses on optimizing the vacuum pressure in the main condenser by employing exergy analysis, a methodology grounded in the principles of the second law of thermodynamics. Exergy analysis offers insights into each system component's exergy efficiency and irreversibility. Furthermore, an energy assessment is conducted to offer insights into each component's energy consumption or utilization. Energy and exergy rates are computed for every state and component within the power plant, encompassing the steam receiving header, separator, demister, turbine, main condenser, inter condenser, after condenser, and cooling tower. The exergy analysis findings reveal that the exergy rate derived from the production well amounts to 95327 kW, generating 52882 kW of electricity and producing a system exergy efficiency of 55.47%. The turbine experiences the highest irreversibility, totaling 12874 kW. Adjustments are made to the main condenser vacuum pressure to optimize the system, aiming to identify the optimal setting that maximizes both exergy efficiency and power output. The optimization outcomes indicate that reducing the vacuum pressure in the main condenser leads to enhanced exergy efficiency and increased power output. The optimal vacuum pressure obtained is 0.1 bar, resulting in the highest exergy efficiency and output power of 57.42% and 54738 kW, respectively, with the lowest irreversibility of 32751.07 kW.

Keywords— Exergy; efficiency; irreversibility; main condenser; optimization.

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I. INTRODUCTION

Geothermal energy has great potential because it is environmentally friendly and sustainable. In this case, a geothermal energy development program is needed to optimize production and utilization to overcome the electricity crisis, especially in Indonesia, one of the countries with the largest geothermal potential in the world [1]–[3]. Electricity production from geothermal energy in Indonesia ranks third after the United States and the Philippines, with a total installed energy capacity of 1,197 MW [3]–[5]. Besides, geothermal energy development for electricity generation is projected at 7.2 GW in 2025 and 17.6 GW in 2050 [6], [7]. Currently, the potential for geothermal energy in Indonesia that has been utilized as a new power plant is 1,948.30 MW in 13 geothermal working areas [7]–[9].

In Indonesia, the Kamojang highlands represent one of the geothermal energy production sites, boasting a total

geothermal energy potential of 235 megawatts electric (MWe) [10]–[12]. The Kamojang highlands have a reservoir type dominated by steam with reservoir temperatures ranging from 177–253.4°C, as geothermal power plants in the Kamojang area principally use the direct-dry steam cycle [3]. According to Sharmin [13], a direct-dry steam cycle occurs when the fluid at the wellhead is in the vapor phase so that the steam can be directly channeled to the turbine. The turbine will convert heat energy into mechanical energy and drive a generator to produce electrical energy. Since 1989, PT. Indonesia Power's Kamojang Power Generation and O&M Services Unit (POMU) has operated three generating units consistently delivering 142 megawatts of electricity, which is integrated into the Java-Bali interconnection network for distribution. The steam used to generate the 142 MW of power is supplied by PT. Pertamina Geothermal Energy through its 30 production wells with an average pressure of 6.7–6.8 bar absolute [14]. The power generated to meet the needs in the area has increased quite a bit from year to year.

However, the characteristics of production wells every year have a decrease in the quality produced by the wells, and there tends to be a decrease in steam quality [15]–[17].

Besides the potential decline in steam quality at the Kamojang geothermal power plant, another consequence could be a reduction in the efficiency and overall effectiveness of various components within the power plant. These components, including turbines, generators, condensers, and cooling towers, have operated for 33 years, leading to inefficiencies and losses within the system. This aligns with the principles of the second law of thermodynamics, which asserts that no perfectly efficient energy conversion processes exist. There must be a decrease in the quality of energy in it [18], [19]. Various things can be made to re-evaluate the processes that occur in geothermal power plants and optimize the components in the plant.

The evaluation process in geothermal power plants usually uses a thermodynamic approach, namely energy and exergy analysis. The analysis is carried out by calculating the energy and exergy of each component and determining the amount of exergy destroyed in each component [20]–[22]. Utilizing exergy analysis is a technique that can be employed to optimize the steam turbine cycle. It is also a method of analyzing thermal systems that combines the first and second laws of thermodynamics [5], [20], [23]. This approach enables the determination of losses within a system, their origins, and their specific locations, thereby facilitating enhancements in the system's overall performance or its each component.

