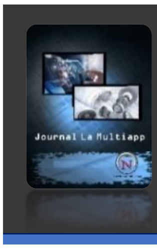

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The Effect of Cooling Water Inlet Emperature (CWIT) on Efficiency USC 1050 MW Steam Power Plant

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Abstract

This research explores the impact of the Cooling Water Inlet Temperature (CWIT) on the efficiency and operational costs of the Ultra Supercritical (USC) 1050 MW Coal-Fired Power Plant (PLTU) in Indonesia. With Indonesia's growing dependence on PLTU as a primary source of electricity, maintaining operational efficiency is critical. The study was conducted at the PLTU Jawa 7 change to 1050 USC type power plan using quantitative descriptive-analytical methods, and data was collected from both the Distributed Control System (DCS) and BMKG. The analysis focuses on how varying CWIT affects condenser pressure, thermal efficiency, Net Plant Heat Rate (NPHR), and fuel consumption. The findings indicate that an increase in CWIT results in higher condenser pressure, reduced vacuum quality, and lower thermal efficiency, leading to an increase in NPHR and higher fuel costs. Furthermore, the research assesses the economic impact, highlighting daily fuel cost penalties and opportunity losses due to reduced electricity generation. The study also provides strategies for mitigating the negative effects of CWIT, including enhanced cooling water flow, condenser cleaning, and the addition of cooling towers. In conclusion, the research emphasizes the importance of controlling CWIT to optimize plant performance and reduce operational costs.

Introduction

The Coal-Fired Power Plant (PLTU) remains a crucial source of energy in Indonesia's electricity sector. According to the Ministry of Energy and Mineral Resources (2022), there are at least 253 units of PLTUs scattered across the nation, contributing over 60% of the national electricity supply. This heavy reliance on PLTUs is largely due to coal being considered the cheapest energy source, its abundance, and the well-established technology used in power generation (Resosudarmo et al., 2023; Charamba et al., 2025; Smarte Anekwe et al., 2024; Sahin et al., 2026). In line with Indonesia's 35,000 MW National Strategic Project, PLTU plays a central role in achieving the target electricity growth of 7.5-10.5% per year, corresponding with the projected economic growth of 5-7% per year. However, despite its strategic position, Indonesia’s PLTUs face serious operational challenges, particularly regarding cooling systems and condensers, which are heavily dependent on the temperature of the surrounding water bodies (Jørgensen & Ma, 2025; Pospolita et al., 2022; Milovanović et al., 2024; Portugal-Pereira et al., 2024; Xie et al., 2024).

Most Indonesian PLTUs still use subcritical and supercritical technologies, with an average thermal efficiency of just 30-40% (Adven Brilian et al., 2024; Moh Jaelani et al., 2022). This is far below the Ultra Supercritical (USC) technology, which can achieve efficiencies above 45% with operating pressures ranging from 254-357 bar and steam temperatures of 600-

700°C. The USC technology operates based on high-pressure and temperature thermodynamics, which reduces coal consumption per kWh compared to conventional plants. However, the efficiency benefits from USC technology heavily depend on the ability of the condenser system to maintain low and stable vacuum pressure. The condenser's function is to convert exhaust steam from the turbine into condensate water, creating a vacuum at the turbine exhaust side. The higher the vacuum, the more energy the turbine can extract. Small disruptions in the condenser system, particularly from increases in the Cooling Water Inlet Temperature (CWIT), can lead to higher backpressure, decreased turbine expansion efficiency, and ultimately, a decrease in overall power plant efficiency.

In Indonesia, the majority of PLTUs use seawater as the main cooling medium due to its abundant availability, especially for large coastal PLTUs (Djazuli & Rahmawati, 2025; Prabowo et al., 2025; Firdaus, 2021; Yudha et al., 2021). However, seawater temperatures are highly affected by seasonal variations, daily cycles, geographic location, and global climate phenomena such as El Niño and long-term ocean warming. A rise in seawater temperature, even by just 1-3°C from the design conditions, can disturb the condenser's thermal balance. This occurs because the temperature difference between the turbine steam and cooling water (known as the Log Mean Temperature Difference or LMTD) shrinks, leading to a decrease in the heat transfer coefficient (Almeshaal & Choubani, 2023; Frank et al., 2021; Safari et al., 2022; Veeraraghavan et al., 2025). As a result, the condensation rate slows, the vacuum pressure drops, and backpressure increases. Technically, each 1°C rise in CWIT can increase the Net Plant Heat Rate (NPHR) by about 0.2-0.3%, depending on the unit's capacity and condenser design. In large units (600-1000 MW), this small deviation can cause significant increases in coal consumption (Wang et al., 2025; Zhang et al., 2010).

The situation becomes even more complex with modern PLTUs like 1050 MW USC, designed with highly specific operational conditions, such as CWIT 29.2 ± 0.24°C, ambient air temperature of 26.9°C, 81% relative humidity, 1010.6 hPa barometric pressure, and an elevation of 1.8 meters above sea level. The performance guarantees (e.g., 991 MW net output/unit and 2199.1 kcal/kWh net heat rate) are calculated based on these conditions. In reality, however, actual operational conditions often deviate due to changes in seawater temperature, especially during the dry season or phenomena like ocean warming (Bilgili et al., 2024; Orysiak et al., 2025; Garcia-Soto et al., 2021; Qiao et al., 2025; Neka et al., 2025). Even slight temperature deviations can cause significant compliance gaps (differences between actual performance and manufacturer’s guarantees), leading to higher fuel costs, lower net output sold to the PLN grid, and ultimately decreased economic efficiency.

The challenges are further exacerbated by the rising temperatures of the sea surface in Indonesian waters due to global climate changen (Dong et al., 2024). Data from the BMKG and the IPCC show that the average seawater temperature in Indonesia has increased by about 0.2-0.4°C per decade. This indicates that the thermal design conditions of PLTUs, which were established 10-15 years ago, are becoming increasingly mismatched with the current operational realities. Without adaptation strategies, these temperature deviations will continue to erode plant efficiency and raise operational costs each year. Over the long term, this could affect the reliability of the national energy system, reserve margins, and PLN’s financial sustainability, especially amid pressure for energy transition and the demand for emission reductions (Apriliyanti et al., 2024; Shahzad & Jasińska, 2024).

