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Research Article

Thermodynamic Performance Assessment and Efficiency Evaluation of a Condensing Steam Turbine in a Geothermal Power Plant: A Case Study of Ulubelu Unit 3, Indonesia

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Abstract

The increasing demand for electricity and the transition toward sustainable energy systems have intensified the utilization of geothermal resources for power generation. Steam turbines are key components in geothermal power plants, and their performance directly influences overall plant efficiency and reliability. This study aimed to evaluate the thermodynamic performance and efficiency of a condensing steam turbine operating at Ulubelu Geothermal Power Plant Unit 3, Indonesia. Operational data were collected from the Central Control Room over a ten-day observation period and analyzed using thermodynamic property calculations based on saturated steam tables. Turbine performance was assessed through isentropic efficiency analysis, while linear regression was employed to examine the relationship between steam mass flow rate and turbine efficiency. The results showed that the turbine achieved an average efficiency of 82.49%, with values ranging from 82.14% to 83.12%. The average isentropic turbine power and plant efficiency were 63.28 MW and 80.84%, respectively. Compared with the design efficiency of 87.06%, the turbine experienced a performance reduction of approximately 4–5%. Overall, the turbine remained within the acceptable industrial efficiency range, indicating stable operation and reliable performance under actual geothermal plant conditions.

Keywords: *Condensing Steam Turbine; Geothermal Power Plant; Isentropic Efficiency; Operational Data; Thermodynamic Performance.*

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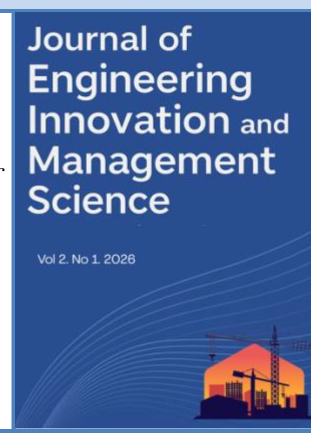

INTRODUCTION

The rapid growth of global energy demand has become one of the most pressing challenges in the modern industrial era. Increasing population, urbanization, industrial expansion, and technological advancement continue to drive higher electricity consumption across the world (Akram et al., 2026; Voumik & Sultana, 2022). Despite ongoing efforts to diversify energy resources, fossil fuels remain the dominant source of electricity generation in many countries. While coal, oil, and natural gas provide reliable and large-scale energy production, their extensive use has resulted in significant environmental consequences. Greenhouse gas emissions from fossil fuel combustion contribute substantially to global warming and climate change, creating concerns regarding long-term environmental sustainability (Bilgili et al., 2024; Singh, 2021). Consequently, governments and energy stakeholders have intensified efforts to accelerate the transition toward cleaner and more sustainable energy systems. According to geothermal energy has emerged as one of the most promising renewable energy sources because of its capability to provide continuous and reliable baseload power (Bertani, 2016). Further emphasized the strategic importance of geothermal resources in supporting sustainable energy development. Unlike intermittent renewable energy sources, geothermal energy can operate continuously regardless of weather conditions. Therefore, geothermal power generation has become increasingly important in achieving global energy security and environmental sustainability (Bertani, 2016; Strušnik, 2022).

Indonesia possesses exceptional geothermal potential due to its geological position within the Pacific Ring of Fire, one of the most volcanically active regions in the world. This unique geographical condition has resulted in extensive geothermal resources distributed across various islands throughout the country. As electricity demand continues to increase alongside economic growth, Indonesia requires substantial additional generation capacity to maintain energy security and support industrial development (Aditya et al., 2025; Erdiwansyah et al., 2021; Kanugrahan et al., 2022). Relying predominantly on fossil-fuel-based power generation may increase environmental pollution and dependence on imported energy resources. Consequently, the development of renewable energy technologies has become a national priority within Indonesia's long-term energy strategy. That Indonesia possesses approximately 40% of the world's geothermal potential, highlighting its strategic role in future energy development (Kabeyi & Jeremiah, 2023). Geothermal power plants offer several advantages, including stable power generation, low greenhouse gas emissions, and reduced land-use requirements compared with many other renewable technologies. These characteristics make geothermal energy particularly suitable for supporting sustainable electricity generation in developing economies. Furthermore, geothermal resources can contribute significantly to reducing carbon emissions while maintaining reliable electricity supply. Therefore, optimizing the operational performance of geothermal power plants is essential for maximizing the benefits of Indonesia's abundant geothermal resources (Bertani, 2016; Kabeyi & Jeremiah, 2023).

In geothermal power plants, thermal energy extracted from geothermal reservoirs is converted into electrical energy through a steam turbine-generator system. Steam produced from geothermal wells is transported through pipelines and processed in separators and scrubbers before entering the turbine. Within the turbine, thermal energy is transformed into mechanical energy, which subsequently drives the electrical generator. Consequently, the steam turbine represents one of the most critical components influencing overall plant efficiency and reliability. Under ideal thermodynamic conditions, steam turbines can achieve efficiencies ranging between 70% and 90% depending on turbine design and operating conditions. However, actual turbine performance often deviates from design specifications due to operational and environmental factors. According to variations in steam pressure, temperature, moisture content, leakage losses, and mechanical degradation can significantly affect turbine efficiency . In geothermal applications, scaling deposits caused by dissolved minerals and non-condensable gases constitute one of the most common operational challenges. These deposits may obstruct steam flow, increase frictional losses, and reduce the effectiveness of energy conversion processes. Disturbances and heat-transfer inefficiencies resulting from deposit accumulation may reduce overall system performance. Therefore, continuous monitoring and thermodynamic performance assessment are essential for identifying efficiency degradation and maintaining optimal turbine operation.

Recent studies on geothermal energy systems have predominantly focused on thermodynamic optimization, exergy assessment, thermoeconomic evaluation, and advanced cycle configurations to enhance energy conversion efficiency and overall system performance. For example, geothermal power generation systems have been investigated through flash-binary cycles, ejector-assisted cycles, and organic Rankine cycle (ORC) configurations, demonstrating significant opportunities for performance improvement through design and operational optimization (Altun & Kilic, 2020; Mondal et al., 2022; Nedaei et al., 2023; Sahana et al., 2023). Other researchers have concentrated on component-level optimization, including geothermal steam turbine seals and blade cascades, as well as the application of digital twin technologies and artificial intelligence to improve turbine operation and predictive maintenance strategies (Chen et al., 2024; Ijaz Malik et al., 2025; Soto et al., 2025). Furthermore, thermodynamic and energy-based analyses have been widely employed to evaluate steam turbine efficiency and identify performance losses under various operating conditions (Medica-Viola et al., 2020; Poljak & Mrzljak, 2023). Despite these advancements, most existing studies rely primarily on simulation models, optimization frameworks, theoretical analyses, or laboratory-scale investigations, whereas studies utilizing actual operational data from commercial-scale geothermal power plants remain relatively scarce. In addition, the influence of steam mass flow rate variations on isentropic turbine efficiency under real operating conditions has not been comprehensively quantified, particularly for condensing steam turbines operating in large-scale geothermal facilities. Consequently, empirical evidence regarding the actual thermodynamic performance of geothermal steam turbines in Indonesian geothermal power plants is still limited. Therefore, this study addresses this gap by evaluating the thermodynamic performance and efficiency of a condensing steam turbine at Ulubelu Geothermal

Power Plant Unit 3 using real operational data and examining the relationship between steam mass flow rate and turbine efficiency under actual field operating conditions.