Several studies on exergy analysis have been carried out, including Rudiyanto et al. in 2017, who conducted an exergy analysis at the Kamojang geothermal power plant, which provided information on the location and magnitude of exergy losses and the level of process inefficiency in the generating system [24]. The condenser, with its exergy destruction of 180783.2 kW, was the site of the largest exergy destruction, followed by the after condenser and the inter-condenser with 5118.7 kW and 2726.2 kW, while other components, including the Steam Receiving Header (SRH), separator, demister, and turbine, had exergy destruction of 96 kW, 401 kW, 760 kW, and 8025 kW. Rudiyanto et al. then carried out an energy analysis and optimization on a geothermal power plant in Dieng, Indonesia, in 2021. The separator had an exergetic efficiency of 95.22%, the scrubber had a value of 99.94%, the demister had a value of 98.34%, the turbine had an exergetic efficiency of 83.91%, the main condenser had a value of 43%, the inter-condenser had a value of 28.69%, the aftercooler had a value of 27.72%, the cooling tower had a value of 66.36%, and the flasher had a value of 74.21%. However, the optimization findings demonstrate that the turbine's irreversibility increases, and the turbine's exergetic efficiency decreases with higher turbine inlet pressure. The optimal turbine inlet pressure is obtained at a pressure of 5.5 bar, with the maximum pressure varying according to the ambient temperature [20].

Additionally, Rudiyanto et al. returned to improving the Kamojang geothermal power plant in 2023 utilizing the Genetic Algorithm approach on wellhead and turbine inlet pressures with respective constraint values of 11–13 bar at the wellhead and 10–11.5 bar at the turbine inlet. They increased the overall exergy efficiency value of 0.11%, i.e., from 51.11% to 51.22% [3]. In order to improve the system's efficiency in real-time based on shifting conditions, it is important to update related to the most recent analysis of the performance and optimization of processes in geothermal power plants.

Considering the issues above, an energy and exergy analysis at the Kamojang Unit 3 geothermal power plant is required to detect the exergy losses. Furthermore, this serves as a guide for management in determining the system's future upgrade and optimization priorities to minimize losses and improve thermodynamic efficiency.

II. MATERIALS AND METHOD

A. Kamojang Geothermal Power Plant Unit 3

PT. Indonesia Power Kamojang Power Generation and Operating & Maintenance Services Unit (POMU) oversees electricity management in the surrounding area. The company is situated in a hilly terrain 42 kilometers southeast of Bandung, in Laksana Village, Ibum District, Bandung Regency, West Java Province, at an elevation of 1500 meters above sea level. The type of geothermal reservoir located in the Kamojang area is a two-phase reservoir type with steam dominance having a temperature of $\pm 245^{\circ}\text{C}$ [24], [25].

PT. Indonesia Power Kamojang POMU is currently managing 7 units of 375 MW geothermal power plants. Three sub-units operate these plants, specifically the Kamojang geothermal power plant in Bandung Regency. Drajat geothermal power plant (1 Unit) is in Garut Regency, and Gunung Salak geothermal power plant (3 Units) is in Sukabumi Regency [26]. In addition to managing power plants owned by Indonesia Power, the company also manages operating and maintenance (O&M) services owned by the State Electricity Company, namely the Ulumbu geothermal power plant with an installed capacity of 4×2.5 MW [14]. The Kamojang geothermal power plant flow diagram is shown in Figure 1.

The Kamojang geothermal power plant, with a power capacity of 140 MW, requires a steam supply of more than 1000 tons/hour from PT. Pertamina Geothermal Energy is divided into units 1 of 220 tons/hour and 2-3 of 420 tons/hour. A Steam Receiving Header (SRH) component is installed on the generating unit to prevent steam flow fluctuations from affecting the generating unit. The SRH is a pressure vessel with a vent valve system for controlling steam flow and pressure. The vent valve system has 6 normally open valves, which function to remove excess steam that enters the system [3], [8], [24].

