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Evaluation of Performance Salak Geothermal Power Plant #1 based on Exergy Analysis

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Abstract.
This study presents an exergy analysis of the Mount Salak Geothermal Power Plant Unit #1 to evaluate its thermodynamic performance and identify inefficiencies. Exergy analysis is employed to assess operational efficiency by considering both energy quantity and quality. Real operational data and CycleTempo simulation software were used to analyze key components, including the turbine, condenser, and gas removal system. Results indicate that the overall exergy efficiency of the system is 66.88%, with the highest exergy losses occurring in the turbine (13.76%) and condenser (10.01%). Two scenarios were simulated to improve performance: (1) adjusting turbine inlet pressure to 7.02 bara and (2) optimizing condenser pressure to 0.10 bara. These adjustments resulted in an increase in overall exergy efficiency to 68.81% and improved power output. The study emphasizes the importance of maintaining optimal operational parameters and addressing component inefficiencies to enhance power generation and extend the plant's operational life. It also highlights the value of exergy analysis as a tool for identifying potential improvements, offering valuable insights for operators seeking to optimize efficiency, reduce energy losses, and ensure the long-term sustainability of geothermal power plants.

Keywords: *turbine; condenser; simulation; CycleTempo; irreversibility*

1 Introduction

Indonesia's geothermal sector plays an essential role in supplying clean and sustainable energy to meet Java-Bali's base load electricity demand. Among its key contributors, the Mount Salak Geothermal Power Plant stands out due to its consistent performance since the mid-1990s. With three operational units, the plant delivers a combined daily output of around 4.32 GWh and maintains a high equivalent availability factor (EAF) averaging 96%. Units 1 and 2 commenced operation in 1994, while Unit 3 followed in 1997. System upgrades in 2004 boosted each unit's output capacity from 55 MWe to 60 MWe. Given its long operational period, efficiency improvements are necessary to maintain optimal performance. Exergy analysis, which evaluates both the quantity and quality of energy transformations, has become a valuable tool to identify irreversibilities within thermal systems. In this context, this study employs CycleTempo simulations to analyze how variations in turbine inlet and condenser pressures influence the exergy efficiency and total output of Mount Salak Unit 1, with the goal of identifying the most favorable operational strategy to minimize losses and enhance power plant sustainability.

2 Process Flow Diagram

The Mount Salak Unit 1 geothermal power generation process begins with the extraction of a two-phase mixture from production wells, containing approximately 25% dry steam. This mixture is first passed through a separation system to remove brine and moisture content, ensuring high steam quality for turbine operation. After separation, the steam flows through a series of conditioning stages, including demisters and strainers, to eliminate residual particulates. Control valves regulate steam pressure and flow into the turbine system. The turbine, coupled to a generator, converts thermal energy into electrical energy, typically operating at 3000 rpm. The generator output is then stepped up to match the grid requirements of the Java-Bali system. Exhaust steam is directed into a direct-contact condenser, where cooling water from the cooling tower facilitates condensation. Non-condensable gases (NCG) are removed using ejectors connected to inter-after condensers. The resulting condensate is partially re-injected into the reservoir and partially recycled through the cooling tower. This closed-loop cycle is crucial for maintaining pressure balance and thermal stability within the geothermal system [9].