Therefore, this study aims to evaluate the thermodynamic performance and efficiency of the Fuji Electric condensing steam turbine operating at PT Pertamina Geothermal Energy (PGE) Tbk Ulubelu Unit 3 using actual operational data collected during plant operation. The study employs thermodynamic property analysis to determine turbine performance indicators, including isentropic turbine power, plant efficiency, and turbine efficiency. In addition, regression analysis is applied to investigate the relationship between steam mass flow rate and turbine efficiency under real operating conditions. Unlike many previous studies that primarily rely on simulation-based approaches, this research utilizes field-operational data obtained directly from a commercial-scale geothermal power plant. The study seeks to provide empirical evidence regarding the actual performance characteristics of geothermal steam turbines operating under industrial conditions. The findings are expected to improve understanding of efficiency degradation mechanisms associated with long-term turbine operation and operational variability. Furthermore, the results may assist plant operators in identifying opportunities for operational optimization and preventive maintenance. The study also contributes to the limited body of literature concerning geothermal turbine performance evaluation in Indonesia. By bridging the gap between theoretical performance predictions and actual operational behavior, the research provides practical insights for enhancing geothermal power plant reliability. Ultimately, the findings are expected to support the sustainable and efficient utilization of geothermal resources for electricity generation.

METHODS

This research employed a field–based engineering analysis approach using operational data obtained during an internship program at the geothermal power plant. The study focused on evaluating the performance of the steam turbine in a geothermal power plant using thermodynamic analysis and actual operational data. Data collection and analysis were conducted through several stages, including field observation, literature study, interviews with plant operators, operational data acquisition, thermodynamic calculation, and performance evaluation.

Data Collection Procedure

Field observation was carried out directly at PT Pertamina Geothermal Energy Tbk Unit 3 and Unit 4 Area Ulubelu to understand the overall geothermal power generation process and the operation of the steam turbine system. Interviews with engineers and operators were conducted to obtain technical clarification regarding turbine operation and monitoring parameters. In addition, operational data were collected from the Central Control Room (CCR) log sheets, including turbine inlet temperature, turbine outlet temperature, generator actual power, and steam mass flow rate. These parameters are essential for determining turbine thermodynamic performance.

Data Processing and Thermodynamic Analysis

The turbine efficiency evaluation was conducted using thermodynamic property analysis based on the saturated water temperature table (Thermodynamic Table A4)[6]. The calculation process began with determining the thermodynamic properties of steam at turbine inlet conditions.

The enthalpy and entropy at turbine inlet were calculated using Equations (1) and (2):

$$h_1 = h_f + x_1(h_g + h_f) \tag{1}$$

$$s_1 = s_f + x_1(s_g + s_f) \tag{2}$$

Equations (1) and (2) are used to determine the thermodynamic state of steam entering the turbine based on the steam quality and saturated water properties[6].

Next, the steam quality at turbine outlet under isentropic conditions was determined using Equation (3):

$$x_2 = \frac{s_1 + s_f}{s_g - s_f} \tag{3}$$

After obtaining the steam quality at turbine outlet, the isentropic outlet enthalpy was calculated using Equation (4):

$$h_{2s} = h_f + x_2(h_g - h_f) \tag{4}$$

The isentropic turbine power was then calculated using Equation (5):

$$W_{is} = \dot{m}(h_1 - h_{2s}) \tag{5}$$

Equation (5) represents the ideal turbine power assuming no internal losses occur during expansion[6].

The plant efficiency was calculated using Equation (6):

$$= \frac{W_{actual}}{W_{is}} \times 100\% \tag{6}$$

Finally, the turbine efficiency was determined using Equation (7)[6]:

$$\eta_{turbine} = \frac{W_{actual}}{\eta_{gen\times} W_{is}} \tag{7}$$

Equation (7) represents the final performance indicator used to evaluate turbine performance under actual operating conditions.

Explanation of Calculation Flow

Equation (1) and Equation (2) are used to determine the thermodynamic state of steam at the turbine inlet. These parameters are crucial because the inlet state determines the maximum available energy that can be converted into mechanical power. Equation (3) is used to determine the steam quality at turbine outlet assuming an isentropic expansion process. This step represents the ideal expansion condition of steam inside the turbine. Equation (4) is used to determine the ideal outlet enthalpy, which represents the theoretical minimum energy remaining in steam after expansion. Equation (5) calculates the isentropic turbine power, representing the maximum theoretical power that can be produced by the turbine. Equation (6) evaluates the overall plant efficiency by comparing actual generator power with the theoretical turbine power. Equation (7) determines the actual turbine efficiency by incorporating generator efficiency into the calculation, resulting in the final turbine performance value.

Description of Symbols

h_1	: Enthalpy at turbine inlet	(kJ/kg)
h_{2s}	: Isentropic enthalpy at turbine outlet	(kJ/kg)
h_f	: Saturated liquid enthalpy	(kJ/kg)
h_g	: Saturated vapor enthalpy	(kJ/kg)
s_1	: Entropy at turbine inlet	(kJ/kg·K)
s_f	: Saturated liquid entropy	(kJ/kg·K)
s_g	: Saturated vapor entropy	(kJ/kg·K)
x_1	: Steam quality at turbine inlet	(-)
x_2	: Steam quality at turbine outlet	(-)
$\dot{m}$	: Steam mass flow rate	(kg/s)
W_{is}	: Isentropic turbine power	(kW)
W_{actual}	: Actual generator power	(kW)
η_{plant}	: Plant efficiency	(%)
$\eta_{turbine}$	: Turbine efficiency	(%)
η_{gen}	: Generator efficiency	(%)

Performance Evaluation

After calculating turbine efficiency for all observation data, statistical and regression analyses were performed to evaluate the relationship between steam mass flow rate and turbine efficiency. The analysis aimed to identify performance trends, efficiency fluctuations, and operational factors influencing turbine performance.