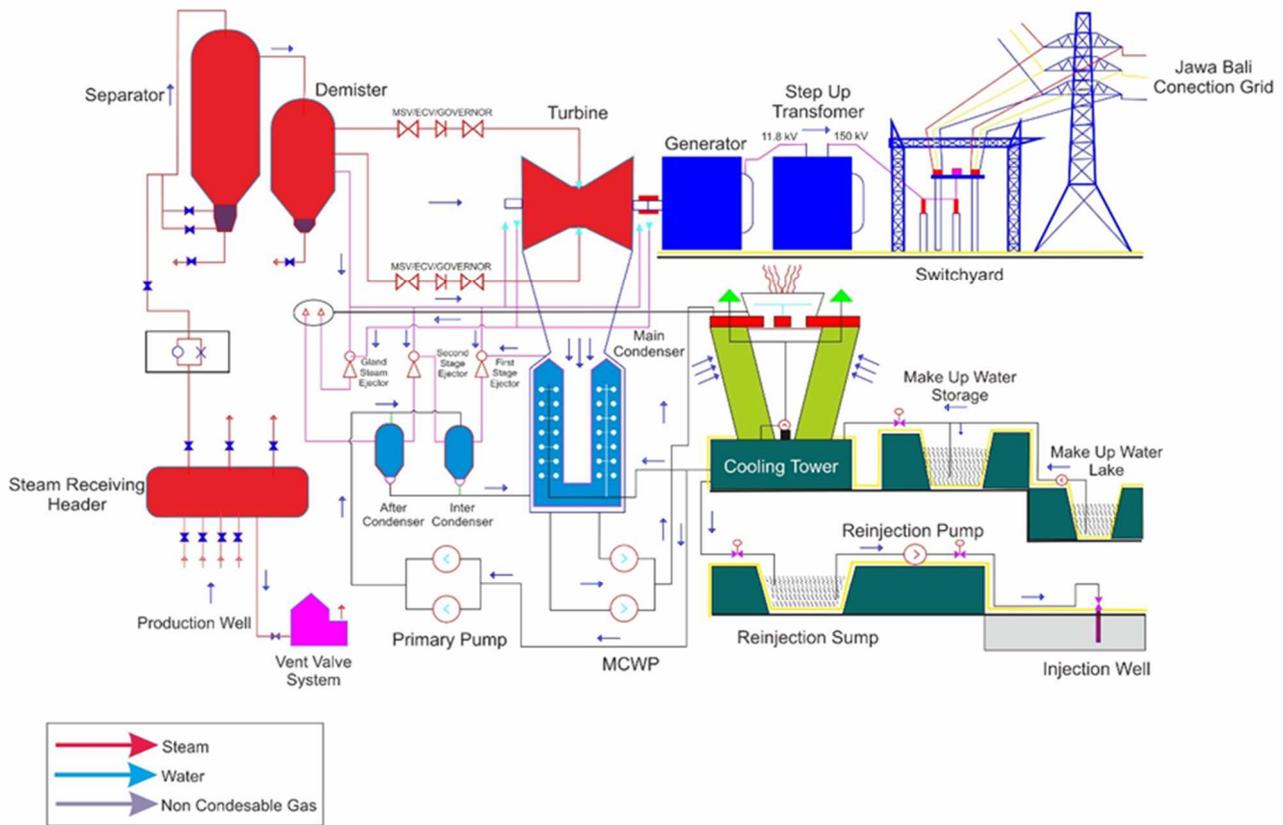


Fig. 1 Schematic diagram of the Kamojang geothermal power plant [14]

B. Schematic and Analysis Study

Exergy analysis used initial data from operating data recorded on the unit 3 log sheet of the Kamojang geothermal power plant. Data from the geothermal power plant's daily operations and production, including temperature, pressure, and steam mass flow rate parameters during the production process and power generation, are gathered. Environmental information for Kamojang includes data on temperature,

pressure, altitude, and humidity. These become the raw data for calculating energy and exergy balances. A mathematical equation for energy and exergy is created using EES software to perform the calculation [27]. Data in the form of tables and diagrams represent the calculation results. By adjusting the vacuum pressure of the main condenser, optimization is carried out based on these findings to enhance the plant's performance. Figure 2 below demonstrates the methodological flow of analysis for this investigation.

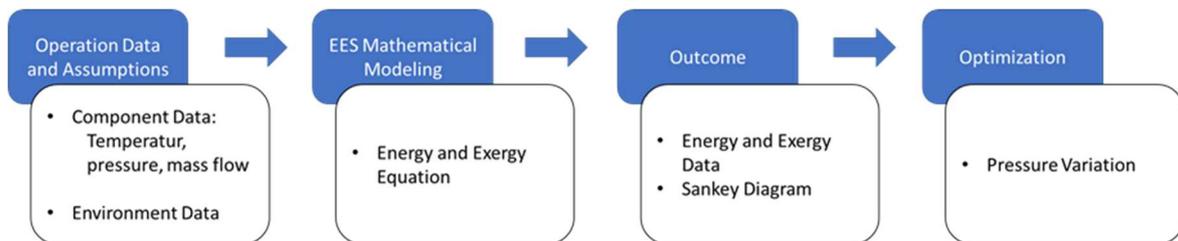


Fig. 2 Research analysis flow

C. Thermodynamic Analysis

Figure 3 shows the schematic for the Kamojang geothermal power plant unit 3 system, which serves as the subject of the

study. The Kamojang geothermal power plant unit 3's operation and production log sheet provided the mass flow rate (\dot{m}), pressure (P), and temperature (T) for each state used in this research.

