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Evaluation of the Design for the Construction of a 100 kW Micro Hydropower Plant (PLTMH) Utilizing Condenser Cooling Water Discharge at a 2×25 MW Coal-Fired Power Plant (CFPP)

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Abstract. *The utilization of residual energy within existing power plant systems represents a promising pathway to enhance energy efficiency and support decarbonization without requiring additional fuel consumption. This study evaluates the feasibility of integrating a micro-hydropower (MHP) system into the condenser cooling water discharge of a coal-fired power plant (CFPP) in Indonesia. A quantitative techno-economic assessment framework is employed, incorporating hydraulic analysis, annual energy production estimation, discounted cash flow (DCF) evaluation, environmental impact assessment, and sensitivity analysis. The results indicate that an average discharge of 1.20 m³/s and an effective head of 8.73 m can generate an actual power output of 77.37 kW, corresponding to an annual electricity production of 610.01 MWh. Economic evaluation shows strong feasibility, with a Net Present Value (NPV) of approximately IDR 3.9–4.0 billion, an Internal Rate of Return (IRR) of about 27%, a Levelized Cost of Energy (LCOE) of approximately IDR 725/kWh, and a payback period of 3.6 years. Sensitivity analysis reveals that capacity factor and discount rate are the most influential parameters affecting LCOE and NPV, respectively, while the system remains financially robust under ±10% variations. From an environmental perspective, the system can reduce carbon emissions by approximately 518 tons CO_2 per year without additional fuel consumption. Compared to conventional river-based micro-hydropower systems, the proposed approach offers higher operational stability, lower resource dependency, and reduced investment risk due to the utilization of continuous industrial flow and existing infrastructure. Overall, the findings demonstrate that integrating micro-hydropower into condenser cooling systems is a technically feasible, economically competitive, and low-risk strategy for improving energy efficiency and supporting incremental decarbonization in thermal power plants. The study contributes to the advancement of infrastructure-based energy recovery approaches and provides a practical framework for industrial-scale implementation.*

Keywords - *Micro-hydropower; Waste energy recovery; Techno-economic analysis; Levelized cost of energy (LCOE); Capacity factor; Sensitivity analysis; Coal-fired power plant (CFPP); Energy efficiency; Industrial decarbonization.*

INTRODUCTION

The growing electricity consumption in the industrial sector, coupled with global commitments to reduce carbon emissions, has positioned energy efficiency as a key strategy in the transition toward sustainable energy systems [1], [2]. Despite the increasing penetration of renewable energy technologies, electricity generation in many countries still relies heavily on fossil fuel–based power plants, which continue to operate as stable baseload units within modern power systems [1]. In this context, enhancing efficiency within existing power plant infrastructure—often referred to as within-plant energy optimization—has emerged as an effective approach to reducing energy losses and emissions without requiring additional primary fuel consumption [3].

In addition to conventional efficiency improvement measures, renewable energy technologies have increasingly been integrated into existing thermal power plants through system retrofitting. For example, previous studies have shown that integrating solar power into conventional power plants can significantly improve system efficiency and provide economic benefits based on techno-economic evaluations [13].

Coal-fired power plants (CFPPs) utilize condenser cooling systems that discharge large volumes of water during operation. This discharge flow contains residual hydraulic energy associated with elevation differences and flow velocity, which can theoretically be converted into electrical energy using small-scale hydropower technologies [4], [5]. However, in most CFPPs, condenser discharge water is released without energy recovery. Existing residual energy recovery practices in thermal power plants predominantly focus on waste heat utilization [2], [3], while the hydraulic energy potential in cooling water systems remains largely underexplored.

Micro-hydropower (MHP) systems have traditionally been developed using natural water resources such as rivers, weirs, and irrigation canals [6], [7]. Previous studies primarily focus on hydrological assessment, turbine selection based on head–flow characteristics, and techno-economic feasibility in natural-flow systems. In contrast, research on integrating MHP systems within industrial cooling water infrastructure—particularly in operating CFPPs—remains limited. Moreover, comprehensive studies that simultaneously evaluate technical performance, economic feasibility, and environmental benefits in such systems are still scarce. This gap highlights the need to explore residual hydraulic energy recovery as an alternative pathway to enhance industrial energy efficiency.

This study evaluates the technical potential and feasibility of integrating a micro-hydropower system into the condenser cooling water discharge of a 2 × 25 MW coal-fired power plant. The research addresses three key questions: (1) What is the recoverable power and energy potential from the condenser discharge flow? (2) Is the proposed system economically viable under typical project conditions? and (3) To what extent can the system contribute to improving energy efficiency and reducing carbon emissions?

A deterministic quantitative approach based on steady-state operating conditions is employed to estimate hydropower potential using flow rate, effective head, and system efficiency parameters [6]. Annual energy production is evaluated within a techno-economic framework, including Net Present Value (NPV), Internal Rate of Return (IRR), and Levelized Cost of Energy (LCOE) indicators [3]. In addition, potential carbon emission reductions are estimated using standard grid emission factors [2].

The analysis indicates that an average discharge of 1.20 m^3/s and an effective head of 8.73 m can generate an estimated power output of 77.37 kW, corresponding to approximately 610.01 MWh of annual electricity production. Economic evaluation, assuming a 10% discount rate and a 20-year project lifetime, yields a positive NPV of approximately IDR 3.9 billion, an IRR of around 27%, and an LCOE of approximately IDR 725/kWh, which is lower than the plant's internal electricity cost. Environmentally, the system has the potential to reduce carbon emissions by approximately 518 tons of CO_2 annually without additional fuel consumption.