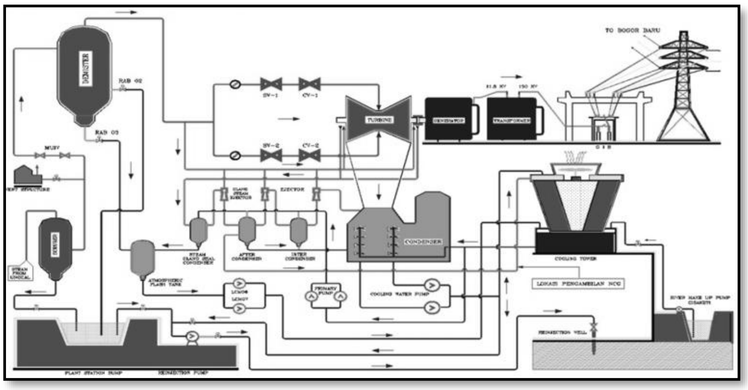

Figure 1 Process Flow Diagram Salak Geothermal Power Plant #1

However, like other power plants that have been operating for a long time, the Salak Geothermal Power Plant #1 also faces performance degradation issues. Key components such as turbines, condensers, and cooling towers experience a decline in efficiency due to their age. Fluctuations in steam quality and system pressure further exacerbate energy losses and reduce the thermodynamic efficiency of the system. In this case, exergy analysis becomes very important. Unlike energy analysis, which only measures the quantity of energy, exergy analysis also considers the quality of energy, thereby identifying significant energy losses and their locations [3]. Exergy is the maximum theoretical work that can be extracted from a system as it reaches equilibrium with its environment, reflecting both the quantity and quality of energy. Total exergy refers to the sum of all exergy entering the system, while output exergy is the portion converted into useful work, such as electricity. Exergy destruction, or irreversibility, represents the loss of exergy due to inefficiencies in system components. Functional exergy efficiency is the ratio between useful output exergy and total input exergy, indicating how effectively the system utilizes available energy. Relative exergy loss describes the proportion of exergy destruction contributed by each component within the overall system.

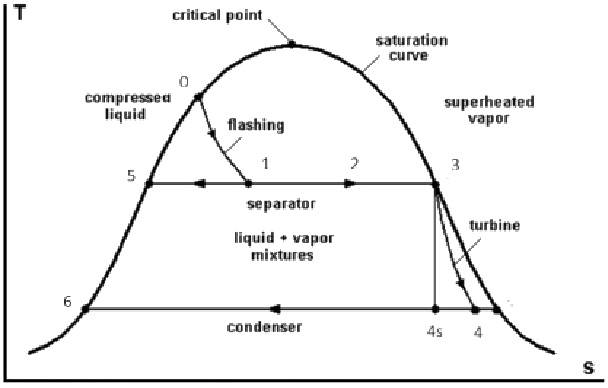

Figure 2 T-S Diagram Salak Geothermal Power Plant #1[2]

In general, the cycle that occurs in a geothermal power plant is illustrated in a T-S diagram, which begins with the flashing of hot fluid, purified in a separator, then the dry steam is fed into a turbine, until it is condensed back into water

2.1 Demister

Demister is a steam treatment device designed to remove entrained moisture and solid particles from the steam flow, thereby ensuring the delivery of high-quality, dry steam to downstream components. By enhancing steam purity, the demister improves the operational efficiency and reliability of critical equipment such as turbines. In geothermal power plants, it plays a vital role in preventing erosion and corrosion, and in maintaining stable thermodynamic conditions throughout the system.

Table 1 Heat Balance Demister Parameter Salak #1

Parameter	**Salak #1**
Manufacturer	Forain Milano Italy
Operating inlet press	7.1 bar abs
Operating temp	165.5 degC
Inlet steam flow	121 kg/s

The exergy equation in demister is[2]:

$$Ex_{in\ demister} = \dot{m}_1.\left[(h_1 - h_0) - T_0(s_1 - s_0)\right]$$

$$Ex_{steam\ output} = \dot{m}_2.\left[(h_2 - h_0) - T_0(s_2 - s_0)\right]$$

$$Ex_{brine} = \dot{m}_5.\left[(h_5 - h_0) - T_0(s_5 - s_0)\right]$$

2.2 Turbine

Mechanical device that converts the thermal energy of high-pressure, high-temperature steam into mechanical rotational energy. This rotation drives a generator to produce electricity. The geothermal steam enters the turbine blades, causing them to spin and transmit torque to the generator shaft. Turbines in geothermal systems are specifically designed to operate with saturated or slightly superheated steam and must accommodate the presence of non-condensable gases and potential impurities. As a critical component in the energy conversion process, turbine performance directly influences the overall efficiency and output of the power plant.

