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Preliminary Exergy Analysis for Performance Optimization at Ulubelu Geothermal Power Plant Unit 1

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Abstract. Indonesia lies within the Ring of Fire, renowned for volcanic activity and geothermal energy potential estimated at 23.7 GW. By 2023, 18 geothermal power plants were operational with a combined capacity of 2,597 MW. The Ulubelu Geothermal Power Plant, supplying 25% of Lampung's electricity, serves as a case study for a preliminary exergy analysis. Using Cycle-Tempo simulation, a thermodynamic model was developed to replicate actual operating conditions and evaluate exergy flows and losses. The system's total exergy input was 50,136 kW, with 16,367 kW (32.6%) destroyed due to irreversibilities, resulting in an overall exergy efficiency of 67.34%. The turbine achieved the highest functional exergy efficiency (82.43%) but also accounted for the largest relative exergy loss (12.43%). Substantial inefficiencies were identified in the condenser (14.88%) and ejector (1.66%). These findings reveal critical sources of exergy destruction, forming the basis for targeted performance improvements. Optimization strategies are prioritized for the turbine and condenser, where losses are most significant.

Keywords: *condenser, cycle-tempo, exergy, geothermal, irreversibility, thermodynamics modeling, turbine,*

1 Introduction

As delineated in the Long-Term Strategy for Low Carbon and Climate Resilience 2050, Indonesia has formally committed to achieving net-zero emissions by the year 2060. Geothermal energy plays a pivotal role in this transition due to its minimal carbon footprint and consistent base-load characteristics [1]. With an estimated potential of 23.7 GW, representing approximately 40% of global reserves, Indonesia had reached a total installed geothermal capacity of 2,597 MW by the end of 2023, distributed across 18 operational power plants [2]. The Ulubelu Geothermal Plant is one of the power plants that has contributed to the Indonesian electricity system, especially in Lampung, since 2012 through units 1 and 2. Meanwhile, units 3 and 4 began operating in 2016 and 2017, respectively, with an installed capacity of 55 MWe each [3]. The four units have collectively contributed 25% to the electricity system of Lampung, functioning as a base load power plant. Therefore, given the importance of maintaining the functionality of the equipment and the operational life of the Ulubelu geothermal plant over a long period of time, improving efficiency is essential to ensure optimal performance.

The enhancement of thermal efficiency in existing geothermal power plants constitutes a pivotal and cost-effective strategy to expedite Indonesia's energy transition agenda. Rather than relying exclusively on capital-intensive new development, the optimization of performance particularly through thermodynamic analysis can yield substantial efficiency enhancements. In this context, the thermodynamic analysis in question is an exergy analysis, which is based on the Second Law of Thermodynamics. Exergy analysis provides a more rigorous evaluation of system inefficiencies than conventional energy analysis. This approach facilitates the identification of impermanence and entropy generation within each component of the power cycle.

Exergy analysis has been employed in numerous geothermal facilities in Indonesia by previous studies, including those conducted by Pambudi et al. (2014), Alimudin et al. (2018), and Rudiyanto et al. (2021). However, these studies frequently offer merely a system-level evaluation, neglecting the necessity of precise quantification of the exergy destruction per component or optimization trajectory [4], [5], [6].

In this study, an exergy analysis of the Ulubelu Unit 1 Geothermal Power Plant was conducted using a Cycle-Tempo model to simulate actual field data. The present study undertakes a rigorous examination and validation of a steady-state thermodynamic model, with the objective of assessing exergy flows and inefficiencies in Unit 1 Ulubelu. The objective of this study is to identify the primary sources of exergy losses and to provide actionable recommendations for performance improvement, with a particular focus on components such as turbines and condensers, where significant degradation is anticipated.