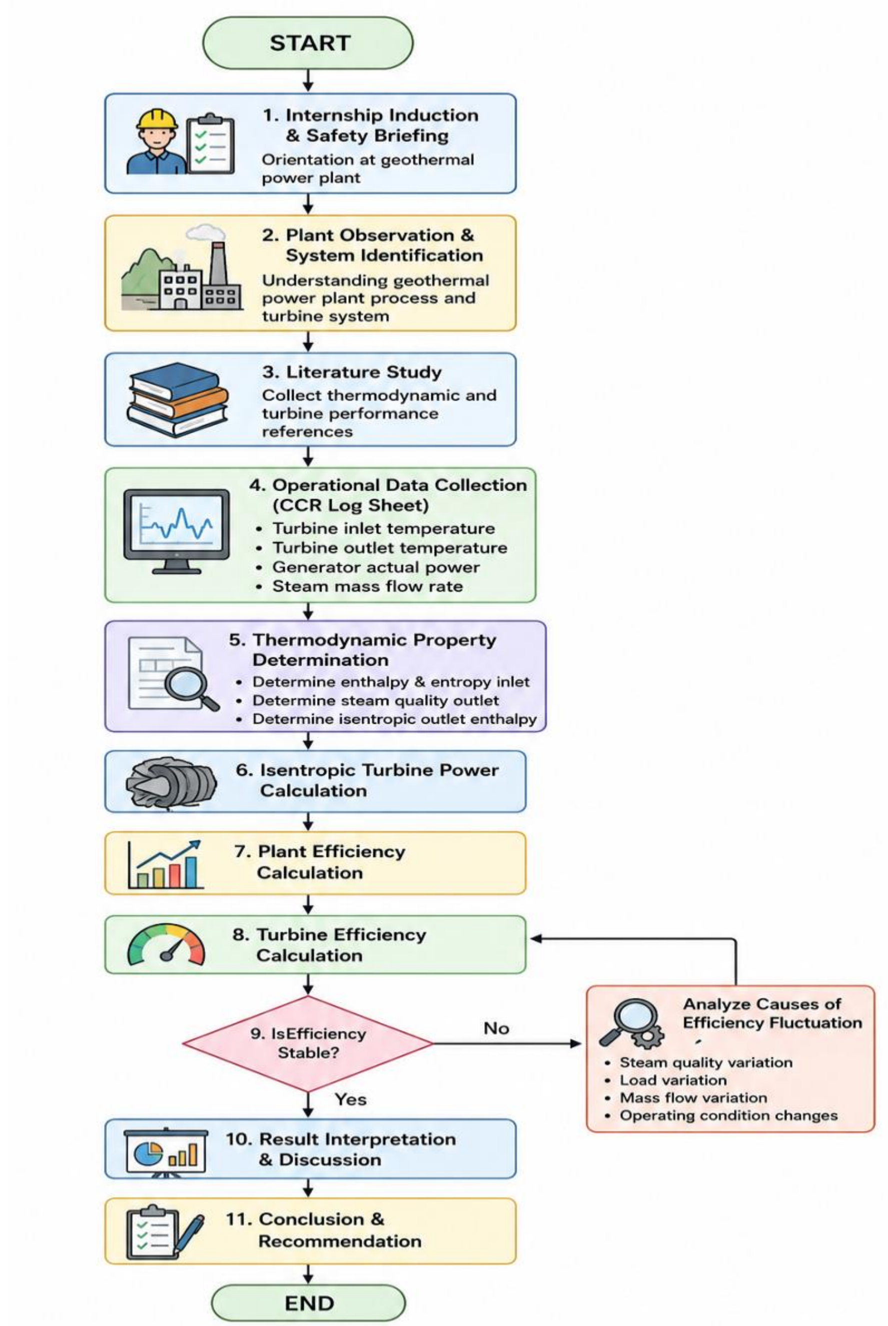

Figure 1. Flowchart of research procedure

The research procedure is illustrated in Figure 1. The study began with internship induction and field observation to understand the geothermal power plant system. Operational data were then collected from the Central Control Room log sheet. The collected data were processed using thermodynamic analysis to determine steam properties, isentropic turbine power, plant efficiency, and turbine efficiency. Finally, performance evaluation and analysis of efficiency fluctuations were carried out before drawing conclusions and recommendations.

RESULT AND DISCUSSIONS

The steam turbine analyzed in this study is a single-casing, double-flow, condensing-type turbine with a design power of 58.805 MW. The turbine specification data were obtained from the manufacturer's manual and used as a reference to evaluate the actual turbine performance during field operation, as shown in Table 1. During the internship period at PLTP Ulubelu Unit 3 and Unit 4, turbine operational data were collected for 10 consecutive days with a 6-hour observation interval. The monitored parameters included steam mass flow rate, turbine inlet pressure, separator outlet temperature as turbine inlet temperature, condenser inlet temperature, and actual generator power.

Table 1. Steam turbine spesification.

Property	Type
Turbine Type	Single Casing, Double Flow, Condensing Type
Rated Output	58.805 MW
Design Pressure	7.6 bara
Design Temperature	168°C
Exhaust Pressure	0,080 bara
Rated Speed	3000 RPM
Number Of Blade Stages	11 x 2 flow

The turbine operating pressure recorded in the field was initially expressed in bar gauge and converted into bar absolute to enable thermodynamic analysis using steam property tables. This conversion is essential because the calculation of thermodynamic properties such as enthalpy and entropy requires absolute pressure values to ensure accuracy. The processed operational data shown in Table 2 indicate that the average turbine operating conditions during the observation period were a steam mass flow rate of 95.90 kg/s, turbine inlet pressure of 6.92 bara, turbine inlet temperature of 164.55°C, condenser inlet temperature of 41.18°C, and actual generator power output of 51.16 MW. These values indicate that the turbine operated close to its design condition, although it had not reached its maximum design performance (Strušnik, 2022).

Table 1. Turbine operation data for 10 days.

Time	$\dot{m}$	$\dot{m}$	P_{in}	T_{out}	Tin	W
	Total Steam	**Total Steam**	**Turbine Inlet Pressure**	**Separator Outlet Temperature**	**Condenser Inlet Temperature**	**W Act Generator**
	(Ton/h)	(kg/s)	bara	(°C)	(°C)	(MW)
07/06/2024 00:00:00	343,845	95,5125	6,944	164,761	40,827	51,271
07/06/2024 06:00:00	347,586	96,5517	6,95	164,837	41,104	51,561
07/06/2024 12:00:00	345,944	96,0956	6,968	164,722	41,856	50,851
07/06/2024 18:00:00	345,104	95,8622	6,949	164,684	41,935	50,638
07/07/2024 00:00:00	346,355	96,2097	6,927	164,684	40,788	51,385
07/07/2024 06:00:00	343,421	95,3947	6,94	164,722	40,59	51,37
07/07/2024 12:00:00	346,94	96,3722	6,876	164,074	42,41	50,737
07/07/2024 18:00:00	347,04	96,4	6,977	164,799	42,45	50,737

