

Analyzing the Effect of Geothermal Steam Quality Employing on Performance of Single Cylinder Double Flow Turbine

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Abstract

The quality of steam in geothermal power plants is of critical importance, as it directly affects the thermodynamic properties of enthalpy and entropy. Consequently, it plays a decisive role in determining the reliability and performance of the turbine system. Operating data obtained from the Quality Control Unit and Central Control Room between 1 and 30 June 2024 were analyzed to determine enthalpy and entropy values through linear interpolation using the *SteamTab Companion* software. This study aims to evaluate turbine efficiency and gross power output as functions of steam quality, enthalpy, non-condensable gas (NCG) content, and silicon dioxide (SiO₂) concentration over a 30-day observation period. The analysis revealed that the highest steam quality (0.8065) corresponded to an isentropic efficiency of 81.83% on day 11. The maximum actual enthalpy of 2506.040 kJ/kg produced a gross power output of 56,130.493 kW. Conversely, the lowest steam quality (0.80281) resulted in an isentropic efficiency of 79.13% and an actual enthalpy of 2496.99 kJ/kg, with a gross power output of 54,823.975 kW on day 3. The geothermal steam contained an average NCG content of 1.34% and an average SiO₂ concentration of 85.2 ppm. These concentrations were found to significantly influence turbine performance, as reflected by the variations in isentropic efficiency and gross power generation. The findings of this study indicate a direct proportional relationship between steam quality and the turbine's isentropic efficiency, enthalpy, and gross power output.

1. Introduction

Geothermal energy is a clean and renewable energy source with the potential to replace fossil fuels in electricity generation on a global scale. Indonesia, with its extensive network of more than 300 geothermal hotspots, represents a particularly promising opportunity for the utilization of geothermal energy [1]. The potential of geothermal energy in Indonesia that is utilised as a new power plant is 1,948.30 MW, distributed across 13 Geothermal Working Areas (WKP) [2]. One of Indonesia's major geothermal power plants is the Kamojang Geothermal Power Plant (PLTP Kamojang) Units 1, 2, and 3, with a total generating capacity of 235 MW, operated by PT Pertamina Geothermal Energy Kamojang. The geothermal steam in the Kamojang field is classified as a dry-steam type, with an average temperature of 181.82 °C and a high enthalpy value. The findings indicate that, in the

context of geothermal development, the enthalpy value serves as one of the most reliable indicators of performance in the geothermal industry. The conversion of geothermal energy into electrical energy is a highly technology- and capital-intensive process; therefore, geothermal power plants must be designed and operated to optimize the utilization of available energy resources.

The expansion of geothermal energy utilization has generated considerable debate within the industry regarding the most appropriate performance indicators for geothermal power development [3], [4]. The discourse surrounding the utilization of geothermal energy largely centers on four key parameters that are commonly employed in the geothermal industry to evaluate performance. These are thermal efficiency [3], [4], geothermal steam quality [5], utilisation efficiency, as well as a newly proposed performance measure, which we call enthalpy efficiency [4]. It is evident that the geothermal industry places primary emphasis on steam quality prior to advancing into further exploration activities. Steam quality serves as a critical parameter for assessing both the energy production potential and the economic viability of geothermal operations. Achieving a high level of precision in this assessment requires the establishment of accurate parameters, including boundary conditions, inputs, and outputs, which must align with a clear understanding of the process objectives. Such clarity ultimately increases the likelihood of identifying appropriate and widely accepted performance indicators within the geothermal industry.