2 Overview Ulubelu Geothermal Power Plant

The Ulubelu Geothermal Power Plant is located in the Waypanas geothermal field, which is within the Muara Dua Sub-District of the Tanggamus Regency in the province of Lampung. The field is distinguished by a high-enthalpy, liquid-dominated reservoir, with temperatures ranging between 250°C and 280°C [7]. Geothermal fluid is extracted from production wells and processed through a surface system designed for single-flash conversion system.

The Ulubelu Geothermal Power Plant facility has an aggregate installed capacity of 220 MW, which is distributed across four units of 55 MW each. The initial two units, commissioned in 2012, utilize a hybrid steam separation configuration involving satellite separators connected to a central unit. Units 3 and 4, which have been operational since 2016–2017, employ a centralized vertical cyclone separation system.

The process of generating electricity at Ulubelu involves the extraction of a mixture of two-phase fluids from the well, which are then directed towards a separation system that has been meticulously designed to remove water that is saline and water that has been captured. The occurrence of this phenomenon is contingent upon the specific unit in question, manifesting through the presence of either a hybrid satellite-center or a vertical-centered cyclone [8]. The vapor is subjected to a series of conditioning processes, including filtration and demistification, to ensure its purity prior to its entry into the turbine. The movement of the turbine, which is integrated with the generator, is initiated by the control valve, resulting in the generation of electricity [4]. The exhaust gas is directed towards the surface of the condenser, where the refrigerant liquid undergoes condensation. The process entails the discharge of non-condensable gas (NCG) through an ejector, with the residual water being returned to its reservoir via an injection well or integrated into the cooling system. The closed-loop system plays a crucial role in maintaining thermal and pressure balance within the system during prolonged operational periods. [9].

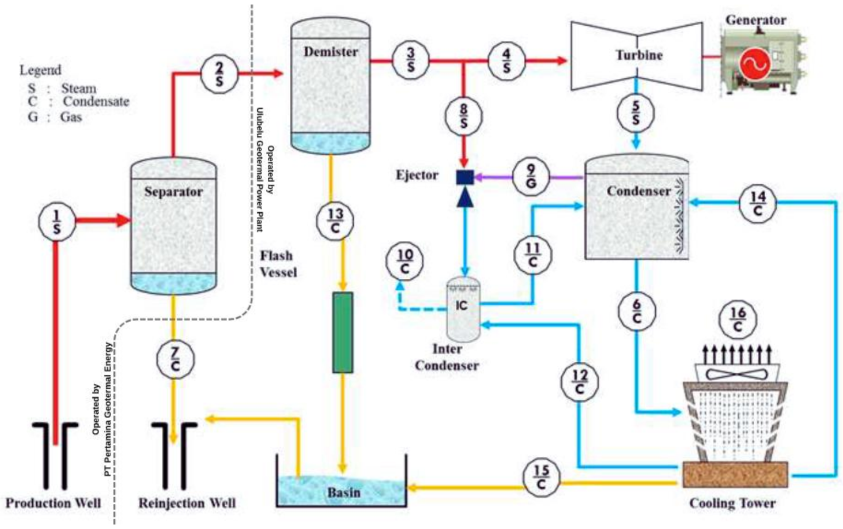


Figure1. Simplified schematic diagram of Ulubelu Geothermal Power Plant (Alimudin, 2018, with modification) [5]

3 Method of Analysis

3.1 Source of Data

The study utilizes Cycle-Tempo 5.1.7 simulation, a specialized software designed for modeling energy and exergy flows based on actual data from the Ulubelu Unit 1 geothermal power plant. The requisite thermodynamic and operational data to perform the simulation were obtained from PT. Pertamina Geothermal Energy (PGE), which has documented its steam supply data, operating parameters, and production log sheet records at the Ulubelu Unit 1 power plant. The utilized parameter data encompasses mass flow rate ($\dot{m}$), temperature (T), and pressure (P) at each node shown in Fig.1.

