Frontiers in Water and Environment 10, Issue 1 (2026) 55-65

Frontiers in Water and Environment

Journal homepage:
https://karyailham.com.my/index.php/fwe/index
ISSN: 2785-9029

Performance Analysis of Hydropower Generation Based on Inflow and Capacity Factor at PLTA Wlingi

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ARTICLE INFO

Article history:
Received 29 March 2026
Received in revised form 18 May 2026
Accepted 10 June 2026
Available online 6 July 2026

Keywords:
Hydropower performance; power plant efficiency; water discharge analysis; operational hours; energy conversion

ABSTRACT

Hydropower is an important renewable energy source that converts water potential into electrical energy through turbine–generator systems. The performance of a hydropower plant is influenced by several operational parameters such as water inflow, reservoir elevation, operational hours, and installed capacity. Therefore, evaluating these parameters is necessary to understand how effectively water resources are utilized for electricity generation. This study aims to analyze the operational performance of PLTA Wlingi using operational data from 2021 to 2025. The research mesthod includes hydraulic power calculation based on water discharge and head, capacity factor analysis, and ratio analysis between operational parameters such as operational hours, inflow, generated power, and capacity factor. The results show that the capacity factor of the hydropower plant varies between 32% and 52.9%, depending on operational hours and water availability. The analysis also indicates that the relationship between inflow and generated power remains relatively stable, with an average requirement of approximately 4.3 m^3/s of inflow to produce 1 MW of electrical power. In addition, the ratio analysis shows that approximately 23.5 operational hours are required to achieve 1% capacity factor and around 2.3 m^3/s inflow is associated with a 1% capacity factor increase. These results indicate that the operational performance of the hydropower plant is strongly influenced by water availability and plant operating conditions. The findings of this study provide useful insights for evaluating hydropower plant performance and improving the management of water resources for electricity generation.

1. Introduction

Hydropower is one of the most widely utilized renewable energy sources for electricity generation due to its high efficiency, reliability, and relatively low environmental impact compared to fossil fuel–based power plants [1]. Hydropower plants convert the potential and kinetic energy of water into electrical energy through turbine–generator systems [2], where the performance of

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electricity generation is strongly influenced by several operational parameters such as water inflow, reservoir elevation, operational hours, and installed generating capacity [3]. Evaluating these parameters is essential to understand how effectively the available water resources are converted into electrical energy and to assess the operational performance of a hydropower plant. One important indicator used to measure the operational performance of a power plant is the capacity factor, which represents the ratio between actual electricity generation and the maximum possible generation based on the installed capacity [4]. In Indonesia, PLTA Wlingi plays an important role in supplying renewable electricity to the regional power system. However, the actual power generation of a hydropower plant does not always reach its installed capacity due to variations in water availability and operational conditions. Therefore, analyzing the relationship between inflow discharge, operational hours, generated power, and capacity factor is important to evaluate the performance of the hydropower plant [5].

1.1 State of the Art

Various studies have been conducted to analyze the performance of hydropower plants using different approaches, such as hydraulic power estimation, capacity factor analysis, and operational parameter evaluation. Previous research generally focuses on the influence of inflow discharge, hydraulic head, and operational conditions on electricity generation performance. These studies indicate that variations in water availability significantly affect hydropower generation and plant efficiency. However, comprehensive analyses that simultaneously evaluate the relationship between inflow, operational hours, generated power, and capacity factor using ratio-based analysis are still relatively limited [6,7]. State of the Art on hydropower performance evaluation from several previous studies is presented in Table below.

Table 1
State of the art

Reference	Research Focus	Method	Key Findings
[8]	Hydropower plant performance evaluation	Hydraulic power and efficiency analysis	Inflow and head significantly influence electricity generation efficiency.
[9]	Hydropower operational performance	Capacity factor analysis	Higher inflow increases electricity production and plant utilization.
[10]	Hydropower generation optimization	Hydrological modeling	Accurate inflow prediction improves generation planning and efficiency.
[11]	Hydropower operational analysis	Correlation between inflow and power output	Demonstrates strong relationship between water discharge and generated power.
[12]	Performance analysis of PLTA Wlingi	Hydraulic power estimation, capacity factor analysis, and ratio analysis	Evaluates the relationship between inflow, operational hours, generated power, and capacity factor during 2021–2025.