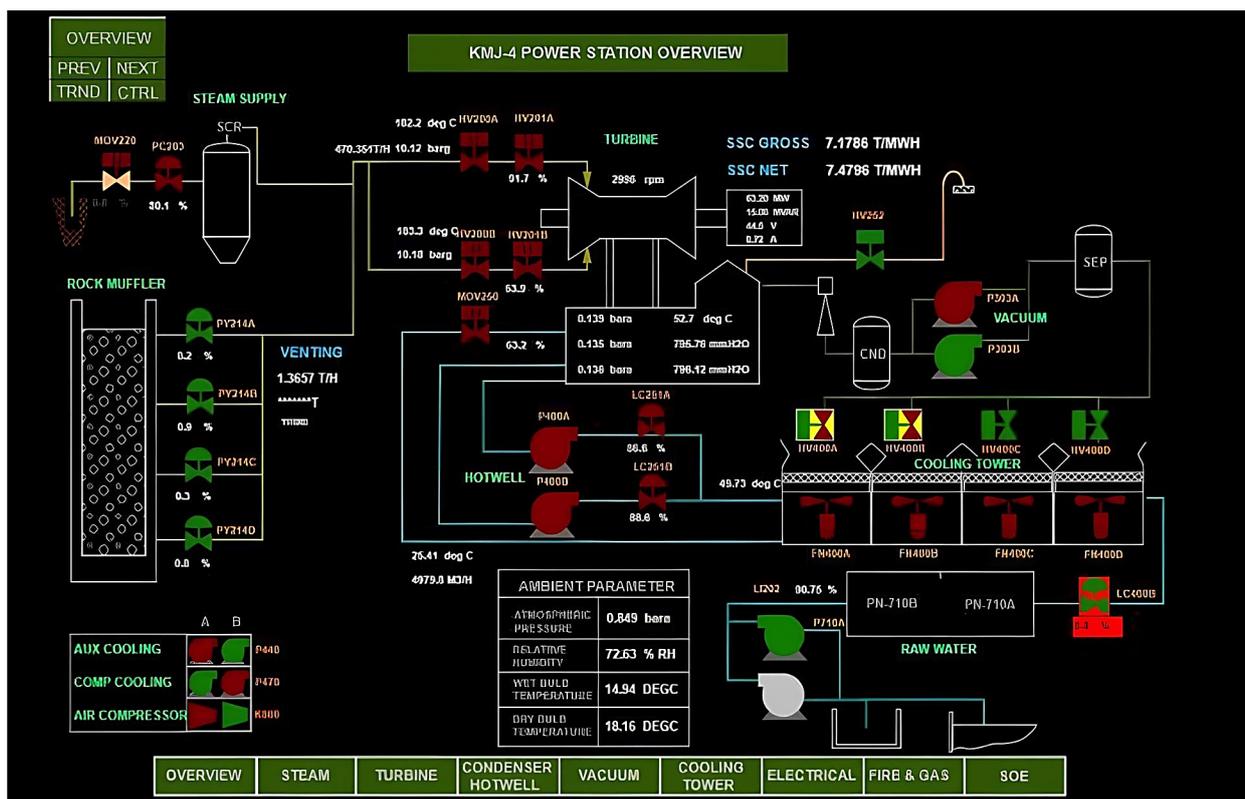


Fig. 1 Process flow diagram of geothermal energy

One of the key components in geothermal power plants is the turbine, which is specifically calibrated to match the steam quality and operational process stages. The single-cylinder, double-flow turbine is commonly employed in geothermal power generation because of its high efficiency in utilizing steam flows from two opposite directions simultaneously [6]. This configuration allows steam to enter from both sides of the cylinder, thereby improving load distribution and reducing axial forces on the rotor, which in turn extends the lifespan of turbine components. These characteristics make this turbine type highly reliable for converting geothermal energy into electrical power with superior efficiency. However, to ensure optimal performance and prevent damage caused by mineral deposition and the accumulation of non-condensable gases (NCG), continuous performance monitoring and evaluation are essential. Maintaining turbine performance is critical for sustaining stable power plant operations, minimizing maintenance costs, and ensuring overall energy efficiency [4].

The utilization of geothermal steam as an energy source requires the removal of impurities before it can be directed to the turbine for power generation. The steam turbine plays a pivotal role in this process, converting the thermal energy of geothermal steam into mechanical energy, which subsequently drives the generator to produce electrical power [7]. However, steam turbines do not always operate under design conditions due to variations in geothermal steam quality. A change in the enthalpy of the steam consequently alters its quality, which in turn

affects the performance of the steam turbine during power generation [8]. As indicated by [9], the quality of steam generated in geothermal power plants is of significant consequence due to its correlation with the entropy and enthalpy values it contains. Achieving a high steam quality will result in increased isentropic efficiency of the turbine, thereby enhancing the power output produced by the generator. The quality of the steam is influenced by the concentration of various minerals and impurities, such as moisture, salt, silica, and sodium. These elements, along with other minerals, can reduce the efficiency and performance of both the turbine and generator, ultimately affecting overall power output.