3.2 Analytical Approach

The thermodynamic performance of Ulubelu Unit 1 was assessed through a combination of first-law (energy) and second-law (exergy) analyses, employing steady-state data and schematic system boundaries. The evaluation of each process unit was conducted by considering the node properties, including pressure, temperature, mass flow rate, specific enthalpy, and entropy. The procedure involves five major steps: system boundary definition, model development, energy analysis, exergy analysis, and validation.

3.2.1 System Boundary

The system was divided into key process components: production wells, separator, steam pipeline, turbine-generator set, condenser, cooling tower, and reinjection wells. Each component was treated as a control volume under steady-state operation, with heat and work exchanges defined at system boundaries.

3.2.2 Model Development in Cycle-Tempo

The plant configuration was reconstructed in Cycle-Tempo by specifying all process nodes, component connections, and operational parameters. Manufacturer data and PGE records were used to define component efficiencies and pressure drops.

3.2.3 Energy Analysis

The energy flow rate $\dot{E}_i$ (kW) at each node was calculated using:

$$\dot{E}_i = \dot{m}_i h_i$$

Where $\dot{m}_i$ is the mass flow rate (kg/s) and h_i is the specific enthalpy (kJ/kg). Total energy balance was performed for each component to calculate useful work output, heat input/output, and system losses.

3.2.4 Exergy Analysis

The spesific physical exergy $\dot{e}_i$ and the exergy flow rate $\dot{X}_i$ were computed using:

$$\dot{e}_i = h_i - h_o - T_o(s_i - s_o);$$
$$\dot{X}_i = \dot{m}_i \dot{e}_i$$

where $\dot{m}_i$ is the mass flow rate (kg/s), h_i and s_i are the spesific enthalpy and entropy at state i and h_o , s_o, and T_o are dead-state reference properties.

Turbine power output and net elctricity generation were calculated using:

$$\sum \dot{E}_{inlet} = \sum \dot{E}_{outlet} + \sum \dot{E}_{loss}$$

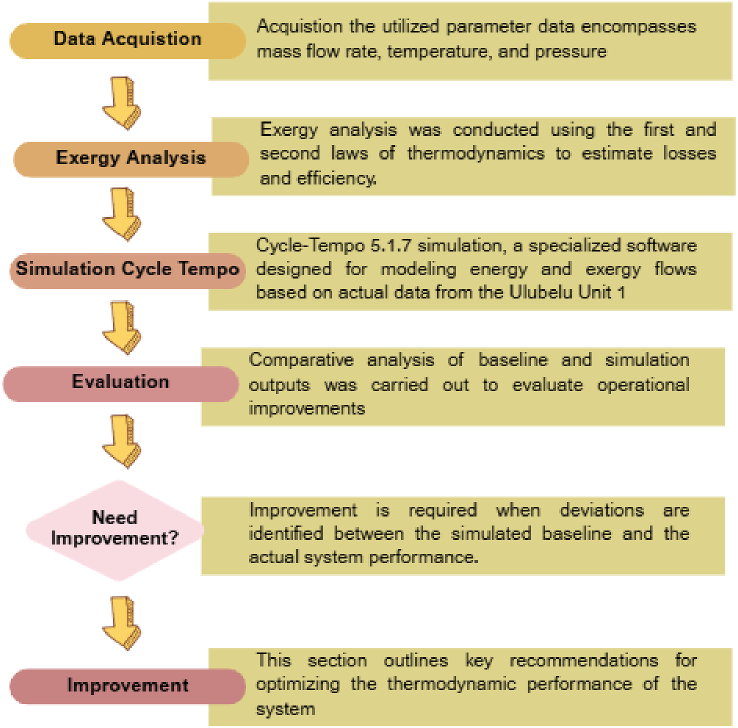
$$\sum \dot{X}_{inlet} = \sum \dot{X}_{trans} + \sum \dot{X}_{waste} + I$$

where I is the rate of irreversibility or exergy destruction. Exergy is considered transferred if it is converted into useful work or forwarded to another active process; otherwise, it is classified as waste.