This research is significant as it provides a detailed examination of the operational challenges faced by coal-fired power plants, particularly those relying on seawater cooling systems, in the context of rising temperatures. The results of this study will contribute to a better understanding of the economic and operational consequences of climate change on Indonesia’s power sector and offer strategies for improving the long-term sustainability of

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PLTUs. Furthermore, this study will provide valuable insights for policy-making and energy transition planning in Indonesia's power industry.

Methods

This study employed a quantitative descriptive analytical approach to examine the effect of seawater cooling temperature on the thermal and economic performance of a coal-fired power plant. The analysis focused on the relationship between Cooling Water Inlet Temperature (CWIT), condenser pressure, thermal efficiency, and Net Plant Heat Rate (NPHR), as well as the resulting economic impacts associated with changes in plant performance.

The research was conducted at a 2 × 1050 MW Ultra Supercritical (USC) coal-fired power plant equipped with a once-through seawater cooling system. This type of cooling system is highly sensitive to fluctuations in seawater temperature, making it an appropriate case for evaluating the influence of environmental temperature changes on power plant performance. The study focused on Units 1 and 2 of the power plant. The research was carried out from September 2025 to March 2026, including the stages of research preparation, data collection, data processing, technical and economic analyses, and final evaluation.

The study utilized both primary and secondary data. Primary operational data were obtained from the plant's Distributed Control System (DCS), while environmental data were collected from the Indonesian Agency for Meteorology, Climatology, and Geophysics (BMKG). Additional secondary data were obtained from technical documents, operational reports, coal price records, electricity tariff information, and relevant scientific literature.

Primary operational data were recorded automatically by the DCS at five minute intervals throughout the observation period. The collected parameters included Cooling Water Inlet Temperature (CWIT), condenser pressure, thermal efficiency, Net Plant Heat Rate (NPHR), generator output, and other supporting operational variables required for thermal performance evaluation. Environmental data obtained from BMKG included seawater temperature and other meteorological variables relevant to plant operation.

Data analysis was performed in four stages. First, descriptive statistical analysis was conducted to summarize the characteristics and trends of operational and environmental data. Second, linear regression analysis was applied to evaluate the relationship between seawater cooling temperature and key thermal performance indicators, including condenser pressure, thermal efficiency, and NPHR. Third, thermodynamic performance calculations were performed using standard power plant performance equations to quantify changes in efficiency resulting from variations in cooling water temperature. Finally, an economic analysis was conducted by estimating additional coal consumption caused by increased NPHR and calculating the associated fuel cost penalties and potential revenue losses resulting from reduced power generation efficiency.

Results and Discussion

Analysis of the Effect of Cooling Water Inlet Temperature (CWIT) on Condenser Pressure

This study analyzes the relationship between Cooling Water Inlet Temperature (CWIT) and condenser pressure in a coal-fired power plant (PLTU), using data taken from unit performance testing during the quarterly period (April–June). The data obtained includes 15 observations from different measurement points, describing the unit's normal operating conditions. CWIT is measured in degrees Celsius (°C), while condenser pressure is measured in mmHg, corrected for operating conditions.

The range of CWIT values in this study is between 29.50°C to 35.00°C, while the condenser pressure is in the range of 679.15 mmHg to 695.00 mmHg. CWIT was chosen as an

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independent variable because it affects heat transfer in the condenser, which in turn affects the condenser's ability to condense turbine exhaust steam. Condenser pressure as a dependent variable reflects the vacuum condition and the performance of the cooling system, which directly affects the efficiency of the power plant cycle.

Table 1. Descriptive Statistics of Research Variables

Variables	Minimum	Maximum	Average	Standard Deviation
CWIT (°C)	27.80	32.37	30.56	0.94
Condenser Pressure (mmHg)	683.00	688.50	684.81	1.19

The data shows that CWIT has a narrow variation, with an average of 30.56°C and a standard deviation of 0.94°C, indicating stability in the fluctuation of cooling water temperature during the observation period. The condenser pressure ranged from 683.00 mmHg to 688.50 mmHg, with an average of 684.81 mmHg and a standard deviation of 1.19 mmHg, indicating the operational stability of the condenser system. These data are valid for further analysis of the relationship between cooling water temperature and condenser performance.

Table 2. Linear Regression Test Results

Model	Variables	B	Std. Error	Beta	t	Sig.
1	(Constant)	723,458	0.717	—	1008,503	0.000
	CWIT	-1.265	0.023	-0.992	-53,901	0.000

Linear Regression Equation

Condenser Pressure= 723.458−1.265×CWIT

Simple linear regression was performed to test the effect of Cooling Water Inlet Temperature (CWIT) on condenser pressure. The analysis results showed that the CWIT regression coefficient was -1.265, which means that every 1°C increase in cooling water temperature causes a decrease in condenser pressure of 1.265 mmHg. This indicates a negative relationship between CWIT and condenser pressure. A significance value (Sig.) of $0.000 < 0.05$ indicates a significant effect of CWIT on condenser pressure. The calculated t value of -53.901, much greater than the t table, indicates a very strong effect of CWIT on condenser pressure. The standardized Beta coefficient of -0.992 indicates that this relationship is very strong and approaches a perfect linear relationship.

Table 3. of Results of the Determination Coefficient Test

Model	R	R Square	Adjusted R Square	Standard Error of the Estimate
1	0.992	0.983	0.983	0.15683

The test results show that 98.3% of the variation in condenser pressure can be explained by CWIT, while the rest is influenced by other factors such as fouling conditions in the condenser and variations in cooling water flow. The R value = 0.992 indicates a very strong relationship between CWIT and condenser pressure. The Adjusted R Square of 0.983 indicates a stable regression model, while the small standard error value (0.15683) indicates a low level of prediction error.