Several studies have been dedicated to examining how steam quality affects turbine performance, with the aim of improving operational efficiency. One notable study by [10] sought to elucidate the underlying causes of partial load conditions and the impact of steam extraction from the turbine interstage. This research has informed subsequent studies by [11], which further expanded the scope by incorporating considerations such as steam quality, turbine losses, and optimisation techniques. Other research demonstrates that turbine efficiency is significantly influenced by the value of the incoming steam flow rate and the value of the potential heat that can be extracted into load power. In addition to these factors, the heat rate value also exerts an impact on turbine efficiency [12].

The objective of this study is to evaluate the influence of steam quality on turbine performance in geothermal power generation. Several performance metrics are considered, including enthalpy and entropy values, vapor mineral concentration, and steam quality calculations in relation to the turbine's energy generation capacity. The impact of steam quality—particularly the concentrations of non-condensable gases (NCG) and silicon dioxide (SiO_2)—on the isentropic efficiency of turbines has not been extensively examined in previous studies. This aspect represents a critical area for further investigation, as it would enable the geothermal industry to establish more selective criteria for the steam quality utilized in power generation.

2. Methodology

In this study, the analysis utilizes a field database as the primary data source. The collected data are subsequently processed and analyzed, with the results evaluated according to the methodological framework illustrated in Figure 2. The initial dataset includes field measurements such as pressure, temperature, and steam flow rate, as well as field test data on the concentrations of silicon dioxide (SiO_2) and non-condensable gases (NCG) in the geothermal steam. Mathematical equations are employed to perform the required calculations and to determine turbine efficiency, turbine gross work, and steam quality. The resulting datasets, tables, and diagrams are presented as the outcomes of these analyses.