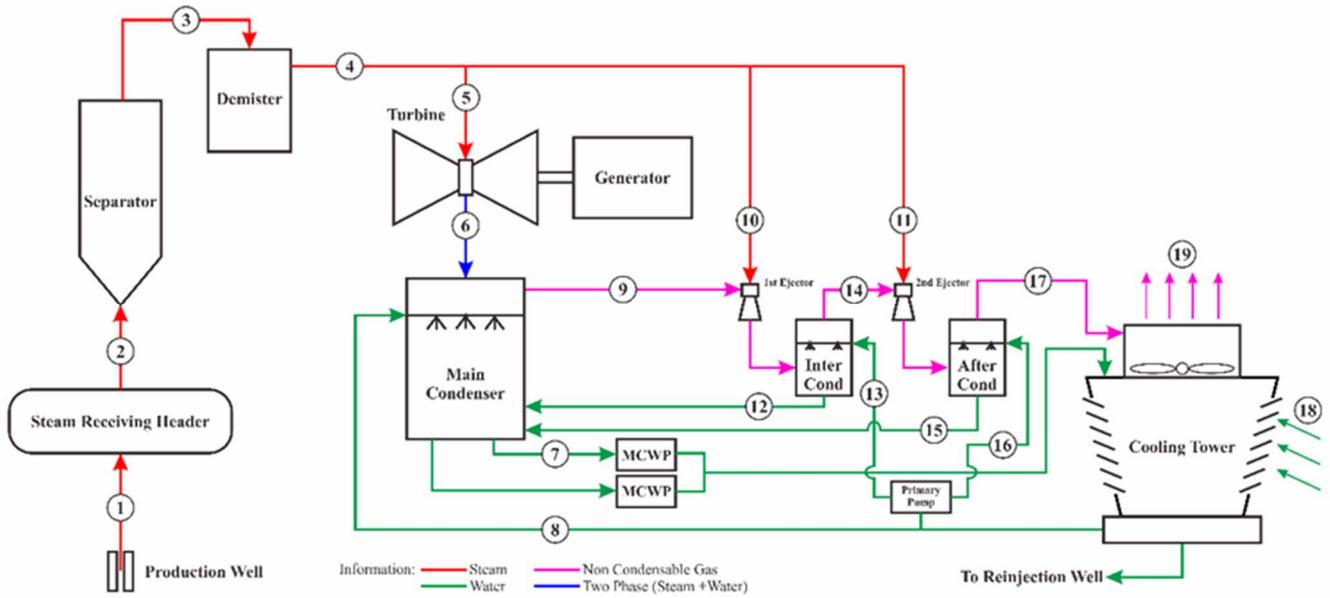


Fig. 3 Scheme of Kamojang Geothermal Power Plant Unit 3

Figure 3 shows the state analyzed in Kamojang geothermal power plant unit 3. Separator, demister, turbine, main condenser, inter-condenser, aftercooler, cooling tower, and flasher are among the Kamojang geothermal power plant's components that have been examined. Energy analysis aims to determine the thermal value of the system in each state. The first law of thermodynamics serves as its foundation. The analysis is presumed to be in a constant state of steady flow. Equations 1 and 2 generally display the energy analysis for each condition as follows:

$$\dot{E}n_{state} = \dot{m} \cdot h_{state} \quad (1)$$

$$\dot{E}n_k = \dot{m} \cdot (h_i - h_0) \quad (2)$$

The heat that enters the system must equal the work generated by the system in the form of power or mechanics, according to the first law of thermodynamics. It can be determined by Equation (3):

$$Q_i - Q_0 = \dot{W}_{output} \quad (3)$$

Furthermore, the thermal efficiency of generators, especially geothermal power plants, can be determined by Equation (4):

$$\eta_{thermal} = \frac{\dot{W}_{output}}{Q_{in}} \times 100\% \quad (4)$$

The system's total exergy (\dot{E}) can be separated into four categories: physical (\dot{E}_{PH}), kinetic (\dot{E}_{KN}), potential (\dot{E}_{PT}), and chemical (\dot{E}_{CH}), assuming no nuclear, magnetic, electrical, or surface tension influences. Equation (5) can be used to express the system's overall exergy rate.