The summary of previous studies presented in Table above shows that most research has focused on analyzing hydropower performance using hydraulic power estimation, capacity factor evaluation, and the relationship between inflow and generated power [13,14]. These studies consistently indicate that water discharge and hydraulic conditions play a significant role in determining electricity production and plant efficiency. However, the majority of existing research tends to examine these parameters separately or focuses only on specific aspects of hydropower performance. Therefore, a more comprehensive approach is needed to evaluate the interrelationship between multiple operational parameters simultaneously [15]. In this context, this study contributes by integrating hydraulic power analysis, capacity factor evaluation, and ratio-based analysis to provide a more complete assessment of hydropower plant performance at PLTA Wlingi during the period 2021–2025.

2. Methodology

This study employs a quantitative analysis approach to evaluate the operational performance of PLTA Wlingi using operational data from 2021 to 2025. The data used in this research include inflow discharge, reservoir elevation, operational hours, generated electrical power, and installed capacity[16]. The collected data were first verified and processed to obtain representative annual values. Furthermore, hydraulic power was calculated based on the relationship between water discharge, head, gravitational acceleration, water density, and system efficiency. The capacity factor was also determined to evaluate the utilization level of the installed generating capacity. In addition, several ratio analyses were conducted to examine the relationship between operational hours, inflow, generated power, and capacity factor [17]. The results of these calculations were then presented in the form of tables and graphical visualizations to facilitate interpretation of the hydropower plant performance. The overall research procedure is illustrated in the methodology flowchart shown in Figure 1.

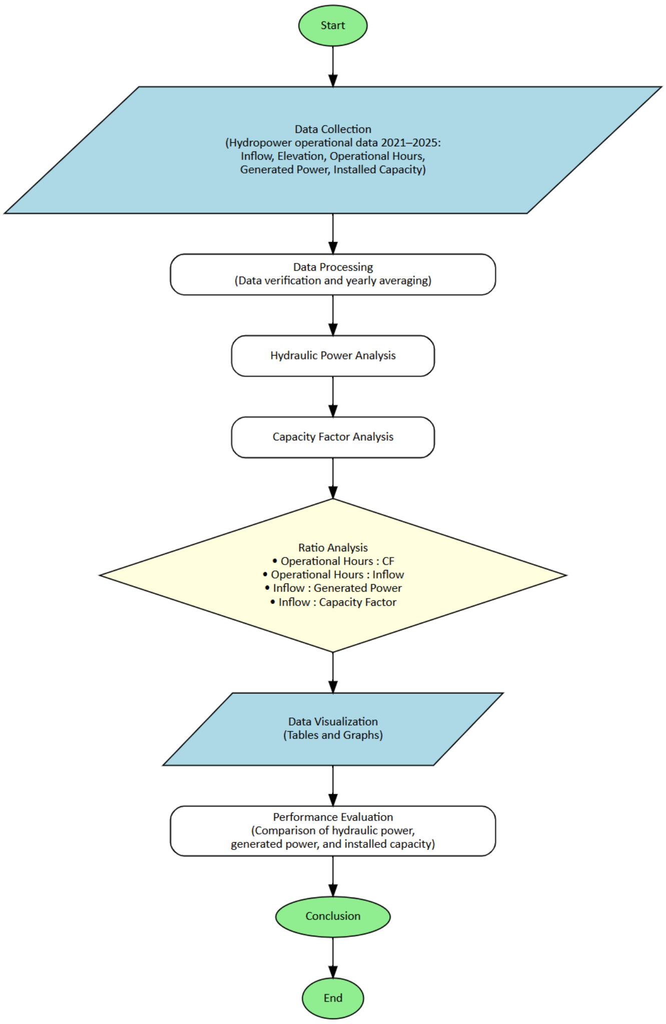

Fig. 1. Flowchart

Before performing the analysis, several fundamental equations are used to calculate the hydraulic power potential and to evaluate the operational performance of the hydropower plant. These equations are essential for estimating the theoretical energy available from water flow and for assessing how effectively the installed generating capacity is utilized during operation. The hydraulic power equation is applied to determine the potential power generated from the inflow discharge and effective head, while the capacity factor equation is used to measure the level of utilization of the installed capacity based on the actual generated power and operational hours. The equations used in this study are presented as follows [18].