07/08/2024 00:00:00	346,276	96,1878	6,956	164,665	40,669	51,515
07/08/2024 06:00:00	345,371	95,9364	6,918	164,627	40,353	51,706
07/08/2024 12:00:00	344,9	95,8056	6,948	164,131	42,173	50,745
07/08/2024 18:00:00	346,492	96,2478	6,95	164,551	41,737	50,905
07/09/2024 00:00:00	346,747	96,3186	6,934	164,551	41,262	51,21
07/09/2024 06:00:00	346,68	96,3	6,943	164,589	40,986	51,355
07/09/2024 12:00:00	346,313	96,1981	6,948	164,322	42,489	50,6
07/09/2024 18:00:00	344,669	95,7414	6,964	164,703	42,845	50,256
07/10/2024 00:00:00	345,433	95,9536	6,923	164,551	41,5	50,92
07/10/2024 06:00:00	345,763	96,0453	6,929	164,627	41,421	51,241
07/10/2024 12:00:00	345,929	96,0914	6,945	164,627	41,658	50,989
07/10/2024 18:00:00	345,433	95,9536	6,967	164,856	42,41	50,798
07/11/2024 00:00:00	343,94	95,539	6,887	164,665	40,669	51,225
07/11/2024 06:00:00	342,583	95,162	6,894	164,627	40,986	51,248
07/11/2024 12:00:00	345,398	95,944	6,897	164,169	41,698	50,89
07/11/2024 18:00:00	347,239	96,455	6,935	164,627	41,579	51,187
07/12/2024 00:00:00	346,01	96,114	6,904	164,551	41,065	51,263
07/12/2024 06:00:00	343,241	95,345	6,87	164,513	39,403	51,668
07/12/2024 12:00:00	345,709	96,030	6,905	164,055	41,262	51,035
07/12/2024 18:00:00	343,11	95,308	6,897	164,742	40,867	51,05
07/13/2024 00:00:00	346,481	96,245	6,926	164,513	40,59	51,576
07/13/2024 06:00:00	341,711	94,920	6,889	164,627	40,55	51,141
07/13/2024 12:00:00	346,536	96,260	6,934	164,589	41,104	51,416
07/13/2024 18:00:00	345,954	96,098	6,91	164,513	40,827	51,385
07/14/2024 00:00:00	344,043	95,568	6,881	164,513	40,788	51,195
07/14/2024 06:00:00	343,242	95,345	6,88	164,513	40,313	51,195
07/14/2024 12:00:00	343,974	95,548	6,868	164,169	40,313	51,286
07/14/2024 18:00:00	342,849	95,236	6,856	164,627	40,748	50,951
07/15/2024 00:00:00	343,743	95,484	6,895	164,589	40,55	51,324
07/15/2024 06:00:00	345,576	95,993	6,905	164,589	40,471	51,569
07/15/2024 12:00:00	345,558	95,988	6,917	164,169	40,906	51,294
07/15/2024 18:00:00	346,481	96,245	6,932	164,665	40,669	51,576
Avarage	345,2405	95,9001	6,9209	164,5527	41,1793	51,1566

Using saturated steam property tables, thermodynamic properties at the turbine inlet and outlet were determined. The analysis shows that the average turbine inlet enthalpy was 2741.66 kJ/kg, while the isentropic outlet enthalpy was 2081.92 kJ/kg. The enthalpy difference produced an average isentropic turbine power of 63.28 MW. By comparing the actual generator power with the isentropic turbine power, the average plant efficiency was found to be 80.84%, and the average turbine efficiency was 82.49%. This efficiency still falls within the typical steam turbine efficiency range reported in the literature, namely 70–90%, indicating that the turbine remains in a reliable operating condition despite experiencing a performance reduction compared with the design efficiency of 87.06%, as shown in Table 3 (Strušnik, 2022).

Table 2. Turbine efficiency calculation results

Date	h_1 Turbine Inlet Enthalpy (kJ/kg)	h_2 Turbine Outlet Enthalpy (kJ/kg)	s_1 Isentropic Turbine Outlet Enthalpy (kJ/kg)	x_1 Turbine Inlet Vapor Fraction -	x_2 Turbine Vapor Fraction -	W_T Isentropic Turbine Power (MW)	η_{plant} Plant Efficiency %	$\eta_{turbine}$ Turbine Efficiency %
07/06/2024 00:00:00	2741,883	2079,296	6,661	0,99	0,793	63,2853	81,02	82,67
07/06/2024 06:00:00	2741,966	2080,765	6,660	0,99	0,794	63,8400	80,77	82,41
07/06/2024 12:00:00	2741,841	2085,604	6,661	0,99	0,795	63,0614	80,64	82,28
07/06/2024 18:00:00	2741,799	2086,181	6,662	0,99	0,795	62,8490	80,57	82,22
07/07/2024 00:00:00	2741,799	2079,262	6,662	0,99	0,793	63,742	80,61	82,26
07/07/2024 06:00:00	2741,841	2077,972	6,661	0,99	0,793	63,3295	81,12	82,77
07/07/2024 12:00:00	2741,132	2090,656	6,667	0,99	0,797	62,6878	80,94	82,59
07/07/2024 18:00:00	2741,925	2088,996	6,661	0,99	0,796	62,9423	80,61	82,25
07/08/2024 00:00:00	2741,778	2078,596	6,662	0,99	0,793	63,7900	80,76	82,41
07/08/2024 06:00:00	2741,737	2076,795	6,662	0,99	0,793	63,7921	81,05	82,71
07/08/2024 12:00:00	2741,195	2089,07	6,666	0,99	0,796	62,4771	81,22	82,88
07/08/2024 18:00:00	2741,654	2085,333	6,663	0,99	0,795	63,1694	80,58	82,23
07/09/2024 00:00:00	2741,654	2082,465	6,663	0,99	0,794	63,4921	80,66	82,30
07/09/2024 06:00:00	2741,695	2080,702	6,662	0,99	0,794	63,6536	80,68	82,33
07/09/2024 12:00:00	2741,403	2090,484	6,665	0,99	0,796	62,6171	80,81	82,46
07/09/2024 18:00:00	2741,82	2091,642	6,662	0,99	0,797	62,2488	80,73	82,38
07/10/2024 00:00:00	2741,654	2083,901	6,663	0,99	0,795	63,1137	80,68	82,33
07/10/2024 06:00:00	2741,737	2083,226	6,662	0,99	0,794	63,2468	81,02	82,67
07/10/2024 12:00:00	2741,737	2084,656	6,662	0,99	0,795	63,1397	80,76	82,40
07/10/2024 18:00:00	2741,987	2088,604	6,660	0,99	0,796	63,1060	80,50	82,14
07/11/2024 00:00:00	2741,778	2078,596	6,662	0,99	0,794	63,360	80,85	82,50
07/11/2024 06:00:00	2741,737	2080,603	6,663	0,99	0,794	62,915	81,46	83,12
07/11/2024 12:00:00	2741,236	2086,097	6,666	0,99	0,796	62,857	80,96	82,61
07/11/2024 18:00:00	2741,737	2084,179	6,663	0,99	0,795	63,425	80,70	82,35
07/12/2024 00:00:00	2741,654	2081,278	6,663	0,99	0,794	63,471	80,77	82,41
07/12/2024 06:00:00	2741,612	2071,393	6,664	0,99	0,792	63,902	80,86	82,51
07/12/2024 12:00:00	2741,112	2083,762	6,667	0,99	0,795	63,125	80,85	82,50
07/12/2024 18:00:00	2741,862	2079,586	6,662	0,99	0,794	63,120	80,88	82,53
07/13/2024 00:00:00	2741,612	2078,517	6,664	0,99	0,794	63,819	80,82	82,46
07/13/2024 06:00:00	2741,737	2077,979	6,663	0,99	0,794	63,004	81,17	82,83
07/13/2024 12:00:00	2741,695	2081,413	6,663	0,99	0,794	63,559	80,90	82,55
07/13/2024 18:00:00	2741,612	2079,943	6,664	0,99	0,794	63,585	80,81	82,46
07/14/2024 00:00:00	2741,612	2079,708	6,664	0,99	0,794	63,256	80,93	82,58
07/14/2024 06:00:00	2741,612	2076,852	6,664	0,99	0,793	63,382	80,77	82,42
07/14/2024 12:00:00	2741,236	2077,748	6,666	0,99	0,794	63,395	80,90	82,55
07/14/2024 18:00:00	2741,737	2079,170	6,663	0,99	0,794	63,100	80,75	82,39
07/15/2024 00:00:00	2741,695	2078,078	6,663	0,99	0,794	63,365	81,00	82,65
07/15/2024 06:00:00	2741,695	2077,603	6,663	0,99	0,793	63,748	80,89	82,55
07/15/2024 12:00:00	2741,236	2081,317	6,666	0,99	0,795	63,345	80,98	82,63
07/15/2024 18:00:00	2741,778	2078,596	6,662	0,99	0,794	63,828	80,80	82,45
Avarege	2741,656	2081,916	6,663	0,99	0,794	63,278	80,84	82,49