The component-level energy efficiency η_E and exergy efficiency η_{II} were compued as:

$$\eta_E = \frac{\sum \dot{E}_{outlet}}{\sum \dot{E}_{inlet}} \; ; \; \eta_{II} = \frac{\sum \dot{X}_{trans}}{\sum \dot{X}_{inlet}} \; ; \eta_{net} = \frac{\sum \dot{W}_{net}}{\sum \dot{X}_{inlet}}$$

3.3 Methodology



Acquistion the utilized parameter data encompasses mass flow rate, temperature, and pressure

Exergy analysis was conducted using the first and second laws of thermodynamics to estimate losses and efficiency.

Cycle-Tempo 5.1.7 simulation, a specialized software designed for modeling energy and exergy flows based on actual data from the Ulubelu Unit 1

Comparative analysis of baseline and simulation outputs was carried out to evaluate operational improvements

Improvement is required when deviations are identified between the simulated baseline and the actual system performance.

This section outlines key recommendations for optimizing the thermodynamic performance of the system

Figure 2. Methodology flowchart

The methodological framework adopted in this study is illustrated in Fig. 2. It begins with data acquisition, where the operational parameters including mass flow rate, temperature, and pressure were collected from Ulubelu Unit 1 production log sheets provided by PT Pertamina Geothermal Energy (PGE). The dataset covers hourly measurements spanning January 2021 to December 2022 and was preprocessed to remove outliers and interpolate missing values, ensuring consistency for subsequent analysis.

The next stage involves exergy analysis, where first-law (energy) and second-law (exergy) principles were applied to estimate system efficiencies and identify sources of irreversibility. A thermodynamic model of the plant was then developed using Cycle-Tempo 5.1.7, a specialized simulation software, to replicate the plant's configuration and operational conditions.

Following simulation, an evaluation step was conducted by comparing the baseline plant performance with simulation outputs. This comparison allowed for the identification of discrepancies and potential operational inefficiencies.

When deviations between simulated results and actual data were observed, a need for improvement was recognized. This prompted the formulation of recommendations aimed at enhancing the thermodynamic performance of the system. Finally, the improvement stage outlines key strategies that could be implemented to optimize energy utilization and reduce exergy destruction within the plant.

4 Results and Discussion

4.1 Conversion Process and Exergy Analysis

The Ulubelu Unit 1 geothermal power plant operates as a dry steam system, where steam undergoes purification in a demister before entering the turbine. Table 1 presents the exergy analysis results under baseline operation. The turbine receives the highest exergy inflow (61,792 kW) and delivers 50,815 kW as useful work, achieving a functional exergy efficiency of 82.16%. Despite this, the turbine accounts for the largest absolute exergy destruction of 10,977 kW (13.25% of system losses).

Table 1. Baseline exergy flows and losses in Ulubelu Unit 1 components

Number	**Aparatus**	**Exergy transmitted from system [kW]**			**Exergy Losses (%)**
		Exergy in	**Exergy out**	**Losses**	
1	Turbine	61,792	50,815	10,977	13.25%
2	Condensor	9,132	0	9,132	11.02%
3	Ejector	529	0	529	0.64%
4	Demister	171	0	171	0.21%
5	Intercondens	2,404	0	2,404	2.90%
Overall Exergy Efficiency					**68.64%**

Steam exiting the turbine enters a surface condenser, which exhibits complete exergy destruction of its 9,132 kW inflow. This corresponds to 11.02% of total system losses, underscoring the irreversibility inherent in condensation processes. The cooling system, rejecting approximately 21.5 MW of thermal energy to the environment, contributes further to exergy degradation.

Auxiliary systems such as the ejector, demister, and intercondenser collectively account for smaller exergy shares but remain relevant due to their inefficiencies. For example, the ejector exhibits a loss of 529 kW (0.64%), while the intercondenser contributes 2,404 kW (2.90%) of exergy losses.