Table 2 Heat Balance Turbine Parameter Salak #1

Parameter	**Salak #1**
Manufacturer	Ansaldo Compenti
Steam inlet press	6.63 bar abs
Exhaust steam press	0.12 bar abs
Steam temperature	162 degC

The exergy equation in turbine is[2]:

$$Ex_{in\ turbin} = \dot{m}_3.\left[(h_3 - h_0) - T_0(s_3 - s_0)\right]$$

$$Ex_{out\ turbin} = Ex_4 + W_t$$

$$Ex_4 = \dot{m}_4.\left[(h_4 - h_0) - T_0(s_4 - s_0)\right]$$

2.3 Condenser

Heat exchange device where exhaust steam from the turbine is condensed through direct mixing with cooling water. Unlike surface condensers, this type of condenser allows steam and cooling water to come into direct physical contact, resulting in efficient heat transfer and rapid condensation. The process reduces the steam to liquid phase (condensate), which can then be recirculated or re-injected into the reservoir. Direct contact condensers are commonly used in geothermal systems due to their simplicity, lower cost, and effectiveness in handling large volumes of low-pressure steam containing non-condensable gases.

Table 3 Heat Balance Condenser Parameter Salak #1

Parameter	**Salak #1**
Manufacturer	Ansaldo Gie
Type	Direct contact
Volume	504 m^3
Pressure	0.12 bar abs

The exergy equation in condenser is[2]:

$$Ex_{in\ cond} = Ex_4 + Ex_9$$

$$Ex_9 = \dot{m}_9.\left[(h_9 - h_0) - T_0(s_9 - s_0)\right]$$

$$Ex_{out\ cond} = Ex_6 = \dot{m}_6.\left[(h_6 - h_0) - T_0(s_6 - s_0)\right]$$

2.4 Cooling Tower

Cooling tower in a geothermal power plant is a heat rejection system that removes excess heat from the cooling water used in the condenser by transferring it to the atmosphere. It operates by allowing hot condensate or cooling water to flow downward through a fill structure while ambient air is drawn or forced upward, promoting evaporative cooling. This process lowers the temperature of the water, which is then recirculated back to the condenser to absorb more heat from the turbine exhaust steam. Cooling towers are essential for maintaining low condenser pressure and ensuring the thermodynamic efficiency and continuous operation of the geothermal power cycle.

Table 4 Reference environment cooling tower Salak #1

Parameter	**Salak #1**
Altitude	±800 masl
Pressure	±912 mbar
Air Temp out	20-26 degC
Relative Humidity	34-75 %

3 Methodology

The methodology of this study is based on exergy analysis to assess the thermodynamic performance of the Mount Salak Geothermal Power Plant

Unit #1. The first step involved collecting operational data from the plant, including steam flow rates, pressures, temperatures, and the specifications of key components such as the turbine, condenser, and demister. This data forms the basis for calculating the exergy values associated with various components in the system. Exergy is calculated using thermodynamic property equations that consider the energy input, output, and destruction in the system. The exergy destruction represents the irreversibility within each component, highlighting the loss of useful work. The study specifically focuses on key components, such as the turbine and condenser, which are identified as the main sources of exergy losses.