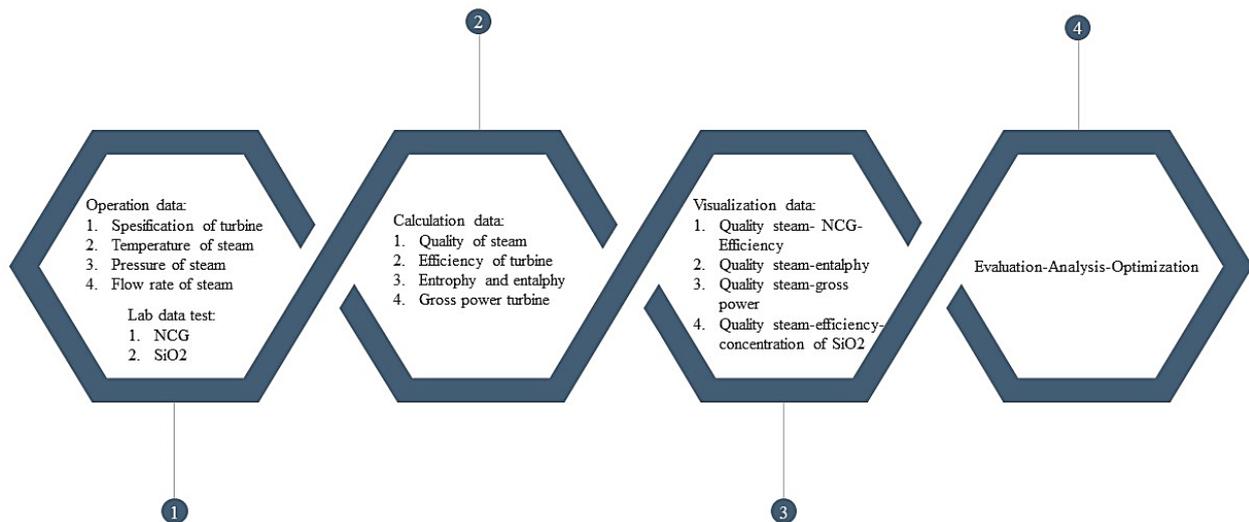


Fig. 2 Stages of the research

2.1. Specification of Single Cylinder Double Flow Turbine Power Generation System

The steam turbine employed in this study is a single-casing, double-flow, condensing type with a design output capacity of 63 MW. The average operating data recorded in June 2023 are as follows: turbine inlet pressure, 10.074 bar; turbine inlet temperature, 181.817 °C; turbine outlet temperature, 54.125 °C; turbine outlet pressure, 0.150 bar; average steam flow rate, 118.331 kg/s; and average output power, 55,344 kW (55.34 MW). A rotational speed of 3000 rpm generates dynamic electrical power with a three-phase current, a frequency of 50 Hz, and a voltage of 11.8 kV. The specifications of turbine single cylinder double flow are described in Table 1.

Table 1 Specification of turbine

Vendor	Fuji Electric System
Model	Single Casing, Double Flow, Condensing Type
Output	63 MW
Pressure (Input)	11.0 bar absolute
Pressure (Output)	0,016 bar absolute
Temperature	184,07 °C
Steam Flow (m/s)	116,260 kg/s
Speed	3000 rpm
Stage	2x12 Reaction Stage

2.2. Single Cylinder Double Flow Turbine Operation Conditions

Actual field data on pressure, temperature, and geothermal steam flow rate were collected from 1 June 2023 to 30 June 2023. The data collection was conducted based on records from the Central Control Room and condensate content analyses. These field data were used to determine the inlet superheated enthalpy (h_1), inlet superheated entropy (s_1), saturated vapor enthalpy (h_{g2}), saturated liquid enthalpy (h_{f2}), saturated liquid entropy (s_{f2}), and saturated vapor entropy (s_{g2}). The calculations were performed using the *ChemicalLogic SteamTab Companion* software, which applies thermodynamic correlations based on the turbine inlet temperature and steam pressure.

Table 2 Operation conditions of geothermal steam

Time	Flowrate (kg/s)	Input		Output		Components			
		P (barg)	T (°C)	P (barg)	T (°C)	SiO2 (ppm)	Ca (ppm)	pH	NCG (%)
1	118,48	10,10	181,96	0,15	54,55	86	0.068	5.03	1.25
2	117,94	10,02	181,56	0,15	53,50	84	0.072	5.01	1.33
3	117,52	9,92	181,21	0,14	52,09	80	0.074	5.01	1.75
4	117,61	9,97	181,37	0,14	53,12	87	0.073	5.01	1.22
5	118,43	10,10	181,93	0,15	54,41	87	0.074	5.03	1.22
6	118,36	10,09	181,90	0,15	54,26	85	0.076	5.04	1.38
7	118,08	10,04	181,67	0,15	53,64	85	0.076	5.04	1.55
8	117,93	10,01	181,55	0,14	53,19	80	0.072	5.04	1.58
9	118,25	10,08	181,84	0,15	54,18	86	0.069	5.03	1.20
10	118,16	10,06	181,78	0,15	54,09	89	0.070	5.02	1.05
11	119,23	10,18	182,14	0,16	55,44	91	0.068	5.03	1.18
12	119,09	10,15	182,08	0,15	54,91	88	0.071	5.02	1.16
13	118,85	10,14	182,07	0,15	54,90	88	0.070	5.03	1.20
14	118,64	10,12	182,01	0,15	54,68	86	0.068	5.04	1.25
15	118,82	10,13	182,02	0,15	54,87	88	0.071	5.05	1.20
16	118,66	10,12	182,01	0,15	54,85	86	0.070	5.03	1.35
17	118,24	10,08	181,85	0,15	54,21	82	0.066	5.01	1.68
18	118,24	10,07	181,84	0,15	54,09	82	0.068	5.03	1.55
19	117,96	10,01	181,59	0,15	53,52	84	0.072	5.05	1.60
20	118,08	10,04	181,76	0,15	53,86	84	0.068	5.04	1.33
21	118,50	10,11	182,00	0,15	54,65	86	0.066	5.01	1.20