$$\dot{E} = \dot{E}_{PH} + \dot{E}_{KN} + \dot{E}_{PT} + \dot{E}_{CH} \quad (5)$$

The temperature, enthalpy, and entropy of materials or components are always correlated with physical exergy.

Equation (6) gives the exergy rate in a closed system at a specific state:

$$\dot{E} = \dot{m} \cdot (h - h_0) - T_0(s - s_0) \quad (6)$$

Exergy destruction is the loss of work potential due to irreversibility during a process. Exergy destruction is frequently referred to as irreversibility. Equation (7) can be used to calculate each component's irreversibility value's value:

$$\dot{i} = \Sigma \dot{E}_{in} - \Sigma \dot{E}_{out} \quad (7)$$

Exergy efficiency can measure the efficiency of resource use by using exergy. Exergy efficiency can accurately assess an energy system's performance from a thermodynamic perspective. The general Equation for determining the exergy efficiency of components uses Equation (8):

$$\eta_{exergy} = \frac{\Sigma \dot{E}_{out}}{\Sigma \dot{E}_{in}} \times 100\% \quad (8)$$

However, to determine the exergy efficiency of the system using Equation (9):

$$\eta_{system} = \frac{\dot{W}_{output}}{\dot{E}_{in}} \times 100\% \quad (9)$$

III. RESULTS AND DISCUSSION

The operation data of the Kamojang Geothermal Power Plant, including pressure (P), temperature (T), and mass flow rate (\dot{m}), are entered to start the analysis. The daily log sheet served as the data for this analysis. Using the Engineering Equation Solver (EES) software, operational data from the Kamojang geothermal power plant in each state is simulated and calculated to determine each state's enthalpy, entropy, energy rate, and exergy rates. Table 1 displays the simulation and calculation results.

TABLE I
ENERGY AND EXERGY EVALUATION OF THE KAMOJANG GEOTHERMAL POWER PLANT

State	Stream		P	T	m	h	s	Energy	Exergy
	From	To	bar	°C	kg/s	kJ/kg	kJ/kg.K	kW	kW
0	Environment		0.813	17.6		73.87	0.2618		
1	Production well	SRH	6.7	167	118.06	2761	6.723	326018	95632
2	SRH	Separator	6.5	167	118.06	2760	6.733	325864	95127
3	Separator	Demister	6.3	167	118.06	2759	6.744	325705	94605
4	Demister	Turbine & Ejector	5.7	167	118.06	2754	6.777	325189	92931
5	Demister	Turbine	5.7	167	114.49	2754	6.777	315356	90121
6	Turbine	Main Condenser	0.11	51.3	114.49	2280	7.158	261043	23149
7	Main Condenser	Cooling Tower	2.94	48.4	3512.43	202.6	0.683	711743	22375
8	Cooling Tower	Main Condenser	0.813	31.6	3311.11	132.4	0.4585	438273	4369
9	Main Condenser	1 st Stage Ejector	0.41	33	0.24	2339	6.808	561.4	87.1
10	Demister	1 st Stage Ejector	5.7	167	1.79	2754	6.777	4930	1409
11	Demister	2 nd Stage Ejector	5.7	167	1.54	2754	6.777	4242	1212
12	Inter Condenser	Main Condenser	0.813	50	43.62	209.3	0.7037	9131	306.7
13	Primary Pump	Inter Condenser	3.05	31.6	41.67	132.4	0.4585	5516	54.98
14	Inter Condenser	2 nd Stage Ejector	0.41	59.9	0.07	2339	6.808	163.7	25.41
15	After Condenser	Main Condenser	0.81	50	43.43	209.3	0.7037	9091	305.3
16	Primary Pump	After Condenser	3.05	31.6	41.67	132.4	0.4585	5516	54.98
17	After Condenser	Fan Stack CT	0.813	42.6	0.05	2666	7.43	133.3	25.45
18	Environment	Cooling Tower	0.813	17.6	3891	73.87	0.2618	287456	0
19	Cooling Tower	Environment	0.813	34.4	3891.0	144.1	0.4968	560926	7746

A. Energy Analysis of the Kamojang Geothermal Power Plant

Table 1 is used to examine the enthalpy, entropy, energy rate, and exergy rate for each state for each main component of the Kamojang geothermal power plant. The first law of thermodynamics concept regarding energy conservation is used in energy analysis to evaluate the system's performance [28], [29]. Table 2 shows the energy rate values for each component.