The scatterplot shows a negative linear relationship between CWIT and condenser pressure. The data points form a downward trend, which confirms the regression analysis results, which show that the higher the CWIT, the lower the condenser pressure. Increasing CWIT reduces the effectiveness of heat transfer in the condenser, causing an increase in condenser pressure and a decrease in vacuum quality. This increases the backpressure in the turbine, which reduces turbine efficiency and increases fuel consumption. This decrease in vacuum quality also causes an increase in the Net Plant Heat Rate, which affects the thermal efficiency of the

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Rankine cycle. These results emphasize the importance of controlling CWIT to maintain plant operation stability and efficiency.

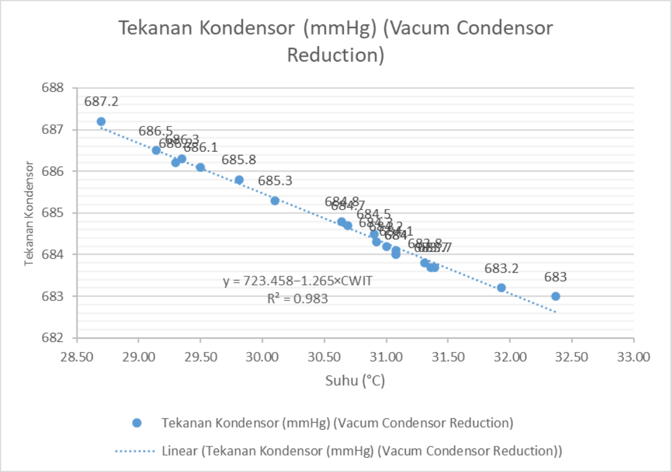

Figure 1. Scatter Diagram of the Relationship between CWIT and Condenser Pressure

Impact of CWIT on Thermal Efficiency and Net Plant Heat Rate (NPHR)

Evaluate the effect of Cooling Water Inlet Temperature (CWIT) on the thermal performance of the plant, especially the net thermal efficiency and Net Plant Heat Rate (NPHR), using direct calculations based on actual operating data.

Calculation of Thermal Efficiency and NPHR

CWIT affects condenser performance in the Rankine cycle. Increasing CWIT reduces the temperature difference between the turbine exhaust steam and the cooling water, decreasing heat transfer efficiency and increasing condenser pressure. This leads to an increase in NPHR and a decrease in net thermal efficiency.

For example, a simulation of calculating NPHR with the following formula.

$$NPHR = \frac{\dot{V}_{fuel}\ X\ HHV\ X\ 252}{P_{net}}$$

It is known:

Net energy = 169,450.05 kWh

Fuel flow = 39.00 kNm³/hour

HHV = 1,125.04 BTU/SCF

NPHR calculation:

$$NPHR = \frac{39{,}00\ X\ 1.125{,}04\ X\ 252}{169.450{,}05}$$

$$NPHR = 2.435{,}50\ kCal/kWh$$

Efficiency:

$$n = \frac{860}{2340{,}00} X100\%$$

$$n = 36{,}80\%$$

Table 4. Thermal Efficiency and NPHR Operating Data

No	CWIT (°C)	Net Energy (kWh)	Fuel Flow (kNm³/hour)	HHV (BTU/SCF)	NPHR (kCal/kWh)	Net Efficiency (%)
1	35.00	169,450.05	39.00	1,125.04	2,435.50	35.31
2	34.10	169,490.00	39.20	1,110.00	2,410.20	35.70
3	33.22	169,511.62	39.60	1,075.95	2,364.21	36.38
4	32.80	169,580.00	40.00	1,080.00	2,350.00	36.60
5	32.10	169,630.00	40.20	1,082.00	2,340.00	36.80
6	31.50	169,680.00	40.50	1,078.00	2,355.00	36.50
7	31.00	169,720.00	40.80	1,076.00	2,370.00	36.20
8	30.50	169,760.00	41.00	1,075.00	2,390.00	35.90
9	30.00	169,790.00	41.10	1,076.00	2,410.00	35.60
10	29.80	169,810.00	41.15	1,077.00	2,430.00	35.30
11	29.60	169,822.00	41.18	1,077.30	2,445.00	35.10
12	29.50	169,784.75	41.20	1,077.65	2,459.66	34.96

Table 4 shows the relationship between CWIT, NPHR, and efficiency. At a high CWIT (35°C), the NPHR reached 2,435.50 kCal/kWh with an efficiency of 35.31%. As the CWIT decreased, the NPHR also decreased, and the efficiency increased. However, at a lower CWIT (29.50°C), the NPHR increased and the efficiency decreased. This indicates that the relationship between CWIT and efficiency is not completely linear. These results indicate that the CWIT has a significant influence on the thermal performance of the plant, but its influence is also influenced by other factors, such as variations in operating load and auxiliary power consumption.

Sensitivity Analysis to Determine Changes in NPHR and Net Thermal Efficiency Due to Changes in Cooling Water Inlet Temperature (CWIT)

A sensitivity analysis was conducted to determine the impact of changes in CWIT on NPHR and net thermal efficiency. Sensitivity was calculated using the formula:

$$Sensitivitas\ NPHR = \frac{\Delta NPHR}{\Delta CWIT}$$

$$Sensitivitas\ Efisiensi = \frac{\Delta Efisiensi}{\Delta CWIT}$$

Where:

SNPHRS = NPHR sensitivity (kCal/kWh per °C)

Sη = efficiency sensitivity (% per °C)

ΔNPHR = change in NPHR value (kCal/kWh)

Δη = change in efficiency (%)

ΔCWIT = change in cooling water temperature (°C)

Example of sensitivity calculation No. 1:

$$S_{NPHR} = \frac{2410,20 - 2435,50}{34,10 - 35,00}$$

$$S_{NPHR} = \frac{-25,30}{-0,90}$$

$$S_{NPHR} = 28,11 kCal/kWh\ °C$$

Example of sensitivity calculation No. 2:

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$$S_n = \frac{35,70 - 35,31}{34,10 - 35,00}$$

$$S_n = \frac{0,39}{-0,90}$$

$$S_n = -0,43\%\ per\ °C$$

Table 5. of CWIT Sensitivity Analysis on NPHR and Efficiency

CWIT (°C)	NPHR (kCal/kWh)	Efficiency (%)	ΔCWIT	ΔNPHR	ΔEfficiency	NPHR sensitivity	Efficiency Sensitivity
35.00	2435.50	35.31	-	-	-	-	-
34.10	2410.20	35.70	-0.90	-25.30	0.39	28.11	-0.43
33.22	2364.21	36.38	-0.88	-45.99	0.68	52.26	-0.77
32.80	2350.00	36.60	-0.42	-14.21	0.22	33.83	-0.52
32.10	2340.00	36.80	-0.70	-10.00	0.20	14.29	-0.29
31.50	2355.00	36.50	-0.60	15.00	-0.30	-25.00	0.50
31.00	2370.00	36.20	-0.50	15.00	-0.30	-30.00	0.60
30.50	2390.00	35.90	-0.50	20.00	-0.30	-40.00	0.60
30.00	2410.00	35.60	-0.50	20.00	-0.30	-40.00	0.60
29.80	2430.00	35.30	-0.20	20.00	-0.30	-100.00	1.50
29.60	2445.00	35.10	-0.20	15.00	-0.20	-75.00	1.00
29.50	2459.66	34.96	-0.10	14.66	-0.14	-146.60	1.40

Table 5 shows the sensitivity between CWIT, NPHR, and efficiency. In the initial data (Nos. 1–5), a decrease in CWIT is followed by a decrease in NPHR and an increase in efficiency, consistent with theory. However, in the subsequent data (Nos. 6–12), this pattern is inconsistent, indicating the influence of other factors such as variations in operating load, fuel flow rate, and auxiliary power consumption. Overall, the sensitivity provides a clearer picture of the relationship between CWIT and plant performance, although other factors may influence the results.

Determination of Representative Sensitivity

$$S_{NPHR} \approx 32,93\ kCal/kWh\ °C$$

$$S_n \approx -0,51\%\ per\ \ °C$$

Sensitivity analysis shows that CWIT has a significant impact on the thermal performance of the power plant, where every 1°C increase in cooling water temperature causes an increase in NPHR and a decrease in efficiency. However, this relationship is not completely linear across all operating conditions as it is influenced by other operational factors. Therefore, controlling CWIT within the optimal range is crucial for maintaining the efficiency and performance of a steam-fired power plant.

Analysis of Performance Deviation Against Manufacturer's Warranty Value

Evaluate the difference between the actual performance of the plant and the manufacturer's guaranteed performance, taking into account the influence of actual operating conditions such as Cooling Water Inlet Temperature (CWIT) and environmental conditions. The evaluation is carried out in two stages: normalization of operating conditions and calculation of performance deviations from the manufacturer's guaranteed parameters. This normalization is important to correct for biases that may arise due to differences between actual and design conditions.

Table 6. Actual Operational Data and Supporting Parameters

Load (MW)	CWIT (°C)	Vacuum (mmHg)	Tdry (°C)	Twet (°C)	RH (%)	Actual NPHR (kCal/kWh)	Fcw	Famb	NPHR Design
181.45	35.00	679.69	31.60	26.30	65.7	2435.50	1.06	1.01	2199

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180.90	34.10	682.50	31.20	26.00	66.5	2410.20	1.05	1.01	2199
178.74	32.50	686.04	30.67	25.70	69.6	2364.21	1.04	1.00	2199
179.50	32.00	687.80	30.50	25.50	68.2	2350.00	1.03	1.00	2199
180.20	31.20	689.10	30.40	25.20	67.5	2340.00	1.02	1.00	2199
179.80	31.00	690.20	30.30	25.10	66.9	2355.00	1.02	1.00	2199
180.50	30.50	691.30	30.10	24.90	65.8	2370.00	1.01	1.00	2199
180.80	30.20	692.10	30.00	24.70	64.7	2390.00	1.01	1.00	2199
181.00	30.00	693.20	29.90	24.60	63.9	2410.00	1.00	1.00	2199
181.20	29.80	694.10	29.80	24.50	62.5	2430.00	1.00	1.00	2199
181.10	29.60	694.80	29.70	24.40	61.8	2445.00	0.99	1.00	2199
181.00	29.50	694.33	31.70	24.33	50.9	2459.66	0.99	1.00	2199

Based on the table, it can be seen that the variation of CWIT is in the range of 29.50°C to 35.00°C and is followed by changes in the actual NPHR value. At high CWIT conditions, the NPHR value tends to be greater, while at lower CWIT, the NPHR shows a decrease until it reaches a certain condition before increasing again. This shows that the relationship between CWIT and thermal performance is not completely linear, and indicates the influence of other operational factors such as load, vacuum conditions, and fuel characteristics.

Normalization of Operating Conditions

Normalized operating conditions are adjusted to the manufacturer's design conditions to mitigate the influence of external factors such as cooling water temperature. The normalization formula used is:

NPHRnorm=NPHRactual×Fcw×Famb

Information:

NPHRnorm = normalized NPHR (kCal/kWh)

Actual NPHR = NPHR from field measurements

Fcw = correction factor due to CWIT

Famb = ambient condition correction factor

Example Calculation For the 1st data:

NPHRnorm=2435.50×1.06×1.01

NPHRnorm=2435.50×1.0706

NPHRnorm=2607.88 kCal/kWh

Table 7. NPHR After Normalization

No	CWIT (°C)	Actual NPHR	Fcw	Famb	NPHR Normalization
1	35.00	2435.50	1.06	1.01	2607.88
2	34.10	2410.20	1.05	1.01	2555.42
3	32.50	2364.21	1.04	1.00	2458.78
4	32.00	2350.00	1.03	1.00	2420.50
5	31.20	2340.00	1.02	1.00	2386.80
6	31.00	2355.00	1.02	1.00	2402.10
7	30.50	2370.00	1.01	1.00	2393.70
8	30.20	2390.00	1.01	1.00	2413.90
9	30.00	2410.00	1.00	1.00	2410.00
10	29.80	2430.00	1.00	1.00	2430.00
11	29.60	2445.00	0.99	1.00	2420.55
12	29.50	2459.66	0.99	1.00	2435.06

The table shows the NPHR values after normalization, which reflect the actual performance after correcting for CWIT conditions and environmental factors.