Time	Flowrate (kg/s)	Input		Output		Components			
		P (barg)	T (°C)	P (barg)	T (°C)	SiO2 (ppm)	Ca (ppm)	pH	NCG (%)
22	118,29	10,09	181,86	0,15	54,23	86	0.068	5.03	1.45
23	117,98	10,02	181,62	0,15	53,54	82	0.070	5.03	1.56
24	117,64	9,99	181,40	0,14	53,18	81	0.068	5.04	1.60
25	118,49	10,11	181,99	0,15	54,61	82	0.073	5.05	1.35
26	118,03	10,03	181,62	0,15	53,27	80	0.070	5.02	1.55
27	118,36	10,09	181,88	0,15	54,25	88	0.071	5.05	1.22
28	118,40	10,10	181,91	0,15	54,31	88	0.068	5.03	1.30
29	118,47	10,10	181,94	0,15	54,43	87	0.069	5.04	1.20
30	119,19	10,15	182,14	0,16	54,94	88	0.069	5.04	1.12
Average	118,33	10,07	181,82	0,15	54,13	85,2	0,07	5.03	1.35

2.3. Equations of Mathematical

Vapor quality is defined as the proportion of liquid present in the vapor mixture at the turbine outlet. This fractional value is used in calculating the turbine exit enthalpy. Entropy represents the degree of disorder or change within a system under equilibrium conditions. In principle, any system at equilibrium may exhibit a defined entropy state. The vapor quality (geothermal steam) can be determined using the following equation:

$$X_2 = \frac{S_1 - S_{f2}}{S_{g2} - S_{f2}} \quad (1)$$

The term "enthalpy" is used in thermodynamics to express the total amount of internal energy present in a thermodynamic system, including the energy expended in the process of doing work. In order to determine the ideal enthalpy value of steam as it exits the turbine, one may employ the following equation:

$$h_{2s} = h_{f2} + X_2 \cdot (h_{g2} - h_{f2}) \quad (2)$$

The Baumann work equation is employed for the purpose of determining the enthalpy value in the actual conditions at which turbine outlet function.

$$A = 0.425 \cdot (h_1 - h_{2s}) \quad (3)$$

$$h_2 = \frac{h_1 - A \left(1 - \frac{h_{f2}}{h_{g2} - h_{f2}}\right)}{1 + \left(\frac{A}{h_{g2} - h_{f2}}\right)} \quad (4)$$

The isentropic efficiency represents the ratio between the actual performance of a system and the theoretical maximum performance achievable under ideal conditions, given the specified inlet and outlet pressures. The isentropic efficiency of a turbine can be calculated using the following equation (DiPippo, 2008).

$$\eta_{turbine} = \frac{We}{\eta_g} \times 100\% \quad (5)$$

The power generated by the turbine drives the generator to produce electricity. The gross electrical power produced by the generator can be calculated according to the following equation (DiPippo, 2008).

$$W_t = m \cdot s \cdot w_t = x_2 \cdot m \cdot s \cdot w_t \quad (6)$$

$$W_e = \eta_g \cdot W_t \quad (7)$$

3. Results and Discussion

The primary working fluid in geothermal operations is steam extracted directly from the reservoir. The overall performance of the power plant depends on the quality of this steam, which drives the turbines and generators to produce electrical energy. The geothermal steam utilized in this study is classified as *dry steam*, characterized by low moisture content and a relatively high enthalpy value. This research investigates the influence of variations in geothermal steam quality evaluated using the Baumann equation, silicon dioxide (SiO_2) concentration, and non-condensable gas (NCG) content—on turbine performance. Steam quality was assessed based on steam temperature, pressure, enthalpy, and turbine performance parameters. The findings are employed to evaluate the plant's capacity to optimize energy generation efficiency.