TABLE II
ENERGY RATE OF KAMOJANG GEOTHERMAL POWER PLANT COMPONENT

Component	Energy Rate (kW)
Steam Receiving Header	326018
Separator	325864
Demister	325705
Turbine	315438
Main Condenser	718514
Inter Condenser	10879.5
After Condenser	9922
Cooling Tower	999203

The value of the energy rate entering each component is known based on Table 2. The SRH has an energy rate of 326018 kW, the separator has an energy rate of 325864 kW, and the demister has an energy rate of 325705 kW. Due to the pressure drop based on the separation process in the separator,

energy is reduced from the separator to the demister. Without further intervention from outside the system, the steam receiving header, separator, and demister processes run continuously.

The turbine's 315438 kW energy rate runs the generators and produces electricity. According to the calculation, the isentropic turbine work is 67096 kW with an efficiency value of 79.61%, and the actual turbine work has a value of 53416 kW. The main condenser, which has an input energy value of 718514 kW, receives the steam after it has passed through the turbine. The steam from the turbine, which is condensed with cooling water from the cooling tower, is the energy source. The inter condenser has an energy rate of 10879.5 kW, the after condenser has an energy rate of 9922 kW, and the cooling tower has an energy rate of 999203 kW. Calculation results generated a system energy efficiency value of 16.49%.

B. Exergy Analysis of Kamojang Geothermal Power Plant

Table 1 shows the findings of the calculation of the exergy value of each component. An exergy analysis was conducted to figure out the amount, distribution, and source of irreversibility or exergy losses in the key elements of the Kamojang geothermal power plant. This study primarily takes consideration of physical exergy and ignores chemical, potential, and kinetic exergy. According to the calculation results, Table 3 below shows each component's amount of exergy in, exergy out, and irreversibility.

TABLE III
EXERGY RATE IN, EXERGY OUT, AND IRREVERSIBILITY AND EXERGY EFFICIENCY

Component	Exergy in (kW)	Exergy out (kW)	Irreversibility (kW)	Exergy Efficiency (%)
Steam Receiving Header	95327	94821	506	99.47
Separator	94821	94299	522	99.45
Demister	94299	92623	1676	98.22
Turbine	89846	76972	12874	85.67
Main Condenser	28794.4	21862.42	6931.98	75.93
Inter Condenser	1512.12	323.97	1188.15	21.42
After Condenser	1284.97	323.03	961.94	25.14
Cooling Tower	21783	11844	9939	54.37

Based on Table 3 above, the exergy entering the steam receiving header from the production well is 95327 kW, and the exergy leaving is 94821 kW with an irreversibility value of 506 kW and an efficiency of 99.47%. The separator has an inlet exergy of 94821 kW, an outgoing exergy of 94299 kW, and an efficiency of 99.45%. The irreversibility of the separator occurs due to the principle of separation using centrifugal force or cyclone separation, in which steam entering the separator is conditioned to create centrifugal force to create a vortex [30].

The demister has 94299 kW on inlet exergy and 92623 kW on outgoing exergy. A small part of the steam in the demister is used as auxiliary steam in the gas removal system. Hence, the demister efficiency is 98.22%. In the turbine, the exergy values entering and leaving are 89846 kW and 76972 kW, converted into electrical energy of 52882 kW, resulting in the irreversibility value of 12874 kW. The irreversibility is due to the expansion process during which the steam passes through the turbine blades. The irreversibility of the turbine is further impacted by the presence of silica in the steam, which lowers

turbine efficiency and reduces the generator's capabilities to generate electricity [2], [3].

The main condenser, inter condenser, and after condenser are the three parts of the condenser. These components' exergy efficiency is 75.93%, 21.42%, and 25.14%, respectively. The two lowest values of all components are the efficiency values for inter and after the condenser. Exergy entering the main condenser is 28794.4 kW, while exergy leaving is 21862.42 kW. Irreversibility is affected by exhaust steam heat rejection, which is the process of heat loss due to expansion in the turbine. The exergy value entering the cooling tower of 21783 kW with an exergy efficiency value of 55.37%.