Performance Deviation Calculation

After the normalized NPHR value is calculated, the performance deviation is calculated to determine the difference between the normalized actual performance and the manufacturer's design value. The deviation calculation uses the following formula:

$$Deviasi(\%) = \frac{NPHR_{norm} - NPHR_{desain}}{NPHR_{desain}} x100\%$$

Information:

NPHRnorm = NPHR after normalization,

NPHRdesign = NPHR manufacturer's guarantee,

Deviation(%) = percentage deviation of performance from design value.

For example, use the 1st data with the value:

$$Deviasi(\%) = \frac{2607{,}88 - 2199}{2199} x100\%$$

$$Deviasi(\%) = \frac{408{,}88}{2199} x100\%$$

$$Deviasi(\%) = 18{,}59\%$$

The results show that in the 1st data, the generator performance requires more heat energy than the design value to produce the same power, which is reflected in the NPHR deviation of 18.59%.

Table 8. of Deviation of NPHR against Manufacturer's Guarantee Value

CWIT (°C)	Normalized NPHR (kCal/kWh)	Design NPHR (kCal/kWh)	NPHR Difference (kCal/kWh)	NPHR Deviation (%)
35.00	2607.88	2199	408.88	18.59
34.10	2555.42	2199	356.42	16.21
32.50	2458.78	2199	259.78	11.81
32.00	2420.50	2199	221.50	10.07
31.20	2386.80	2199	187.80	8.54
31.00	2402.10	2199	203.10	9.24
30.50	2393.70	2199	194.70	8.85
30.20	2413.90	2199	214.90	9.77
30.00	2410.00	2199	211.00	9.60
29.80	2430.00	2199	231.00	10.50
29.60	2420.55	2199	221.55	10.08
29.50	2435.06	2199	236.06	10.74

The table shows that the NPHR deviation is in the range of 8% to 18%, with the highest deviation at high CWIT conditions, which indicates that increasing CWIT worsens the thermal performance of the plant.

Classification of Operating Expenses

To further understand the effect of CWIT on performance deviation, the data is classified based on operating load levels: Turbine Maximum Continuous Rating (TMCR), Maximum Continuous Rating (MCR), and part-load. At high loads, the system is more sensitive to

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changes in CWIT, while at lower loads, other factors such as fuel variations and condenser cleanliness conditions are more influential.

Table 9. Data Classification Based on Operating Expenses

No	Load (MW)	Load Category	CWIT (°C)	NPHR Deviation (%)
1	181.45	TMCR	35.00	18.59
2	180.90	TMCR	34.10	16.21
3	178.74	MCR	32.50	11.81
4	179.50	MCR	32.00	10.07
5	180.20	MCR	31.20	8.54
6	179.80	MCR	31.00	9.24
7	180.50	TMCR	30.50	8.85
8	180.80	TMCR	30.20	9.77
9	181.00	TMCR	30.00	9.60
10	181.20	TMCR	29.80	10.50
11	181.10	TMCR	29.60	10.08
12	181.00	TMCR	29.50	10.74

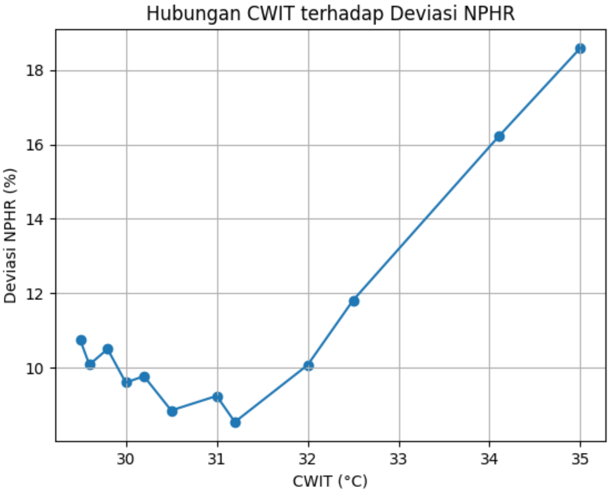

Figure 2. of the Relationship between CWIT and NPHR Deviation

The figure shows that the NPHR deviation tends to be more sensitive to TMCR (high load) conditions compared to MCR. This indicates that at high loads, the system is more dependent on condenser performance, which is affected by cooling water temperature. Increasing CWIT causes an increase in condenser pressure and a decrease in thermal efficiency, which affects heat energy demand. The performance deviation between actual conditions and manufacturer's guarantees indicates that cooling water temperature (CWIT) is a major factor affecting plant performance degradation. The higher the CWIT, the worse the thermal performance, which results in increased fuel consumption and decreased efficiency. Therefore, controlling cooling water temperature and optimizing plant operating conditions are crucial to improve efficiency and reduce electricity production costs.

Economic Impact Analysis of Condenser Performance

To assess the economic impact of power plant performance deviations caused by changes in Cooling Water Inlet Temperature (CWIT). Increasing CWIT causes an increase in the Net Plant Heat Rate (NPHR) and a decrease in net power, which results in increased operational costs and potential revenue loss. The economic analysis was conducted using two approaches: fuel cost penalty and opportunity loss.

Fuel Cost Penalty Calculation

The fuel cost penalty measures the additional fuel costs resulting from an increase in the NPHR. An increase in the NPHR means the plant requires more heat energy to produce the same amount of electricity, thus increasing fuel consumption.