Regression analysis was conducted to evaluate the relationship between steam mass flow rate and turbine efficiency. The linear regression equation obtained was $y = 108.728 - 0.283x$, with a coefficient of determination $R^2 = 0.319$. This result indicates that approximately 31.9% of the turbine efficiency variation is influenced by changes in steam mass flow rate, while the remaining variation is affected by other operational factors such as turbine mechanical condition, steam quality, condenser performance, and geothermal well stability (Abdel Rahman & Dincer, 2020; Bertani, 2016; Kabeyi & Jeremiah, 2023; Kusumo et al., 2024; Strušnik, 2022). The negative slope of the regression line suggests that an increase in steam mass flow rate tends to reduce turbine efficiency. Physically, this phenomenon occurs because higher steam flow increases aerodynamic losses, turbulence, and internal friction within turbine blades. Furthermore, the turbine is designed to operate at a specific design point; therefore, operation under off-design conditions results in reduced energy conversion efficiency as the flow incidence angle and expansion characteristics deviate from optimal conditions (Abdel Rahman & Dincer, 2020).

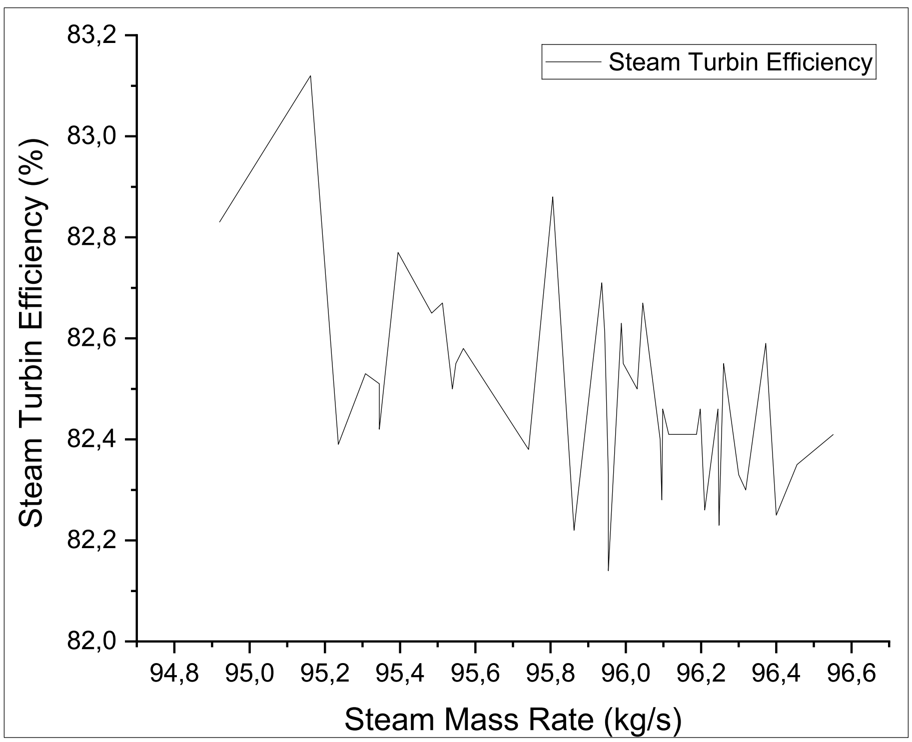

Figure 2. Relationship between steam mass flow rate and turbine efficiency.

Graph 1 illustrates the relationship between steam mass flow rate and steam turbine efficiency at PLTP Ulubelu Unit 3. Based on the graph, turbine efficiency tends to fluctuate within a relatively narrow range of approximately 82.2–83.1% as the steam mass flow rate varies between about 94.8 and 98.6 kg/s. Although the variations are not very large, the graph indicates that changes in steam mass flow rate still influence turbine performance and energy conversion efficiency. At lower steam mass flow rates, turbine efficiency initially increases and reaches its highest value at around 95.1–95.2 kg/s. This condition indicates that the turbine operates close to its optimal thermodynamic condition, where steam expansion through the turbine stages occurs efficiently with minimal internal losses. Under optimal steam flow conditions, the turbine blades can convert thermal energy into mechanical energy more effectively, resulting in higher efficiency (Kusumo et al., 2024; Strušnik, 2022). Stable steam flow also contributes to balanced pressure distribution and improved aerodynamic performance within the turbine.