The next phase of the methodology involved performing simulations using CycleTempo software to investigate potential improvements in the plant's performance. In the simulations, the turbine inlet pressure was varied from its baseline value of 6.00 bara to 7.02 bara to determine the optimal pressure for maximizing turbine efficiency. Similarly, the condenser pressure was adjusted from 0.13 bara to 0.10 bara, in line with the original design conditions, to evaluate the impact of restoring the pressure to its ideal operational level. The simulation results were then compared with actual operating data to assess the changes in exergy efficiency and the overall system performance. By analyzing the results, the study aimed to identify the most effective operational strategies for improving the plant's thermodynamic efficiency and sustainability

4 Results and Discussion

The analysis and calculation of the performance of the Salak Geothermal Power Plant #1 were carried out using actual operating data at the time, namely at a turbine inlet pressure of 6 bar and a condenser pressure of 0.12 bara. Result shows in Salak Geothermal Power Plant #1 had a overall exergy efficiency of 66.88%. For details on the exergy values of each component can see table 5 and Sankey diagram

Table 5 Total Exergy of Salak #1

Parameter	**Exergy transmitted from system (kWe)**			**Ex. Loss**
	Total	**Power**	**Losses**	**(%)**
Demister	1593.51	0	1593.51	1.49
Turbin	75721.80	61003.34	14718.46	13.76
Condenser	10707.55	0	10707.55	10.01
Intercondenser	905.59	0	905.59	0.85

Aftercondenser	1358.58	0	1358.58	1.27
Overall Exergy Efficiency	**66.88%**			

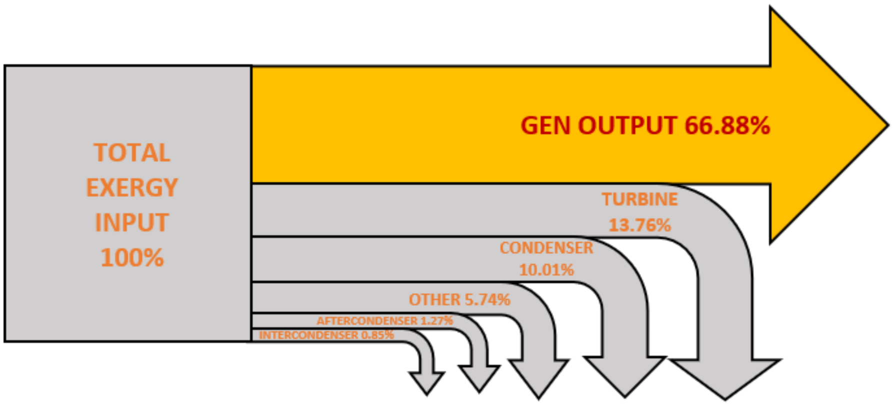

Figure 3 Sankey diagram overall process Salak #1

The Sankey diagram represents the exergy balance in a thermodynamic system, with the total exergy input set to 100%. The diagram shows the distribution of exergy to various components of the system, leading to a generation output of 66.88%. Exergy losses is allocated to the turbine 13.76%, condenser 10.01%, and aftercondenser 1.27% and intercooler 0.85%. Additionally, smaller portions of exergy are from the other components in total 5.74%. An evaluation of the performance of salak #1 based on exergy analysis has been completed, and the results show that the turbine and condenser have the highest losses. Therefore, simulations will be conducted to improve the performance of these two components.

The first option repair in the turbine components, the analysis shows that the turbine has the greatest exergy losses which has losses of 13.76%. To improve the exergy efficiency of the turbine, repairs, cleaning, or even replacement of the turbine blades are typically performed. These activities can only be carried out if the power generation unit is in a prolonged shutdown state, which requires obtaining permits that are not easily obtained. Another method to optimize the exergy efficiency of the turbine is by adjusting the inlet pressure to achieve optimal output and SSC.