Hydraulic Power Equation

The hydraulic power produced by a hydropower plant can be calculated using the following equation[19]:

$$P = g \times H \times Q \times \rho \times \eta \quad (1)$$

where:
P = hydraulic power generated
g = gravitational acceleration (9.81 m/s²)
H = effective head or water height difference (m)
Q = water discharge or inflow rate (m³/s)

ρ (rho) = density of water (1000 kg/m³)
η (eta) = efficiency of the system
This equation is commonly used to estimate the theoretical hydraulic power that can be produced from water flow in a hydropower plant.

Capacity Factor Equation

The capacity factor of a hydropower plant can be determined using the following equation [20]:

$$CF(\%) = \frac{(Installed\ Capacity \times Operational\ Hours)}{(Power \times Operational\ Hours)} \times 100\% \qquad (2)$$

where:
CF (%) = capacity factor of the power plant (%)
Installed Capacity = maximum installed generating capacity of the power plant s
Power = actual generated electrical power during operation
Operational Hours = total operating hours of the power plant within a certain period (hours)
This equation is used to determine the utilization level of the installed capacity compared to the actual electricity generation. The capacity factor indicates how effectively a power plant operates relative to its maximum installed capacity[21]. In this study, the capacity factor is used to evaluate the operational performance of PLTA Wlingi during the period 2021–2025. The calculated results provide an overview of how efficiently the hydropower plant converts its installed capacity into actual electricity production under varying operational and hydrological conditions.

3. Results

This section presents the results of data analysis related to the operational performance and electricity production of PLTA Wlingi during the period 2021–2025. The analysis is based on several key operational parameters, including capacity factor, operational hours, generated power, reservoir elevation, and inflow conditions. These parameters are used to evaluate the relationship between water availability, plant operation, and electricity production. The results are presented in the form of tables and graphical comparisons to provide a clearer understanding of the performance characteristics of the hydropower plant. Tables 1–6 summarize the operational data and ratio analysis between important variables, while the figures illustrate the comparison between hydraulic power, generated power, and installed capacity. Through this analysis, the operational efficiency and utilization of the hydropower plant can be better understood.

Table 2
Summary of electricity production at PLTA Wlingi

Year	CF(%)	Operational Hours	Power (MW)	Electricity Production (Kwh)
2021	44.3	1029.4	23.9	24661.2
2022	48	1098.8	25.9	28491.2
2023	37.6	924.	20.3	18781.3
2024	32	802.1	17.3	13891.2
2025	52.9	1156.8	28.5	33056.6

The capacity factor (CF) represents the level of utilization of the installed capacity of a hydropower plant during its operational period. It indicates how effectively the plant converts its installed generating capacity into actual electricity production over a certain time. Based on the operational data of PLTA Wlingi, the results summarized in Table 2 Summary of Electricity Production at PLTA Wlingi.

Table 3
Reservoir elevation and inflow

Year	Elevation(m)		Inflow (m3/det)
	Max	Min	
2021	163.5	162.9	102.7
2022	163.5	161.8	115.5
2023	163.5	161.7	90.4
2024	163.4	161.6	70.5
2025	163.5	161.4	123.2

Table 3 presents the reservoir elevation and inflow conditions of PLTA Wlingi during the period 2021–2025. The elevation data consist of the maximum and minimum water levels in the reservoir, which indicate the variation of water storage that can influence the available hydraulic head for electricity generation. Based on the data, the maximum reservoir elevation remains relatively stable at around 163.4–163.5 m, while the minimum elevation varies between 161.4 m and 162.9 m. In addition, the inflow values show noticeable fluctuations each year, ranging from 70.5 m^3/s in 2024 to 123.2 m^3/s in 2025. These variations reflect changes in river discharge entering the reservoir, which are generally influenced by hydrological conditions such as rainfall and upstream water availability. Higher inflow values provide greater water potential for power generation, while lower inflow conditions may limit the available water supply for turbine operation. Therefore, reservoir elevation and inflow play an important role in determining the operational performance and electricity production of the hydropower plant.