However, as the steam mass flow rate continues to increase, the graph shows a gradual decrease and fluctuation in efficiency. This phenomenon may occur because higher steam flow rates can increase turbulence, moisture content, and internal flow losses within the turbine stages. Excessive steam flow may also reduce the effectiveness of steam expansion and increase mechanical stress on turbine components. Consequently, the turbine cannot maintain peak efficiency continuously at higher flow rates. The fluctuations observed in the graph indicate that the relationship between steam flow rate and turbine efficiency is not entirely linear, as turbine performance is simultaneously affected by several operational parameters such as inlet pressure, inlet temperature, condenser pressure, and steam quality (Alibaba et al., 2020; Kabeyi & Jeremiah, 2023; Strušnik, 2022). The relatively stable efficiency trend throughout the observation period demonstrates that the turbine control system and operational management are functioning properly. Despite fluctuations in steam mass flow rate, the efficiency deviation remains small, suggesting that the turbine is still capable of adapting to varying operating conditions without experiencing significant performance deterioration. This stability is important in geothermal power plants because steam supply conditions from geothermal wells naturally fluctuate depending on reservoir conditions and production performance (Alibaba et al., 2020; Kabeyi & Jeremiah, 2023). A comparison between actual and design turbine efficiency indicates a consistent efficiency reduction of approximately 4–5%. This reduction can be attributed to long-term operational factors, as the turbine has been operating continuously since 2016. Continuous exposure to high-temperature and high-pressure steam can gradually cause blade erosion, mechanical wear, and reduced aerodynamic efficiency. In geothermal power plants, mineral scaling and deposits carried by geothermal steam may accumulate on turbine blades and internal surfaces, obstructing steam flow and reducing energy conversion effectiveness. These conditions contribute to additional thermodynamic and mechanical losses during turbine operation (Kusumo et al., 2024).

In addition, aging of auxiliary systems such as separators, condensers, and steam pipelines may also affect overall turbine performance. Inefficient moisture separation or higher condenser temperatures can increase turbine exhaust pressure and reduce the enthalpy drop available for power generation. As a result, the actual turbine efficiency becomes lower than the original design value. Nevertheless, the relatively small efficiency reduction indicates that the turbine and supporting systems are still maintained effectively through periodic inspection, maintenance, and operational monitoring (Kusumo et al., 2024). Overall, the results presented in Graph 1 confirm that the steam turbine at PLTP Ulubelu Unit 3 continues to operate under stable and reliable conditions. Although the actual efficiency is slightly lower than the design efficiency, the turbine still demonstrates good thermodynamic performance with only moderate fluctuations under varying steam mass flow rates. These findings highlight the importance of maintaining steam quality, optimizing operating conditions, and implementing preventive maintenance strategies to sustain turbine efficiency and ensure long-term reliability of the geothermal power generation system.

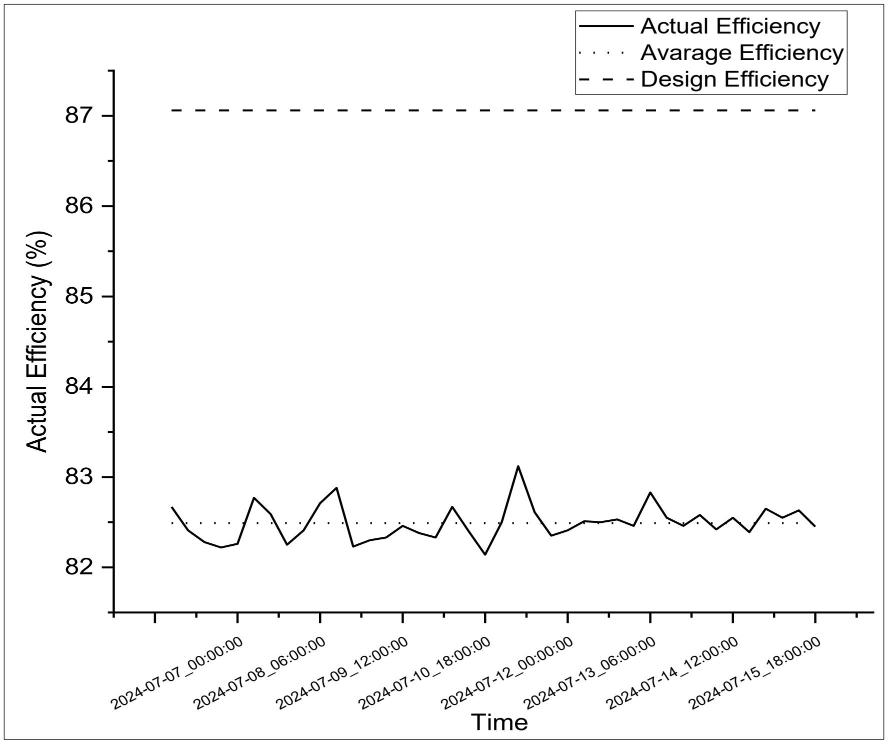

Figure 3. Comparison of actual and design turbine efficiency.

Graph 2 illustrates the comparison between the actual turbine efficiency and the design efficiency of the steam turbine at PLTP Ulubelu Unit 3. Based on the operational data collected during the observation period, the actual turbine efficiency fluctuated around 82–83%, which is slightly lower than the design efficiency but still within an acceptable operating range. This result indicates that the turbine continues to operate reliably and maintains good thermodynamic performance under real operating conditions. The relatively small deviation between actual and design efficiency suggests that the turbine components, steam flow system, and supporting equipment are still functioning effectively without significant performance degradation. The fluctuation of actual efficiency observed in the graph is mainly influenced by variations in operational parameters such as steam mass flow rate, turbine inlet pressure, turbine inlet temperature, condenser temperature, and generator load. When the steam entering the turbine has stable pressure and temperature, the enthalpy drop across the turbine becomes more optimal, resulting in higher turbine power output and efficiency. Conversely, slight decreases in inlet steam quality or unstable operating conditions can reduce the available thermal energy for expansion, causing efficiency to decline. These variations are normal in geothermal power plants because geothermal steam conditions are highly dependent on reservoir and well performance (Bertani, 2016; Patnaik & Sahu, 2023).

The graph also demonstrates that the actual efficiency trend remains relatively stable throughout the observation period, indicating consistent turbine operation and effective plant control systems.

Stable efficiency reflects proper operation of auxiliary systems such as separators, condensers, and cooling systems, which support the thermodynamic cycle of the turbine. In addition, the condenser temperature plays an important role in determining turbine exhaust pressure. Lower condenser temperatures generally improve the turbine expansion process by reducing back pressure, thereby increasing turbine efficiency (Van Nieuwenhuyse et al., 2023). Therefore, maintaining efficient condenser performance is essential to sustaining optimal turbine operation. Another important factor affecting turbine efficiency is the condition of the geothermal production wells supplying steam to the plant. Stable steam production from the wells ensures continuous energy input to the turbine and minimizes fluctuations in operating conditions. If the geothermal wells experience pressure decline, scaling, or unstable steam production, the turbine inlet conditions may deteriorate, reducing turbine efficiency and power generation capacity. Thus, turbine performance is not only determined by the turbine itself but also by the reliability and quality of the geothermal resource system (Apriyana et al., 2021; Kabeyi & Jeremiah, 2023).