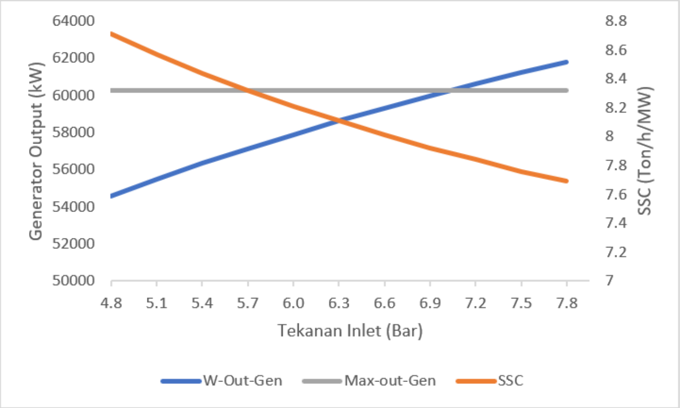

Figure 4 Turbine inlet pressure simulation

The figure 4 shows the simulation results of varying the turbine inlet pressure against the generator output power and SSC value. To obtain maximum generator output, an inlet pressure of 7.02 bara with an SSC value of 7.89 Ton/h/MW is required and exergy losses at 12686.71 kWe. For more details on the exergy values of each component can see at table 6.

Table 6 Total Exergy of Salak #1 simulation with inlet pressure 7.02 bara

Parameter	**Exergy transmitted from system (kWe)**			**Ex. Loss**
	Total	**Power**	**Losses**	**(%)**
Demister	869.45	0	869.45	0.84
Turbin	73965.30	61278.59	12686.71	12.6
Condenser	7913.15	0	7913.15	7.86
Intercondenser	883.84	0	883.84	0.88
Aftercondenser	1343.64	0	1343.64	1.33
Overall Exergy Efficiency	**68.81**			

The second option is to improve the condenser, which is the component with the second highest exergy losses. In this case, optimization can be done by routinely cleaning the nozzle when the unit is stopped and maintaining the temperature of the cooling tower outlet water. In addition, condenser pressure can also be optimized. The following are the results of simulations of condenser pressure changes on generator output and SSC.

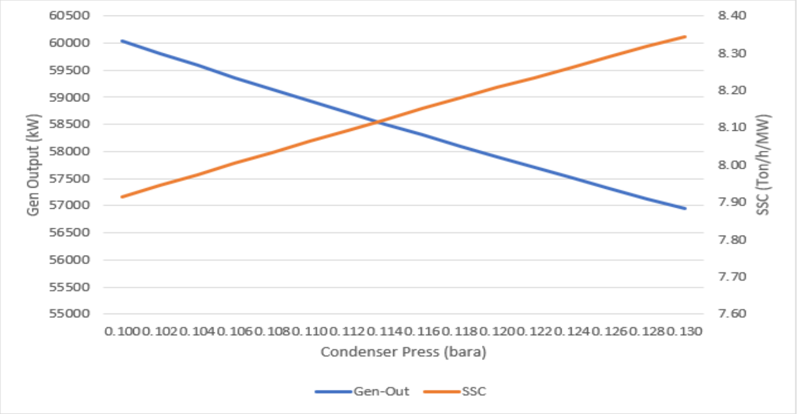

Figure 5 Condenser pressure simulation

Figure 5 shows the simulation data of condenser pressure on generator output and SSC, where the simulation was conducted in the range of 0.10 to 0.13. This range was obtained based on the condenser design data, which was 0.10 at the time of commissioning, with the expectation that returning the condenser pressure to its initial value would improve exergy efficiency. The simulation results indicate that the lower the condenser pressure is maintained, the higher the generator output obtained, which also means the SSC becomes smaller. By returning the condenser pressure to 0.10, a generator output of 60 MW and an SSC of 7.01 tons/h/MW will be achieved. In the Salak Geothermal Power Plant #1 system, the cooling water auxiliary equipment system and gas remover system (GRS) function to maintain the condenser pressure within its normal operating range. The cooling water system operates by supplying cooling water from the cooling tower into the condenser to condense the steam entering from the turbine. The GRS system is designed to extract non-condensable gas (NCG) present within the condenser. The presence of NCG in the condenser can increase condenser pressure due to the non-condensable nature of NCG, necessitating its removal from the condenser. The GRS system consists of an ejector, inter-condenser, and after-condenser. However, as the NCG concentration from the well increases, the current GRS system is unable to maintain condenser pressure at 0.10 as during commissioning. One possible solution is to add a liquid ring vacuum pump (LRVP) component to the GRS system.