Overall, the system achieves an exergy efficiency of 68.64%, indicating that approximately one-third of the input exergy is destroyed. Fig. 3 presents the exergy distribution across major components, with the turbine and condenser contributing the largest shares of exergy destruction, followed by the cooling tower and auxiliary systems.

These findings underscore the turbine and condenser as critical components for targeted efficiency improvements. To investigate the potential for performance enhancement, a series of improvement scenarios was developed and assessed for their impact on overall exergy efficiency.

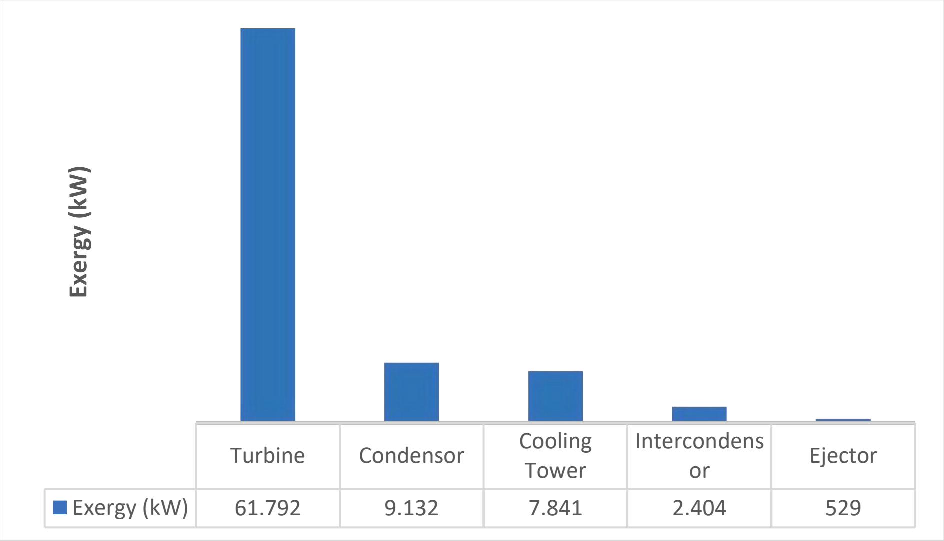


Figure 3. Total exergy distribution under baseline operation.

4.2 Improvements Scenario

To reduce irreversibilities and enhance system performance, the turbine inlet pressure wasincreased from 7.060 bara to 7.063 bara, while the condenser pressure was reduced from 0.13 bara to 0.11 bara. These adjustments created more favorable thermodynamic conditions for steam expansion and condensation processes.

The results, presented in Table 2, demonstrate a measurable improvement in system performance:

- Overall exergy efficiency increased to 68.80%.
- Turbine exergy loss reduced from 13.25% to 13.17%.
- Condenser exergy loss reduced from 11.02% to 10.43%.
- Generator output increased to 50 MW, representing an efficiency gain at the system level.

Table 2. Exergy performance after improvement scenario

Number	**Aparatus**	**Exergy transmitted from system [kW]**			**Exergy Losses (%)**
		Exergy in	**Exergy out**	**Losses**	
1	Turbine	60,679	50,928	9,751	13.17%
2	Condensor	7,723	0	7,723	10.43%
3	Ejector	499	0	499	0.65%
4	Demister	471	0	471	0.64%
5	Intercondens	2,374	0	2,374	2.70%
Overall Exergy Efficiency					**68.80%**

This scenario underscores the sensitivity of exergy performance to operational parameters and provides a basis for operational fine-tuning.