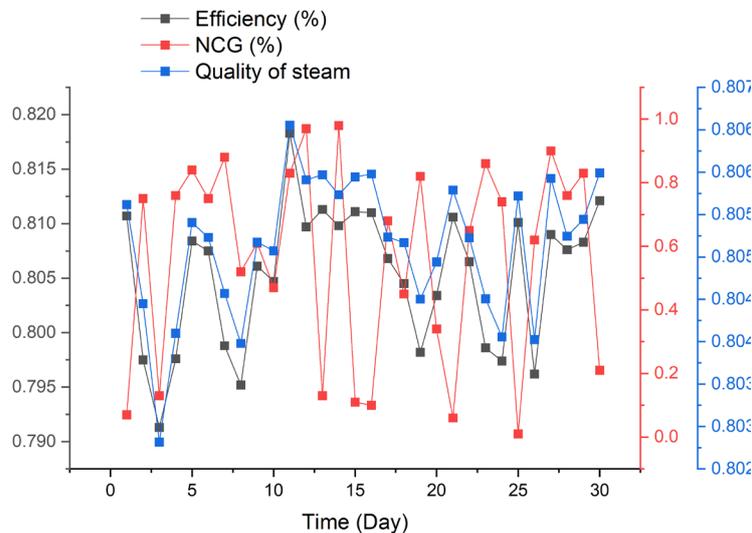


Fig. 3 NCG's effect on turbine efficiency

Figure 3 illustrates the inverse relationship between the concentration of non-condensable gases (NCG) and the efficiency of the steam turbine. As the NCG content in geothermal steam increases, the overall steam quality decreases. Since NCGs possess a lower enthalpy than pure steam, their presence reduces the average enthalpy per unit mass of the steam mixture. Consequently, the amount of useful heat available for conversion into mechanical work decreases, leading to a reduction in turbine work output per unit mass of steam. Therefore, an increase in NCG concentration in geothermal steam corresponds to a decline in turbine efficiency.

Non-condensable gases (NCGs) are gases that cannot be condensed under typical steam turbine operating conditions. Common NCGs present in geothermal steam include methane (CH_4), nitrogen (N_2), and oxygen (O_2). The presence of NCGs in steam can significantly influence the efficiency and performance of steam turbines. Their accumulation reduces the mass flow rate of steam through the turbine and decreases the work produced per unit mass of steam. Furthermore, additional energy is required to extract these gases in the condenser system, which not only degrades steam quality but also increases the potential for corrosion within the power plant infrastructure [4].

Previous research has demonstrated that the presence of 10% NCG in geothermal steam results in a 25% reduction in net work output relative to a clean steam system [13]. The concentration of non-condensable gases (NCG) in geothermal steam is a critical parameter for estimating the recoverable work output. When the NCG concentration exceeds 0.1%, flashing the wellhead to remove these gases can significantly enhance work recovery. However, both thermodynamic and economic factors must be carefully considered in the design of geothermal power plants to ensure efficient and cost-effective NCG separation (Gökçen Akkurt, 2008). It is observed that an increase in non-condensable gas (NCG) content leads to a rise in turbine outlet pressure, which consequently reduces turbine output. This decrease in performance adversely affects the overall economic efficiency of power plant operations [14]. The presence of geothermal steam containing NCG has been shown to reduce power efficiency. This is due to a decrease in the specific expansion work within the turbine, which adversely affects turbine performance [13], [15].