Input data:

Design NPHR = 2199 kcal/kWh

Net energy (Enet) = 169,500 kWh/day

Coal price (Ccoal) = Rp. 900,000/ton

HHV of coal = 4,200,000 kcal/ton

Formula:

$$Fuel\ Cost\ Penalty = \Delta NPHR\ x\ E_{net}\ x\ \frac{C_{coal}}{HHV_{coal}}$$

Calculation Example (CWIT 35°C)

$$\Delta NPHR = 2435{,}50 - 2199 = 236{,}50$$

$$Fuel\ Cost\ Penalty = 236{,}50\ x\ 169.500\ x\ \frac{900.00}{4.200.000}$$

$$Fuel\ Cost\ Penalty = 236{,}50\ x\ 169.500\ x\ 0{,}2143$$

$$Fuel\ Cost\ Penalty\ \approx Rp\ 8.57\ juta/hari$$

Table 10. Fuel Cost Penalty for 12 Periods

No	CWIT (°C)	Actual NPHR	NPHR Design	ΔNPHR	Energy (kWh/day)	Fuel Cost Penalty (Rp/day)
1	35.00	2,435.50	2,199.00	236.50	169,450.05	8,587,486
2	34.10	2,410.20	2,199.00	211.20	169,490.00	7,670,633
3	32.50	2,364.21	2,199.00	165.21	169,511.62	6,001,075
4	32.00	2,350.00	2,199.00	151.00	169,580.00	5,487,124
5	31.20	2,340.00	2,199.00	141.00	169,630.00	5,125,249
6	31.00	2,355.00	2,199.00	156.00	169,680.00	5,672,160
7	30.50	2,370.00	2,199.00	171.00	169,720.00	6,219,026
8	30.20	2,390.00	2,199.00	191.00	169,760.00	6,948,034
9	30.00	2,410.00	2,199.00	211.00	169,790.00	7,676,934
10	29.80	2,430.00	2,199.00	231.00	169,810.00	8,405,595
11	29.60	2,445.00	2,199.00	246.00	169,822.00	8,952,045
12	29.50	2,459.66	2,199.00	260.66	169,784.75	9,483,448

The table shows that the fuel cost penalty ranges from Rp5.13 million to Rp9.48 million per day, depending on the CWIT. This pattern suggests that the higher the NPHR, the higher the daily fuel cost.

Opportunity Loss Calculation

Opportunity loss measures the potential loss of revenue due to a reduction in the net power output of a generator compared to the power guaranteed by the manufacturer. Unlike the fuel cost penalty, which focuses on fuel costs, opportunity loss calculates the lost revenue from electricity that could have been sold to the grid.

Opportunity Loss Formula

$$Opportunity\ Loss = \Delta P_{net}\ x\ t_{operasi}\ x\ Tarif_{listrik}$$

Information:

$$\Delta P_{net} = P_{net,desain}\ x\ P_{net,aktual}$$

With:

ΔPnet= net power reduction (kW)

Pnet,design= net power design/guaranteed (kW)

Pnet,actual = actual net power (kW)

toperasit = operating hours per day

Electricity tariff = electricity tariff (Rp/kWh)

Table 11. period calculation, the following assumptions are used:

Parameter	Mark
Pnet design/guaranteed	181,000 kW
Operating hours	24 hours/day
Electricity rates	Rp1,000/kWh

Calculation Example: Based on the 1st data obtained:

Pnet, design=181,000 kWP

Pnet, actual = 169,450.05 kWP

ΔPnet=181,000−169,450.05

ΔPnet=11,549.95 kW

Furthermore:

Opportunity Loss=11,549.95×24×1,000

Opportunity Loss = Rp277,198,800/day

Table 12. Period Opportunity Loss

CWIT (°C)	Actual Pnet (kW)	Design Net (kW)	ΔPnet (kW)	Operating Hours	Electricity Tariff (Rp/kWh)	Opportunity Loss (Rp/day)
35.00	169,450.05	181,000.00	11,549.95	24	1,000	277,198,800
34.10	169,490.00	181,000.00	11,510.00	24	1,000	276,240,000
32.50	169,511.62	181,000.00	11,488.38	24	1,000	275,721,120
32.00	169,580.00	181,000.00	11,420.00	24	1,000	274,080,000
31.20	169,630.00	181,000.00	11,370.00	24	1,000	272,880,000
31.00	169,680.00	181,000.00	11,320.00	24	1,000	271,680,000
30.50	169,720.00	181,000.00	11,280.00	24	1,000	270,720,000
30.20	169,760.00	181,000.00	11,240.00	24	1,000	269,760,000
30.00	169,790.00	181,000.00	11,210.00	24	1,000	269,040,000
29.80	169,810.00	181,000.00	11,190.00	24	1,000	268,560,000
29.60	169,822.00	181,000.00	11,178.00	24	1,000	268,272,000
29.50	169,784.75	181,000.00	11,215.25	24	1,000	269,166,000

The table shows that opportunity loss ranges from IDR 268.27 million to IDR 277.20 million per day, with the highest value occurring at CWIT 35°C. This pattern indicates that the greater the difference between actual net power and guaranteed power, the greater the potential lost

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electricity revenue. The decrease in net power is caused by deteriorating condenser performance, increased backpressure, and a decrease in the turbine's ability to extract energy from steam.

Sensitivity Analysis of Economic Impact on CWIT

A sensitivity analysis was conducted to determine changes in economic losses due to variations in Cooling Water Inlet Temperature (CWIT). The economic impact was calculated by summing the fuel cost penalty and opportunity loss to obtain the total daily economic loss.