4.3 Implications and Optimization Potential

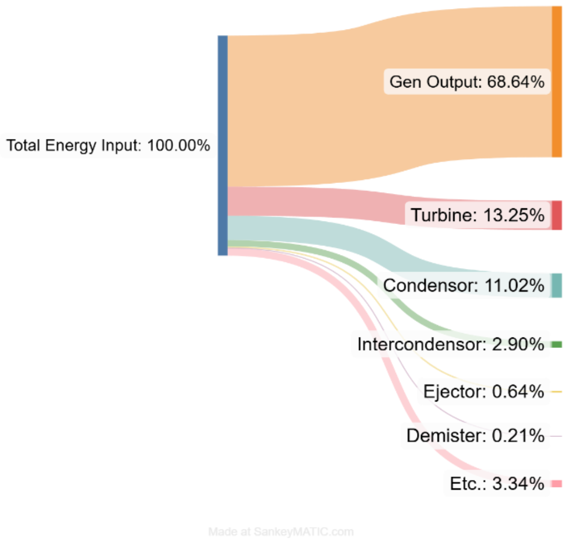


Figure 4. Sankey Diagram

The Sankey diagram and its corresponding analysis highlight the turbine and condenser as priority targets for efficiency improvement. Optimizing turbine nozzle configurations and enhancing condenser cooling capacity could significantly improve exergy utilization. Secondary opportunities exist in auxiliary systems, such as upgrading ejector and intercondenser designs, which also contribute to overall system irreversibilities.

The exergy analysis further provides insights into the locations and causes of inefficiencies in the Ulubelu Unit 1 power plant. For the turbine, optimization efforts may focus on revisiting nozzle arrangements, improving internal blade design, and assessing actual versus isentropic performance.

In contrast, the high irreversibility observed in the condenser suggests limitations in cooling capacity or heat rejection. Strategies such as increasing cooling water flow rate, enhancing heat exchanger performance, or adopting hybrid cooling systems could effectively reduce these losses.

Finally, although auxiliary components like the ejector and demister account for a smaller share of total losses, their long-term inefficiencies remain relevant. Applying advanced thermohydraulic simulations and retrofitting targeted technologies may further enhance their performance and contribute to overall system efficiency gains.

4.4 System Performance Comparison and Further Work

Compared to similar geothermal plants such as the Dieng single-flash unit (exergy efficiency 38.19%), Ulubelu's dry-steam configuration exhibits superior performance at 68.64%. However, the potential for further improvement remains, particularly in mitigating condenser-related irreversibility and optimizing auxiliary systems.

Future research should incorporate dynamic simulations under varying ambient and load conditions, exergy costing, and multi-objective optimization.

4.5 Recommendations for Optimization

The analysis highlights two key factors that lead to total exergy loss: the turbine, and condenser. These findings provide a clear direction for future optimization efforts.

Recommendations for system improvement include:

- Turbine Optimization:
  To make the turbine work better, it's suggested to improve its isentropic efficiency by redesigning the nozzles, better shaping the blades, and regularly checking inside to reduce mechanical losses and buildup. Implementing real-time performance monitoring and maintenance scheduling based on deviation from expected exergy output may further enhance turbine efficiency.

- Condenser Optimization:
  Improving condenser performance can be achieved by increasing the surface area for heat transfer, optimizing the cooling water flow rate, or incorporating hybrid cooling systems to enhance thermal rejection, particularly during peak ambient temperatures. Ensuring proper removal of non-condensable gases via ejector systems and minimizing vacuum losses is also essential to lower backpressure and improve condensation rates.

5 Conclusion

This study applied energy and exergy analyses to Ulubelu Unit 1 using Cycle-Tempo simulation. The baseline evaluation identified an overall exergy efficiency of 68.64%, with the turbine and condenser as key contributors to system irreversibility.

A pressure adjustment scenario demonstrated an improved efficiency of 68.80% and a generator output increase to 50 MW. The findings underscore the value of operational fine-tuning and component upgrades in enhancing system performance.

Future research should look at combining technical and economic assessments of the suggested improvements, use exergy costing methods, and include models that account for changing operations to evaluate how the system performs under different loads and environmental conditions. These strategies align with Indonesia's national objective of achieving net-zero emissions by 2060 and point to the importance of geothermal optimization in the country's energy transition framework.

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