Table 4
Ratio of operational hours to capacity factor

Year	Operational Hours	CF(%)	Operational Hours : CF(%)
2021	1029.4	44.3	23.2
2022	1098.8	48	22.8
2023	924	37.6	24.5
2024	802.1	32	25
2025	1156.8	52.9	21.8
Average			23.5

The relationship between operational hours and the capacity factor (CF) of PLTA Wlingi during the period 2021–2025 is summarized in Table 4. The ratio shown in the last column is obtained by dividing the operational hours by the capacity factor for each year. This calculation is intended to illustrate how the duration of plant operation relates to the level of utilization of the installed generating capacity. Based on the results, the ratio values range from 21.8 to 25, with an average value of 23.5. From this comparison, it can be interpreted that for every 1% increase in the capacity factor, the hydropower plant needs to operate for approximately 23.5 hours on average. The highest ratio occurs in 2024 with a value of 25, indicating that although the plant operated for 802.1 hours, the resulting capacity factor was relatively low at 32%. Conversely, the lowest ratio appears in 2025 with a value of 21.8, which corresponds to the highest operational hours (1156.8 hours) and the highest capacity factor (52.9%). These results suggest that higher operational hours generally contribute to better utilization of the generating capacity, although the relationship is also influenced by other factors such as water availability and plant operating conditions.

Table 5
Ratio of operational hours to inflow

Year	Operational Hours	Inflow (m3/det)	Operational Hours : Inflow (m3/det)
2021	1029.4	102.7	10
2022	1098.8	115.5	9.5
2023	924.	90.4	10.2
2024	802.1	70.5	11.3
2025	1156.8	123.2	9.3
	Average		10

An analysis of the relationship between operational hours and inflow at PLTA Wlingi during the period 2021–2025 is shown in Table 5. The ratio in the last column is obtained by dividing the operational hours by the inflow value for each year. This calculation is used to illustrate how the duration of plant operation corresponds to the amount of water discharge entering the reservoir. Based on the results, the ratio values range from 9.3 to 11.3 with an average value of 10. From this comparison, it can be interpreted that to support an increase of approximately 1% in the capacity factor, an inflow value of around 10 m^3/s is required on average. The highest ratio occurs in 2024 with a value of 11.3, indicating that although the plant operated for 802.1 hours, the inflow was relatively low at 70.5 m^3/s. In contrast, the lowest ratio appears in 2025 with a value of 9.3, corresponding to the highest inflow of 123.2 m^3/s and operational hours of 1156.8 hours. These results indicate that higher inflow generally supports longer plant operation, although the operational duration is also influenced by water management strategies and plant operating conditions.

Table 6
Ratio of inflow to generated power

Year	Inflow (m3/det)	Power (MW)	Inflow (m3/det) : Power (MW)
2021	102.7	23.9	4.2
2022	115.5	25.9	4.4
2023	90.4	20.3	4.4
2024	70.5	17.3	4
2025	123.2	28.5	4.3
	Average		4.3

In Table 6. The ratio in the last column is obtained by dividing the inflow value by the generated power for each year. This analysis is used to illustrate how much water discharge is required to produce a certain amount of electrical power. Based on the results, the ratio values range from 4.0 to 4.4 with an average value of 4.3. From this comparison, it can be interpreted that on average an inflow of about 4.3 m^3/s is required to generate 1 MW of electrical power. The highest ratios occur in 2022 and 2023 with a value of 4.4, indicating that relatively higher inflow was needed to produce the corresponding electrical power in those years. In contrast, the lowest ratio appears in 2024 with a value of 4.0, when the inflow was 70.5 m^3/s and the generated power was 17.3 MW. Overall, these results indicate that the relationship between inflow and generated power remains relatively stable, suggesting that the hydropower plant operates with a consistent performance in converting water discharge into electrical energy.