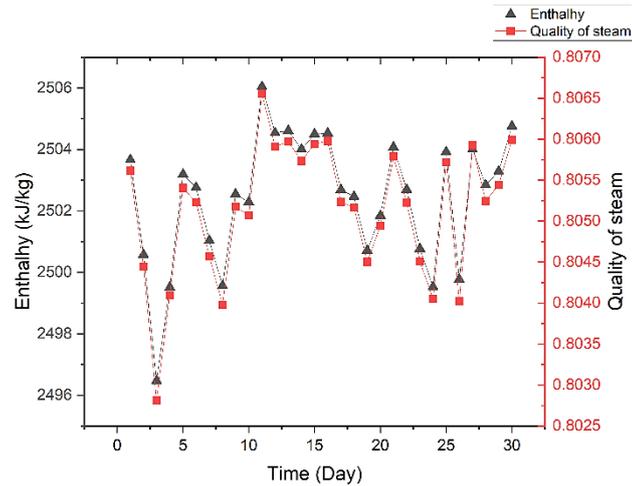


Fig. 4 Steam quality-enthalpy correlation

The concepts of vapor quality and enthalpy are fundamental in thermodynamics, particularly within the context of geothermal power generation. These two parameters are interrelated and exert a significant influence on the efficiency of converting geothermal energy into electrical power. Figure 4 illustrates a direct proportional relationship between vapor quality and turbine efficiency. The highest vapor quality value of 0.8065, corresponding to an actual enthalpy of 2506.040 kJ/kg, was observed on day 11. In contrast, the lowest vapor quality value of 0.8028, resulting in an actual enthalpy of 2496.469 kJ/kg, was recorded on day 3. As posited by [16], enthalpy is a thermodynamic term signifying the quantity of internal energy present in a thermodynamic system. This energy can be utilized for mechanical work. Therefore, a higher enthalpy value corresponds to a greater amount of internal energy that can be harnessed by the turbine for energy production. As the temperature of the substance (in this case, vapor) increases, the kinetic energy of its constituent particles also rises. This kinetic energy forms part of the internal energy of a substance, which represents the primary component of enthalpy [17]. Figure 4 shows that a low actual enthalpy of steam indicates lower steam quality. The specific enthalpy value is directly proportional to vapor quality; that is, the higher the vapor quality, the higher the specific enthalpy value. This is because dry saturated vapor possesses higher internal energy compared to saturated water. In other words, drier vapours contain more heat energy [3]. This conclusion is supported by the findings of [18] research, which demonstrated that the enthalpy value of dry steam is higher than that of binary steam. This results in a higher energy output and conversion efficiency.

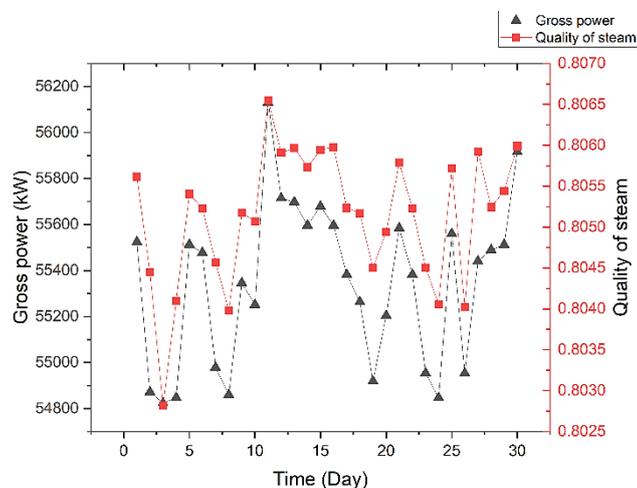


Fig. 5 Steam quality-gross power turbine correlation

Gross turbine power is defined as the total output power produced by a steam turbine, derived from the kinetic energy of the steam that drives the turbine blades. Figure 5 illustrates that steam quality is directly proportional to the gross power generated by the turbine. The highest steam quality value of 0.8065 produced

56,130.493 kW of gross power on day 11, while the lowest steam quality value of 0.8028 resulted in the production of 54,823.975 kW of gross power on day 3. This is consistent with the research conducted by [9], [19], which stated that the vapour quality is directly proportional to the power produced by the generator. The quality of the vapor is directly proportional to the enthalpy value, as shown in Figure 4. Therefore, it can be concluded that an increase in vapor quality corresponds to a rise in enthalpy. A higher enthalpy value signifies greater internal energy within the vapor, which is converted into kinetic energy as the steam expands through the turbine nozzles. This increase in kinetic energy generates higher thrust on the turbine blades, resulting in faster rotor rotation and, consequently, enhanced power output. [18] posits that the quality of steam is inversely correlated with the enthalpy value; as the enthalpy value increases, so does the dryness of the steam, as indicated by a reduction in the steam moisture value. The reduction in gross power output is influenced by several factors, including decreases in temperature and pressure, as well as the presence of steam impurities that are not effectively removed. These impurities can cause corrosion and erosion of turbine components, thereby disrupting the steam flow over the turbine blades and reducing overall performance.