Mathematically, the total economic impact is calculated as follows:

Total Loss = Fuel Cost Penalty + Opportunity Loss

To determine the level of economic sensitivity to CWIT, the equation is used:

$$S_{ekonomi} = \frac{\Delta Total\ Kerugian}{\Delta CWIT}$$

with:

Sekonomi = sensitivity of economic losses to CWIT (Rp/day per °C)

Δ Total Loss = change in total economic losses

ΔCWIT = change in cooling water temperature

Table 13. of Total Economic Impact Due to CWIT Variations

No	CWIT (°C)	Fuel Cost Penalty (Rp/day)	Opportunity Loss (Rp/day)	Total Loss (Rp/day)
1	35.00	8,587,486	277,198,800	285,786,286
2	34.10	7,670,633	276,240,000	283,910,633
3	32.50	6,001,075	275,721,120	281,722,195
4	32.00	5,487,124	274,080,000	279,567,124
5	31.20	5,125,249	272,880,000	278,005,249
6	31.00	5,672,160	271,680,000	277,352,160
7	30.50	6,219,026	270,720,000	276,939,026
8	30.20	6,948,034	269,760,000	276,708,034
9	30.00	7,676,934	269,040,000	276,716,934
10	29.80	8,405,595	268,560,000	276,965,595
11	29.60	8,952,045	268,272,000	277,224,045
12	29.50	9,483,448	269,166,000	278,649,448

Economic Sensitivity Calculation Simulation

For example, sensitivity is calculated on the 1st and 2nd data intervals.

It is known:

Total Loss1=285,786,286

Total Loss2=283,910,633

CWIT1=35.00∘C

CWIT2=34.10∘C

So:

ΔTotal Loss=283,910,633−285,786,286

ΔTotal Loss=−1,875,653

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$\Delta CWIT = 34.10 - 35.00 = -0.90{}^{\circ}C$

$Economy = -1{,}875{,}653 / -0.90$

$Sekonomi = 2{,}084{,}059$ Rp/day per${}^{\circ}C$

These results indicate that in the first to second data interval, every 1°C decrease in CWIT can reduce total economic losses by approximately IDR 2.08 million per day. Conversely, every 1°C increase in CWIT has the potential to increase economic losses within that range.

These results indicate that in the first to second data interval, every 1°C decrease in CWIT can reduce total economic losses by approximately IDR 2.08 million per day. Conversely, every 1°C increase in CWIT has the potential to increase economic losses within that range.

Table 1.14 of Economic Sensitivity to Changes in CWIT

Interval	ΔCWIT (°C)	ΔTotal Loss (Rp/day)	Economic Sensitivity (Rp/day/°C)
1–2	-0.90	-1,875,653	2,084,059
2–3	-1.60	-2,188,438	1,367,774
3–4	-0.50	-2,155,071	4,310,142
4–5	-0.80	-1,561,875	1,952,344
5–6	-0.20	-653,089	3,265,445
6–7	-0.50	-413,134	826,268
7–8	-0.30	-230,992	769,973
8–9	-0.20	8,900	-44,500
9–10	-0.20	248,661	-1,243,305
10–11	-0.20	258,450	-1,292,250
11–12	-0.10	1,425,403	-14,254,030

The table shows the economic sensitivity based on changes in CWIT. The economic impact is more sensitive at higher CWIT ranges because it is directly related to decreased condenser performance, increased NPHR, and decreased net power. Overall, CWIT management needs to be carried out in conjunction with condenser performance optimization and net power efficiency control to minimize the economic impact of the plant.

Technical Mitigation Strategy Analysis

This analysis aims to formulate corrective measures to mitigate the negative impact of Cooling Water Inlet Temperature (CWIT) on the thermal and economic performance of the power plant. Increasing CWIT has been shown to increase condenser pressure, NPHR, and reduce efficiency and net power, resulting in increased fuel costs and potential revenue loss. Mitigation strategies are evaluated through Rankine cycle thermodynamic simulations and sensitivity analysis.

Table 15. of Technical Strategies for Mitigating the Impact of CWIT on Power Plant Performance and Costs

Mitigation Strategy	Technical Mechanism	Effect on Condenser Pressure	Effect on Thermal Efficiency	Effect on NPHR	Effect on Net Power Output	Implementation Complexity	Economic Benefit	Time Horizon
Increase cooling water flow rate	Increase heat removal capacity in the condenser	Decrease	Increase	Decrease	Increase	Low	Reduces fuel cost penalties	Short-term
Condenser cleaning (online/offline)	Remove fouling and scale deposits	Significant decrease	Significant increase	Significant decrease	Increase	Low to Medium	Improves efficiency and reduces	Short-term

	from condenser tubes						operating costs	
Cooling water flow distribution optimization	Optimize cooling water distribution to enhance heat transfer	Decrease	Increase	Decrease	Increase	Low	Improves overall system efficiency	Short-term
Chemical treatment of the cooling water system	Minimize biofouling, corrosion, and scaling	Decrease	Increase	Decrease	Stable	Low	Reduces long-term performance degradation	Medium-term
Condenser retrofit (tube replacement or heat transfer area expansion)	Increase condenser heat transfer capacity	Significant decrease	Significant increase	Significant decrease	Increase	High	Requires substantial investment but provides high long-term returns	Long-term
Load operation optimization	Operate the unit within the optimal load range	Stable	Increase	Decrease	Stable	Low	Reduces operational cost fluctuations	Short-term
Installation of a cooling tower	Reduce cooling water inlet temperature before entering the condenser	Significant decrease	Significant increase	Significant decrease	Increase	High	Significantly reduces fuel and operating costs	Long-term
AI- and IoT-based performance monitoring	Detect performance degradation through real-time monitoring and predictive analytics	Stable	Increase	Decrease	Stable	Medium	Optimizes maintenance and operational costs	Medium-term
Condenser vacuum optimization	Improve vacuum by repairing leaks and optimizing air ejector performance	Decrease	Increase	Decrease	Increase	Low	Reduces energy losses and improves efficiency	Short-term
Preventive maintenance scheduling	Perform scheduled maintenance to maintain condenser performance	Stable	Increase	Decrease	Stable	Low	Maintains long-term operational efficiency and minimizes maintenance costs	Medium-term

The table presents various mitigation strategies that differ in terms of technical and economic impact, as well as implementation complexity. Some short-term strategies, such as condenser cleaning and cooling water flow optimization, have proven effective in reducing condenser pressure and improving thermal efficiency. On the other hand, long-term strategies such as condenser upgrades or the addition of cooling towers require significant investment but can yield significant long-term cost savings. Strategies that improve heat transfer in the condenser (such as condenser cleaning and increasing cooling water flow) have an immediate impact by reducing condenser pressure, which improves Rankine cycle efficiency. This leads to a decrease in NPHR and an increase in net power. Preventive strategies such as chemical treatment and digital monitoring help prevent long-term performance degradation, although their impact is slower to become apparent.