Table 7
Ratio of inflow to capacity factor

Year	Inflow (m3/det)	CF(%)	Inflow (m3/det) : CF(%)
2021	102.7	44.3	2.3
2022	115.5	48	2.4
2023	90.4	37.6	2.4
2024	70.5	32	2.1
2025	123.2	52	2.3
	Average		2.3

An analysis of inflow and capacity factor (CF) at PLTA Wlingi during the period 2021–2025 is shown in Table 7. The ratio in the last column is obtained by dividing the inflow value by the capacity factor for each year. This calculation is intended to illustrate how the amount of water discharge entering the reservoir corresponds to the utilization level of the installed generating capacity. Based on the results, the ratio values range from 2.1 to 2.4 with an average value of 2.3. The highest ratios occur in 2022 and 2023 with a value of 2.4, indicating that relatively higher inflow was associated with the achieved capacity factor in those years. In contrast, the lowest ratio appears in 2024 with a value of 2.1, when the inflow was 70.5 m^3/s and the capacity factor decreased to 32%. From this comparison, it can be interpreted that to produce 1% of capacity factor, an average inflow of approximately 2.3 m^3/s is required. Overall, these results indicate that variations in inflow influence the capacity factor, since greater water availability generally supports higher plant utilization and improved electricity generation performance.

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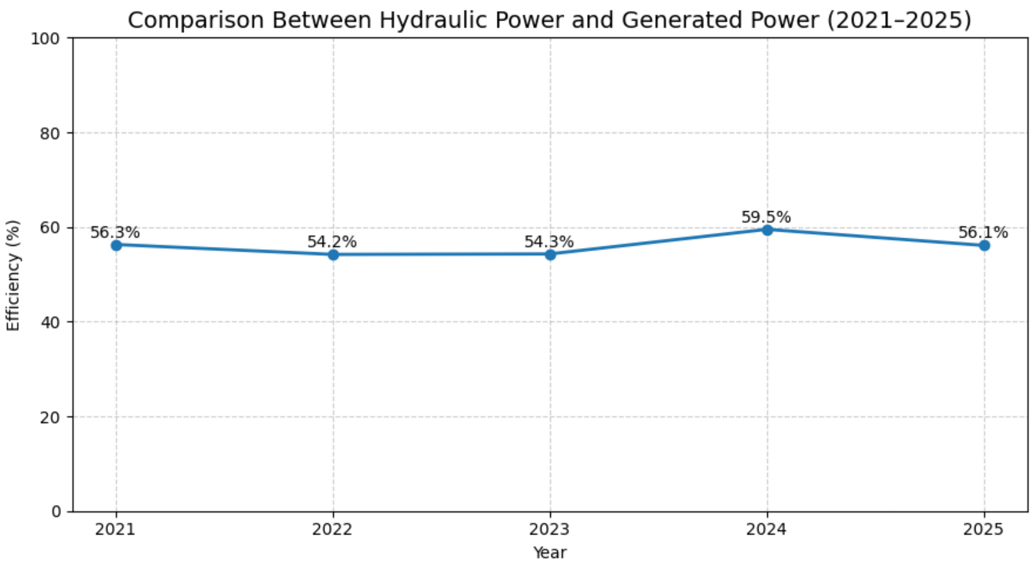