The difference between actual and design efficiency may also be associated with mechanical and operational losses occurring during long-term operation. Friction losses in turbine blades, steam leakage, moisture content in steam, and minor fouling within the turbine system can gradually reduce performance compared to ideal design conditions. In practical operation, achieving design efficiency continuously is difficult because design values are generally based on ideal or near-optimal conditions. Nevertheless, the obtained efficiency values indicate that the turbine still performs efficiently and remains suitable for continuous operation (Van Nieuwenhuyse et al., 2023). Overall, the results confirm that the steam turbine at PLTP Ulubelu Unit 3 operates under stable and efficient conditions. The average efficiency of approximately 82–83% demonstrates good energy conversion performance and indicates that the geothermal power plant system is functioning effectively (Apriyana et al., 2021). However, opportunities for further optimization still exist through improved operational control, preventive maintenance, optimization of condenser performance, and enhancement of steam quality from geothermal production wells. Continuous monitoring and periodic performance evaluation are therefore essential to maintain long-term reliability and improve the overall efficiency of the geothermal power generation system.

Discussion

The results of this study indicate that the condensing steam turbine at PLTP Ulubelu Unit 3 operated with an average turbine efficiency of 82.49%, which reflects stable thermodynamic performance under actual field conditions. This value remains within the commonly reported efficiency range for industrial steam turbines, which generally varies between 70% and 90% depending on turbine design, operating conditions, steam quality, and maintenance status. The obtained efficiency also demonstrates that the turbine was still able to convert geothermal steam energy into mechanical energy effectively despite operating continuously for several years. Compared with the design efficiency of 87.06%, the observed efficiency reduction of approximately 4–5% suggests the presence of moderate performance degradation. This finding is consistent with, who emphasized that steam turbine performance may decline due to condenser inefficiency, mechanical losses, sealing problems, and deviations from optimum operating conditions (Strušnik, 2022). Similar observations were reported in the Kamojang dry-steam geothermal power plant, where operational optimization was required to maintain turbine performance in a 55 MW geothermal unit (Kusumo et al., 2024). The relatively small deviation between actual and design efficiency in the present study suggests that the turbine and its supporting systems remain in an acceptable operating condition. However, the reduction also indicates that long-term operation, minor mechanical wear, and potential internal deposits may have begun to affect energy conversion efficiency. From a thermodynamic perspective, the difference between actual and ideal performance is expected because real turbines experience irreversible losses during steam expansion. Therefore, the efficiency value obtained in this study provides important empirical evidence regarding the actual performance condition of a commercial-scale geothermal steam turbine in Indonesia.

The average isentropic turbine power obtained in this study was 63.28 MW, while the actual generator output averaged 51.16 MW, resulting in an average plant efficiency of 80.84%. This relationship indicates that not all theoretical energy available from steam expansion could be converted into electrical power due to mechanical, thermal, and generator-related losses. Such a condition is consistent with fundamental thermodynamic principles, where actual power conversion systems always experience irreversibilities caused by friction, turbulence, heat losses, leakage, and non-ideal expansion processes. That energy conversion and heat transfer processes in engineering systems are influenced by temperature gradients, fluid flow characteristics, and equipment effectiveness. In geothermal applications, these losses may be more complex because the steam supplied from geothermal wells can contain moisture, dissolved minerals, and non-condensable gases. That hybrid geothermal systems experience exergy destruction in several components, including turbines, condensers, and heat exchange units, due to non-ideal energy conversion processes (Alibaba et al., 2020). That geothermal-based cogeneration systems require careful thermodynamic assessment to identify energy losses and improve system performance (Abdel Rahman & Dincer, 2020). The findings of the present study support these earlier conclusions by demonstrating that actual operational efficiency is lower than design efficiency even when the turbine remains stable. This confirms that thermodynamic assessment using real operational data is necessary to distinguish between theoretical performance potential and actual field performance. Thus, the observed plant efficiency provides a realistic indicator for evaluating operational reliability and identifying opportunities for performance improvement in geothermal power generation systems.

Regression analysis revealed a negative relationship between steam mass flow rate and turbine efficiency, expressed by the equation $y = 108.728 - 0.283x$ with a coefficient of determination of $R^2 = 0.319$. This result indicates that approximately 31.9% of the variation in turbine efficiency can be explained by changes in steam mass flow rate, while the remaining variation is influenced by other operational factors. The negative slope suggests that increasing steam mass flow rate does not always improve turbine efficiency, particularly when the turbine begins to operate outside its optimal design range. This finding aligns with the concept of off-design turbine operation, where deviations from the designed flow condition can increase aerodynamic losses, blade incidence losses, turbulence, and internal friction. That operational parameters, including condenser vacuum and steam flow behavior, can significantly affect turbine efficiency in steam power systems (Strušnik, 2022). That geothermal power generation technologies require proper control of operating parameters to maintain efficient energy conversion (Kabeyi & Jeremiah, 2023). In the present study, the steam mass flow rate varied within a relatively narrow range, yet its effect on efficiency remained observable through regression analysis. This suggests that even small fluctuations in geothermal steam supply may influence turbine behavior under real operating conditions. Nevertheless, the moderate R^2 value indicates that steam mass flow rate is not the only determinant of turbine efficiency. Therefore, future performance assessments should also incorporate additional variables such as condenser pressure, steam quality, turbine inlet pressure, generator load, and non-condensable gas concentration to obtain a more comprehensive explanation of efficiency variation.

The comparison between actual and design turbine efficiency further indicates that the turbine experienced moderate efficiency degradation during field operation. This degradation can be attributed to several possible mechanisms, including blade erosion, steam leakage, friction losses, scaling deposits, and aging of auxiliary components. In geothermal power plants, scaling is a particularly important issue because geothermal steam often carries dissolved minerals that may precipitate under changing pressure and temperature conditions. Over time, mineral deposits can accumulate on turbine blades, internal surfaces, separators, pipelines, and condenser-related components, thereby reducing steam flow quality and increasing thermodynamic losses. That optimization is necessary in geothermal systems to maintain performance when operational problems occur in steam-related components (Kusumo et al., 2024). That flow and heat transfer disturbances can reduce system effectiveness, which is relevant to the influence of fouling or deposits in thermal systems. In addition, emphasized that condenser performance plays an important role in determining the efficiency of thermal power plants because condenser conditions affect exhaust pressure and available enthalpy drop (Patnaik & Sahu, 2023). The present study supports this view, as variations in condenser inlet temperature may have contributed to fluctuations in turbine efficiency. Although the observed efficiency reduction was not severe, it still indicates the importance of periodic inspection and preventive maintenance. Therefore, managing steam purity, controlling scaling formation, and maintaining condenser performance are essential strategies for sustaining turbine efficiency in geothermal power plants.