Mitigation strategies that can reduce NPHR and increase net power directly reduce fuel cost penalties and opportunity losses. Low-cost strategies, such as operational optimization and routine maintenance, provide quick and efficient results in the short term, while high-investment strategies, such as condenser upgrades and cooling tower additions, provide greater savings in the long term. An optimal mitigation approach should combine short- and long-term strategies, considering technical, operational, and economic factors to improve plant efficiency, reduce costs, and ensure operational sustainability.

Effect of Cooling Water Inlet Temperature (CWIT) on Condenser Pressure

The results show that Cooling Water Inlet Temperature (CWIT) significantly affects condenser pressure and system vacuum conditions. Increasing CWIT reduces the temperature difference between the turbine steam and the cooling water, reducing the heat transfer rate, and increasing condenser pressure, which degrades the vacuum quality. This has an impact on decreasing thermal efficiency, because the energy required to produce the same power increases. This finding is consistent with the theory that increasing coolant temperature reduces condensation effectiveness and Rankine cycle efficiency (Wang et al., 2024; Ma et al., 2024). However, the relationship between CWIT and condenser pressure is not always linear, especially at low CWIT. This indicates the presence of other factors such as fouling, uneven distribution of cooling water flow, and operational conditions that affect condenser performance (Zhang et al., 2023; Morozyuk et al., 2023; Ben-Mansour et al., 2023).

Impact of Cooling Water Inlet Temperature (CWIT) on Thermal Efficiency and Net Plant Heat Rate (NPHR)

Increasing CWIT directly impacts thermal efficiency and Net Plant Heat Rate (NPHR). Increasing CWIT reduces the effectiveness of heat transfer, which causes NPHR to increase. This means the plant requires more fuel energy to produce the same power. Increasing NPHR also reduces thermal efficiency because higher condenser pressure limits the energy that can be extracted by the turbine (Kulakov et al., 2023; Albdour et al., 2024). However, under some conditions of low CWIT, efficiency and NPHR do not always show significant changes, indicating the presence of other factors affecting plant performance, such as fuel quality and equipment condition (Wasisto & Wahjudi, 2024; Elkelawy et al., 2025).

Performance Deviation to Manufacturer's Warranty Value

The analysis results show significant deviations between the actual performance of the plant and the manufacturer's guaranteed values, particularly for NPHR and net power. These deviations reflect the difference between design conditions and actual operating conditions. An increase in CWIT is the main factor causing the NPHR to increase above the design value, indicating that the plant requires more energy to produce the same power (Nedismanto et al., 2023; Djaeni et al., 2025). The normalization process shows that even when external factors are taken into account, the actual performance remains below the manufacturer's design value, caused by internal factors such as fouling and operational imperfections (Saffiudeen et al., 2026; Pawar & Dondapati, 2026).

Economic Impact of Changes in CWIT on Power Plant Operating Costs

Changes in CWIT significantly impact the operational economics of power plants, particularly in terms of fuel cost penalties and opportunity loss. Increasing CWIT leads to higher NPHR and fuel consumption, which in turn increases fuel costs (Wibowo et al., 2023). Furthermore, the decrease in net power due to increased condenser pressure also results in a loss of electricity revenue that could have been sold (Ali, 2025). These economic impacts demonstrate that CWIT is a critical variable in determining electricity production costs, particularly in high-temperature environments (Lehr & Rehdanz, 2024; Srivastava et al., 2025).

Analysis of Technical Strategies for Mitigation of Performance Decline and Economic Impact

Mitigation strategies that focus on improving condenser performance, such as condenser cleaning, increasing cooling water flow, and optimizing flow distribution, have been shown to be effective in reducing condenser pressure and increasing thermal efficiency. Preventive strategies such as chemical treatment and digital-based monitoring serve to maintain performance in the medium to long term (Çengel & Boles, 2015). Furthermore, high-investment strategies such as condenser upgrades and cooling tower additions offer significant long-term performance improvements, despite the high initial cost (Polyvianchuk et al., 2025).

Conclusion

Based on the results of technical and economic analysis, this study shows that condenser performance plays a key role in the thermal efficiency and operating costs of a steam power plant. Variations in Cooling Water Inlet Temperature (CWIT) affect condenser pressure, efficiency, Net Plant Heat Rate (NPHR), and net power. The results of the study can be summarized as follows:

Increasing CWIT causes an increase in condenser pressure and a decrease in vacuum quality, reducing heat transfer effectiveness and reducing vapor condensation efficiency, which impacts overall system performance.

Increasing CWIT decreases thermal efficiency and increases NPHR, because increasing condenser pressure reduces the energy that can be converted into electrical power.

Performance deviation analysis shows that despite normalization, the actual NPHR value remains higher than the design, indicating internal factors such as fouling and suboptimal flow distribution.

From an economic perspective, increasing CWIT causes an increase in fuel cost penalties and opportunity losses, with economic losses that can reach millions of rupiah per day.

Mitigation strategies that focus on improving condenser performance, such as cleaning and optimizing cooling water flow, are effective in reducing condenser pressure and increasing system efficiency.

Suggestion

Based on the research results, several suggestions for developing and optimizing generator performance are: 1) CWIT control needs to be done by improving the cooling system and adding facilities such as cooling towers to keep the condenser temperature low; 2) Regular condenser maintenance, including cleaning and fouling control, is essential to maintain effective heat transfer; 3) Implementation of a digital or real-time monitoring system to detect changes in performance early so that corrective actions can be taken immediately; 4) For long-term efficiency, consider investing in condenser upgrades or improved heat transfer technology to reduce NPHR and increase net power; 5) Further research is recommended to examine the influence of other variables such as fuel quality, broader environmental conditions, and energy system integration to obtain a more comprehensive analysis model.

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