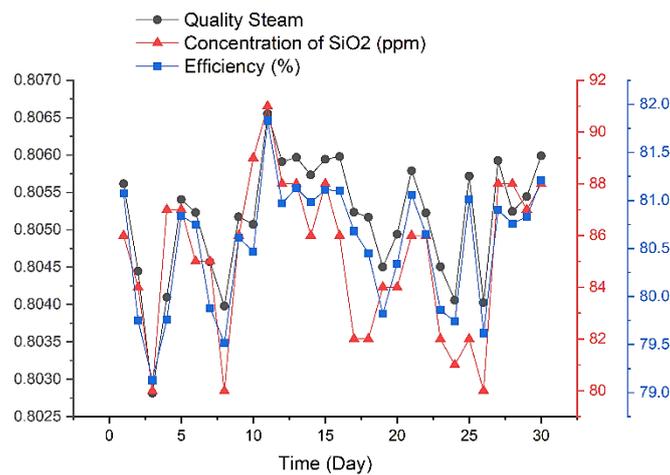


Fig. 6 Steam quality-concentration SiO₂-efficiency correlation

Based on the presented graph, steam quality fluctuates slightly over the 30-day observation period but remains relatively stable, with values consistently around 0.8056. This is in line with the findings reported by [20], who emphasized that maintaining high steam quality is crucial for the efficient operation of power plants and industrial processes. Fluctuations in steam quality can impact turbine performance and overall plant efficiency. In addition to steam quality, the graph shows significant variations in SiO₂ concentration and turbine efficiency. SiO₂ levels fluctuate more noticeably compared to steam quality and efficiency, indicating periods of both higher and lower concentrations. Elevated SiO₂ concentrations can lead to scaling on turbine blades and other critical components, reducing efficiency and increasing maintenance costs [21]. Efficiency values range between approximately 80% and 90%. Similar to SiO₂ concentration, efficiency shows variability but generally trends higher, indicating that the process maintains relatively high efficiency throughout the 30-day period. There appears to be a negative correlation between SiO₂ concentration and efficiency; as SiO₂ concentration increases, efficiency tends to decrease, and vice versa. This inverse relationship aligns with the expectation that higher SiO₂ levels in the steam negatively impact the overall system efficiency. Studies have shown that effective silica removal processes are essential for maintaining high efficiency in steam systems. The negative correlation observed in the graph is consistent with findings by [22], who reported that improved silica removal leads to enhanced operational efficiency.

4. Conclusions

The objective of this study is to evaluate the quality of steam generated from geothermal sources, with particular emphasis on the effects of varying concentrations of non-condensable gases (NCG), silica (SiO₂), and enthalpy on turbine energy output and the overall efficiency of the Kamojang Geothermal Power Plant. A high enthalpy value indicates greater energy output. However, enthalpy exhibits an inverse relationship with steam quality, which directly influences turbine performance in terms of gross power generation and isentropic efficiency. Elevated NCG concentrations reduce both the quality and enthalpy of geothermal steam, thereby diminishing turbine efficiency. In contrast, increased SiO₂ concentrations appear to enhance steam quality and the isentropic efficiency of the turbine.

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Conflict of Interest

Authors declare that there is no conflict of interests regarding the publication of the paper.

Author Contribution

The authors confirm contribution to the paper as follows: **study conception and design:** Author Elli Prastyo and Ninin Asminah, Author Y; **data collection:** Author Muhammad Tarish, Elli Prastyo, Ninin Asminah; **analysis and interpretation of results:** Author Elli Prastyo, Ninin Asminah, Yully Mulyani, and Indah Dhamayanthie; **draft manuscript preparation:** Elli Prastyo, Muhammad Tarish, Ninin Asminah, Indah Dhamayanthie.

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