By comparing the exergy of the product, the electricity produced, and the exergy entering the system from production wells, it is possible to determine the total exergy efficiency of the Kamojang geothermal power plant system and the exergy efficiency of each component. The findings of the calculations indicate that the system's overall exergy efficiency is 55.47%.

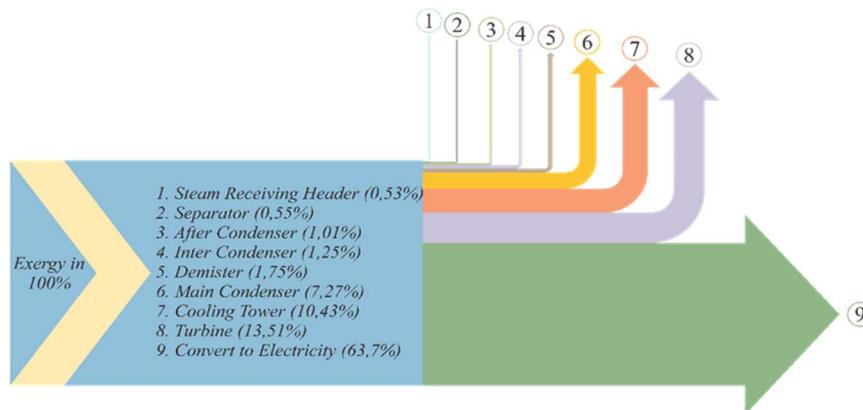


Fig. 4 Sankey diagram of exergy flow of Kamojang geothermal power plant

An overview of the energy efficiency values for each component is shown in the Sankey diagram in Figure 4. The Sankey diagram gives a clearer view of the energy flow at the Kamojang geothermal power plant. The system produces a total exergy rate of 95327 kW. However, not all exergy rates can be transformed into electricity due to exergy destruction caused by the irreversibility of the components in geothermal power plants. The energy lost in the steam receiving header—0.53% or 506 kW—the separator—0.55% or 522 kW—the demister—1.76% or 1676 kW—the turbine—13.51% or 12874 kW—the main condenser—7.27% or 6931.98 kW—the after condenser—1.01% or 961.94 kW—and the cooling tower—10.43% or 9939 kW is shown in Figure 4. 63.7%, or 60727.93 kW, of the total energy can be transformed into electricity.

C. Main Condenser Vacuum Pressure Optimization

As illustrated in Figure 5 below, calculations and simulations were performed to determine the impact of vacuum pressure on the main condenser on the system's energy efficiency and irreversibility. Figure 5 shows that the system's energy efficiency is 57.42% at a main condenser vacuum pressure of 0.1 bar, 56.41% at 0.11 bar, 55.47% at 0.12 bar, 54.61% at 0.13 bar, and 53.8% at 0.14 bar. These

findings show that as the pressure value in the main condenser rises, the system's energy efficiency decreases.

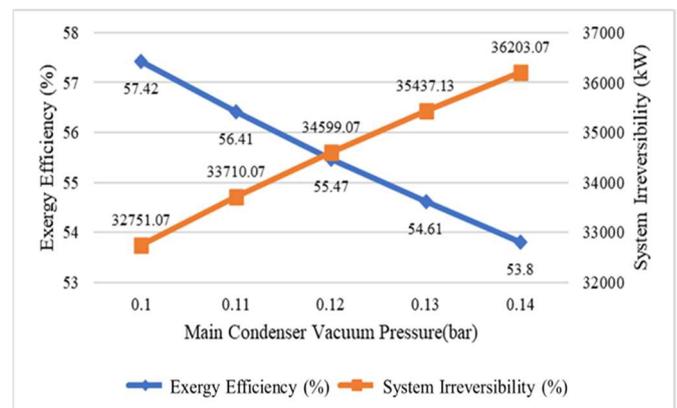


Fig. 5 Graph of main condenser pressure effect on exergy efficiency and irreversibility

At 0.1 bar of pressure, the irreversibility of the system is 32751.07 kW; at 0.11 bar, it is 33710.07 kW; at 0.12 bar, it is 34599.07 kW; at 0.13 bar, it is 35437.13 kW; and at 0.14 bar, it is 36203.07 kW. These findings indicate that the main condenser's higher pressure increases the system's irreversibility. This is negatively correlated to the system's

energy efficiency value. The prior explanation illustrates that the system's energy efficiency value will rise with the main condenser's pressure.