Fig. 2. Hydraulic power

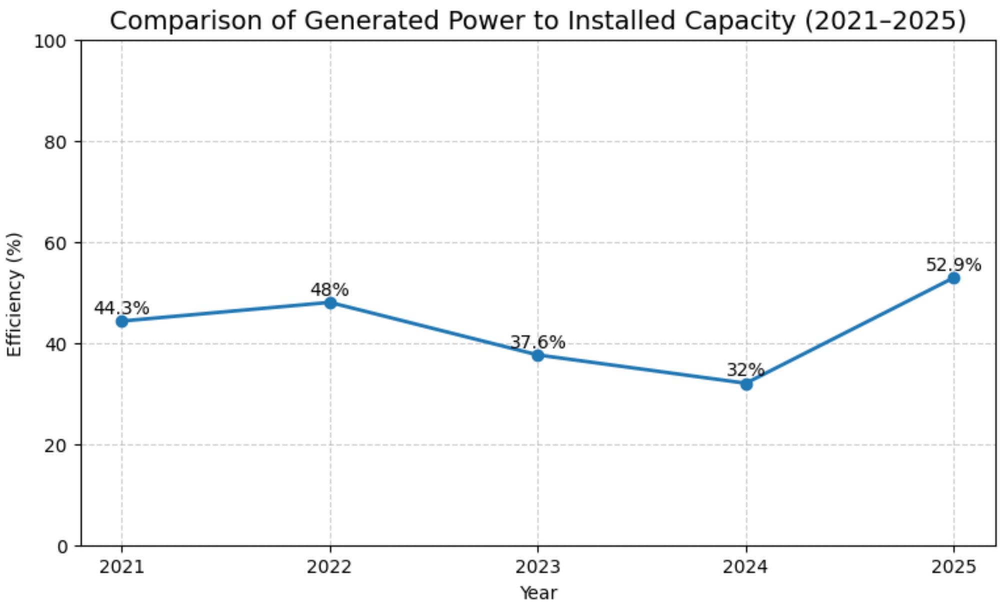

Fig. 3. Generated power

The values of hydraulic power and generated power in Figure 2 and Figure 3 are obtained from hydropower performance calculations based on the relationship between water discharge, head, and system efficiency. In this study, the hydraulic power represents the theoretical power available from the water flow entering the turbine system, which is calculated using hydropower parameters such as gravitational acceleration, effective head, water discharge (inflow), water density, and overall turbine–generator efficiency. The head value is determined from the difference between the reservoir elevation and the turbine outlet level, while the discharge value is obtained from the annual inflow data. By substituting these parameters into the hydraulic power equation, the theoretical hydraulic power for each year can be determined, resulting in values such as 42.5 MW in 2021, 47.8 MW in 2022, 37.4 MW in 2023, 29.1 MW in 2024, and 50.9 MW in 2025.

The generated power shown in the tables represents the actual electrical power produced by the generator, which is obtained from the operational production data of the power plant during the corresponding year. These values reflect the real output of the generating units after accounting for system losses in the turbine and generator. Meanwhile, the installed capacity of the plant is fixed at 54 MW, which represents the maximum electrical power that can be produced when all generating units operate at full rated capacity. The comparison between hydraulic power and generated power indicates the effectiveness of converting water energy into electrical energy, while the comparison between generated power and installed capacity reflects the utilization level of the plant's maximum capability. These calculations allow the operational performance of the hydropower plant to be evaluated under varying hydrological and operational conditions during the 2021–2025 period.

4. Conclusions

The analysis of operational performance at PLTA Wlingi during the period 2021–2025 shows that electricity production is influenced by several key operational parameters, including inflow discharge, operational hours, and installed generating capacity. The results indicate that the capacity factor fluctuates between 32% and 52.9%, reflecting variations in water availability and plant operating conditions each year. The highest plant utilization occurred in 2025 with a capacity factor of 52.9%, while the lowest occurred in 2024 with a capacity factor of 32%.

Further analysis shows that the relationship between operational hours and capacity factor has an average ratio of 23.5, indicating that approximately 23.5 operational hours are required to achieve 1% capacity factor. In addition, the ratio analysis between inflow and generated power shows that an average inflow of about 4.3 m^3/s is required to produce 1 MW of electrical power. Meanwhile, the relationship between inflow and capacity factor indicates that an average inflow of approximately 2.3 m^3/s is associated with a 1% capacity factor. Overall, the results demonstrate that water inflow plays a significant role in determining the operational performance and electricity production of the hydropower plant. These findings provide useful information for evaluating plant efficiency and improving the management of hydropower resources for sustainable electricity generation.

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