5 Conclusion and Recommendation

This study provides a comprehensive analysis of the Mount Salak Geothermal Power Plant Unit #1, revealing significant inefficiencies due to exergy losses in key components. The findings indicate that the plant's overall exergy efficiency is currently 66.88%, with the turbine and condenser experiencing the highest exergy losses (13.76% and 10.01%, respectively). These inefficiencies are largely attributed to aging components, fluctuations in steam quality, and pressure imbalances. This is any recommendation for Salak Geothermal Power Plant #1 to get maximum output generator and high efficiency exergy:

- The turbine, which contributes the largest share of exergy losses, should be the primary focus for optimization. Proposed actions include periodic maintenance, cleaning, and potential replacement of turbine blades during planned shutdowns. Additionally, adjusting the turbine inlet pressure to 7.02 bara can enhance its exergy efficiency, increasing the overall system's performance.
- The condenser, which also experiences significant exergy losses, can benefit from routine maintenance such as nozzle cleaning. More importantly, restoring the condenser pressure to 0.10 bara, as recommended by the simulation, will reduce exergy losses and improve plant output. The integration of a Liquid Ring Vacuum Pump (LRVP) in the gas removal system (GRS) could further support this optimization.
- As part of the plant's ongoing performance improvement strategy, routine exergy audits and performance monitoring should be conducted to ensure that optimal operating conditions are maintained. This will help mitigate energy losses and extend the plant's operational life.
- Future studies could focus on advanced system optimization techniques, such as the integration of renewable energy sources to complement geothermal generation, and the application of more advanced exergy-based methodologies for further performance improvements.

References

[1] Assad, M El Haj., (2021). *Energy and exergy analyses of single flash geothermal power plant at optimum separator temperature. International Journal of Low Carbon Tech* 16, 873-881

[2] Cengel, Y.A., Boles, M.A. (2015). *Thermodynamics: An Engineering Approach* (8th ed.). McGraw-Hill Education, New York

[3] DiPippo Ronald. (2012) Geothermal Power Plants: Principles, Applications, Case Studies and Environmental Impact

[4] Jalilinasrabady, S., Itoi, R., Valdimarsson, P., Saevarsdottir, G., Fujii, H. (2012). *Flash cycle optimization of Sabalan geothermal power plant employing exergy concept*. *Geothermics*, 43, 75–82

[5] Nasruddin, N., Dwi Saputra, I., Mentari, T., Bardow, A., Marcelina, O., Berlin, S. (2020). *Exergy, exergoeconomic, and exergoenvironmental optimization of the geothermal binary cycle power plant at Ampallas, West Sulawesi, Indonesia*. *Thermal Science and Engineering Progress*, 19, 100625

[6] Pambudi, N.A., Itoi, R., Jalilinasrabady, S., Jaelani, K. (2014). *Exergy analysis and optimization of Dieng single-flash geothermal power plant*. *Energy Conversion and Management*, 78, 405–411

[7] Pambudi, N.A., Itoi, R., Jalilinasrabady, S., Jaelani, K. (2015). *Performance Improvement of Single-Flash Geothermal Power Plant Applying Three Cases Development Scenarios Using Thermodynamic Methods*. *Proc. World Geothermal Congress*, Melbourne, Australia

[8] Rudiyanto, B., Bahthiyar, M. A., Pambudi, N. A., Widjonarko, & Hijriawan, M. (2021). *An update of second law analysis and optimization of a single-flash geothermal power plant in Dieng, Indonesia*. *Geothermics*, 96, 102212

[9] Ulum, B., Nurrohman., Ambarita, E. (2017). *Energy and exergy analysis of mount salak geothermal power plant unit 1-2-3. IJTech 7:1217-1228*