Overall, the findings of this study contribute to the literature by providing empirical evidence from a commercial-scale geothermal power plant operating under real field conditions. Many previous studies have emphasized thermodynamic modeling, exergy analysis, and system optimization in geothermal power generation, but fewer studies have used actual operational datasets from operating geothermal turbines. The strategic importance of geothermal energy in supporting sustainable electricity generation, particularly in countries with abundant geothermal resources such as Indonesia. However, the effectiveness of geothermal power generation does not depend solely on resource availability but also on the operational performance of key components such as steam turbines. The present study demonstrates that the Ulubelu Unit 3 turbine remains reliable, with efficiency consistently maintained above 82% throughout the observation period. This stability reflects effective plant control, acceptable turbine condition, and adequate operational management. Nevertheless, the gap between actual and design efficiency indicates that further optimization is still possible through improved monitoring, scaling control, condenser performance enhancement, and data-driven maintenance planning. That comprehensive evaluation of cooling and supporting systems is important for improving geothermal power plant efficiency. From a practical perspective, the results may assist plant operators in identifying operational trends and prioritizing maintenance actions based on efficiency indicators. Therefore, this study strengthens the need for continuous thermodynamic monitoring as a basis for improving reliability, sustainability, and long-term performance of geothermal power generation systems.

Implication

The findings of this study provide important theoretical and practical implications for the operation and management of geothermal power plants. From a theoretical perspective, the study contributes empirical evidence regarding the thermodynamic performance of a commercial-scale condensing steam turbine operating under actual field conditions, thereby enriching the limited literature on operational-data-based performance assessment in geothermal energy systems. The observed average turbine efficiency of 82.49% demonstrates that real operational performance can remain within an acceptable industrial range despite long-term service and deviations from design conditions. The results also confirm that steam mass flow rate significantly influences turbine efficiency, highlighting the importance of considering operational variability when evaluating turbine performance. From a practical standpoint, the identified efficiency reduction of approximately 4–5% relative to the design value indicates the need for continuous performance monitoring to detect early signs of performance degradation. The study further emphasizes the importance of maintaining steam quality, minimizing scaling formation, and optimizing condenser operation to sustain efficient energy conversion. In addition, the regression analysis provides useful information for plant operators in understanding how variations in steam supply conditions affect turbine behavior and overall plant performance. The findings can support the development of predictive maintenance strategies by identifying operational indicators associated with efficiency losses. Furthermore, the study demonstrates the value of utilizing real operational data as a decision-support tool for improving reliability and operational effectiveness in geothermal power generation systems. The results may also serve as a benchmark for evaluating the performance of similar geothermal turbines operating under comparable conditions in other geothermal fields. For energy companies and policymakers, the findings highlight the importance of integrating routine thermodynamic assessment into asset management programs to maximize electricity generation efficiency and extend equipment service life. Ultimately, the implementation of data-driven performance evaluation and proactive maintenance practices can contribute to improving the sustainability, reliability, and economic competitiveness of geothermal power plants in supporting long-term renewable energy development.

Limitation and Suggestion for Further Research

This study has several limitations that should be considered when interpreting its findings. First, the review employed a narrative review approach, which emphasizes comprehensive synthesis and conceptual interpretation rather than the systematic evaluation and quantitative assessment of evidence. As a result, the findings are dependent on the scope, quality, and availability of the literature included in the review. Second, the study relied exclusively on secondary data obtained from published academic and institutional sources, which may not fully capture recent technological developments, operational practices, or policy changes occurring in real-world transportation systems. Third, the review primarily focused on identifying concepts, technologies, benefits, challenges, and opportunities associated with transportation digitalization without conducting empirical validation of their effectiveness in specific transportation settings. Fourth, although the review concentrated on Indonesia, many of the available studies remain conceptual in nature and provide limited evidence regarding implementation outcomes at the local or regional level. Furthermore, the study did not evaluate the economic feasibility, cost-effectiveness, or long-term sustainability performance of individual digital transportation technologies. Future research should therefore employ empirical approaches, including case studies, surveys, longitudinal analyses, and quantitative modeling, to assess the actual impacts of intelligent transportation technologies on transportation efficiency, safety, environmental sustainability, and user satisfaction. Additional studies are also needed to examine digital readiness among transportation agencies, infrastructure operators, policymakers, and end users. Moreover, future investigations should explore governance mechanisms, interoperability frameworks, cybersecurity strategies, and data-sharing models that support integrated transportation ecosystems. Comparative studies involving different cities, regions, or developing countries would further enhance understanding of contextual factors influencing transportation digitalization. Researchers should also examine the relationship between transportation digitalization and measurable sustainability indicators, including carbon emissions, energy consumption, modal shifts, and mobility accessibility. By addressing these limitations and research needs, future studies can provide stronger evidence to support the design and implementation of sustainable, resilient, and inclusive digital transportation systems.

CONCLUSION

Based on the analysis of steam turbine performance efficiency, it can be concluded that the turbine operated in a stable and consistent condition during the 10-day observation period. The highest turbine efficiency was recorded on 11 July 2024 at 06:00 WIB with a value of 83.12%, while the lowest efficiency occurred on 10 July 2024 at 18:00 WIB with a value of 82.14%. The average turbine efficiency obtained during the observation period was 82.49%. These results indicate a high level of operational consistency, as the efficiency values remained within a narrow range above 82%, showing only minor fluctuations throughout the monitoring period. Steam turbine efficiency in geothermal power plants is influenced by several operating parameters. One of the most significant factors is the steam mass flow rate. The analysis shows that an increase in steam mass flow rate tends to reduce turbine efficiency, mainly because the turbine begins to operate under off-design conditions and experiences higher aerodynamic and mechanical losses. In addition, the quality and stability of the geothermal resource play an important role in determining turbine performance. Variations in steam temperature, pressure, and composition directly affect the turbine's ability to convert thermal energy into mechanical power. Consequently, these factors ultimately influence the electrical power output of the geothermal power plant. Overall, the turbine performance at the observed unit can be considered reliable and efficient, with opportunities for further optimization through improved control of operating conditions and steam quality management.

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Agus Apriyanto contributed to conceptualization, methodology, thermodynamic analysis, formal analysis, validation, supervision, writing original draft preparation, project administration, and corresponding author responsibilities. Hafidz Zakiyun Alrasyid contributed to investigation, operational data collection, data curation, thermodynamic property calculations, formal analysis, and writing review and editing. Hanifah Nurjanah Iskandar contributed to investigation, data validation, statistical analysis, visualization, and writing review and editing. Retno Wahyudi contributed to methodology, investigation, validation, visualization, and writing review and editing. Novia Utami Putri contributed to data curation, software, regression analysis, visualization, and writing review and editing. Alexander Sembiring contributed to formal analysis, interpretation of results, validation, and writing review and editing. Farrell Umar Rayhan contributed to supervision, conceptualization, project administration, funding acquisition, validation, and writing review and editing. All authors contributed substantially to the conception and design of the study, critically reviewed the manuscript for important intellectual content, approved the final version of the manuscript, and agreed to be accountable for all aspects of the work.

CONFLICT OF INTEREST

The authors declare that there is no conflict of interest regarding the publication of this manuscript. All contributions were conducted independently and without any financial, commercial, or institutional influence that could be perceived as a potential conflict. The research was carried out solely for academic and professional purposes.

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