Another parameter that is affected by the vacuum pressure on the main condenser is the power output of the generator. The generator's output power strongly influences the generator's exergy efficiency. In order to figure out how vacuum pressure on the main condenser affects output power at the Kamojang geothermal power plant, Figure 6 below shows the data from the calculations and simulations.

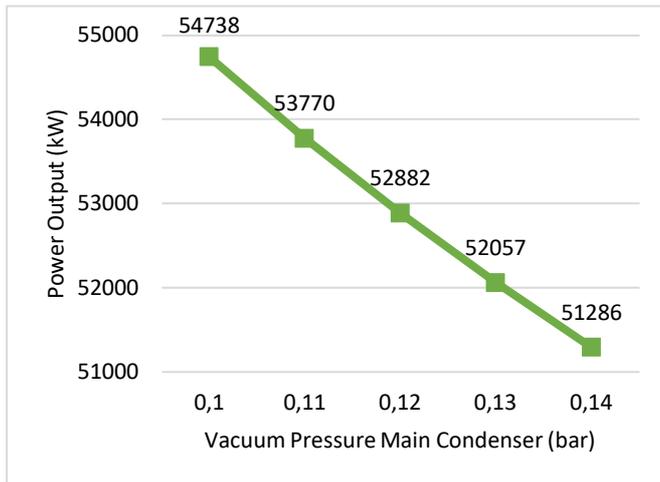


Fig. 6 Effect of main condenser vacuum pressure on output power

Figure 6 shows that the generator output power is based on the effect of vacuum pressure on the main condenser. At a vacuum pressure of 0.1 bar, the generated power is 54738 kW, 0.11 bar is 53770 kW, 0.12 bar is 52882 kW, 0.13 bar is 52057 kW, and at 0.14 bar of 51286 kW. This shows that the greater the pressure in the main condenser, the more the generated power will decrease. This is proportional to the value of the system's exergy efficiency, which also decreases because the exergy efficiency of the system depends on the output power generated by the geothermal power plant.

IV. CONCLUSION

The Kamojang Unit 3 geothermal powerplant production well, which experiences a decline in quality every year, is a challenge amidst the increasing energy needs in the area. To improve the efficiency of the resulting generator in this case, an exergy optimization based on the second law of thermodynamics is carried out. In order to clearly represent the exergy flow in a geothermal power plant, a Sankey diagram is used to analyze the energy and exergy rate of each powerplant component, such as the steam receiving header, separator, demister, turbine, main condenser, inter condenser, after condenser, and cooling tower. Exergy analysis shows that the exergy entering the system from production wells is 95327 kW, the system exergy efficiency value is 55.47%, and the generator output power is 52882 kW. The main condenser is a very important component in a geothermal power plant to maintain optimal turbine performance. Optimization is carried out on the main condenser vacuum pressure by calculation and simulation using EES software. The optimization results show that the most optimal main condenser vacuum pressure value is 0.1 bar with the highest

exergy efficiency of 57.42%, the highest output power of 54738 kW, and the lowest irreversibility of 32751.07 kW.

NOMENCLATURE

\dot{E}	Exergy total	kW
\dot{E}_{PH}	Physical exergy	kW
\dot{E}_{KN}	Kinetic exergy	kW
\dot{E}_{PT}	Potential exergy	kW
\dot{E}_{CH}	Chemical exergy	kW
$\dot{E}n_{state}$	Energy rate state	kW
\dot{m}	Mass flow rate	kg/s
h	Enthalpy	kJ/kg
h_{state}	Enthalpy state	kJ/kg
h_i	Enthalpy input	kJ/kg
h_o	Enthalpy output	kJ/kg
W_{output}	Work	kW
Q_i	Heat input	kJ/s
Q_o	Heat output	kJ/s
$\eta_{thermal}$	Thermal efficiency	%
η_{exergy}	Exergy Efficiency	%
T_o	Surrounding Temperature	K
s	Entropy	kJ/kg.K
s_o	Surrounding entropy	kJ/kg.K
\dot{I}	Irreversibility	kW
\dot{E}_{in}	Exergy input	kW
\dot{E}_{out}	Exergy output	kW
P	Pressure	bar

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