This study contributes to the existing literature by introducing a novel application of micro-hydropower within a coal-fired power plant through the utilization of condenser cooling water discharge. Unlike conventional hydropower systems that depend on natural hydrological variability, the proposed approach leverages a controlled and continuous industrial flow, resulting in improved operational reliability. Furthermore, this research develops an integrated techno-economic-environmental assessment framework that simultaneously evaluates hydraulic performance, energy generation, financial feasibility, and carbon emission reduction. The proposed system is positioned not merely as an additional power generation unit, but as an embedded energy efficiency strategy based on residual energy recovery, offering a low-cost and scalable pathway for enhancing energy utilization in existing thermal power plants.

METHODS

Research Design

This study adopts a quantitative evaluative–analytical approach within a techno-economic assessment (TEA) framework to evaluate the feasibility of utilizing condenser cooling water discharge from a coal-fired power plant (CFPP) as a micro-hydropower (MHP) energy source. This approach is appropriate as the system represents a quantifiable physical–technical process characterized by key parameters such as flow rate, hydraulic head, energy conversion efficiency, investment cost, operating cost, and emission factors. Accordingly, the evaluation is conducted deterministically based on energy conservation principles and discounted cash flow (DCF) analysis.

A systematic step-by-step procedure is implemented to ensure transparency and reproducibility, including: (i) estimation of theoretical hydraulic power based on flow rate and gross head; (ii) calculation of head losses using the Darcy–Weisbach equation; (iii) determination of effective head; (iv) estimation of actual power output considering system efficiency; (v) calculation of annual energy production using capacity factor; (vi) economic feasibility evaluation using DCF methods; (vii) estimation of carbon emission reduction using grid emission factors; and (viii) sensitivity analysis to assess parameter uncertainty.

The selection of key parameters is based on established micro-hydropower design practices and supported by relevant literature [6], [7], [11], [14]. The use of actual operational data enhances the representativeness and reliability of the analysis. Standardized methods are consistently applied, including hydraulic equations, the Darcy–Weisbach formulation, DCF-based economic indicators, and emission factor calculations aligned with international practices. The assumption of steady-state operation reflects typical baseload conditions of CFPP systems, ensuring realistic system representation. Furthermore, sensitivity analysis is employed to evaluate the robustness of results under varying key parameters, thereby strengthening the validity and reliability of the integrated techno-economic-environmental assessment framework.

Hydraulic Potential Analysis

The study site was selected based on the hydropower potential of condenser cooling water discharge at a coal-fired power plant (CFPP) in Balikpapan, Indonesia. The system operates under low-head conditions with an effective head of 8.73 m and is supported by a stable and continuous flow regime during plant operation. These characteristics make it a promising candidate for micro-hydropower development. The hydrological parameters used in this study were obtained from actual operational data, including measured discharge and effective head (Table 1). The use of real field data enhances the accuracy and representativeness of the analysis. These parameters were subsequently applied to support turbine selection and to evaluate the performance and efficiency of the proposed system.

Table 1. Observed Hydrological Data

No. (in days)	Head Effective	Debit (m³/s)
1	8,73	1,19
2	8,73	1,48
3	8,73	1,21
4	8,73	1,18
5	8,73	1,16
6	8,73	1,24
7	8,73	1,14
8	8,73	1,20
9	8,73	1,20
10	8,73	1,19
11	8,73	1,14
12	8,73	1,28
13	8,73	1,22
14	8,73	1,17
15	8,73	1,18
16	8,73	1,16
17	8,73	1,13
18	8,73	1,26
19	8,73	1,15
20	8,73	1,21
21	8,73	1,23
22	8,73	1,19
23	8,73	1,20
24	8,73	1,19
25	8,73	1,21
26	8,73	1,19
27	8,73	1,08
28	8,73	1,31
29	8,73	1,20
30	8,73	1,27
Average	8,73	1,20
Minimum	8,73	1,08
Maximum	8,73	1,48

Table 1 presents the observed daily discharge data used as the primary input for hydraulic modeling. The inclusion of detailed temporal variation ensures transparency and supports reproducibility of the analysis.

1) Theoretical Power

The theoretical hydropower potential of the flow is calculated using the basic equation for converting potential energy into mechanical energy [7], [14]:

$$P_t = pgQH \tag{1}$$

where:
P_t = theoretical power (W)
ρ = water density (1000 kg/m³)
g = gravitational acceleration (9.81 m/s²)
Q = flow rate (m³/s)
H = gross head (m)

Equation (1) represents the maximum theoretical energy potential, assuming no hydraulic losses or system inefficiencies.

2) Effective Head

The effective head is determined by considering head losses due to friction along the conduit [7], [15]:

$$H_{ef} = H_{bruto} - h_f \tag{2}$$

The friction losses are calculated using the Darcy–Weisbach equation:

$$h_f = f \frac{L}{D} \frac{V^2}{2g} \tag{3}$$

where:
f = darcy friction factor
L = pipe/channel length (m)
D = hydraulic diameter (m))
V = flow velocity (m/s)

3) Actual System Power

The actual output power of the micro-hydropower system is determined by considering turbine and generator efficiencies [4], [6]:

$$P = pgQH_{ef}\eta_{total} \tag{4}$$

This formulation is widely used in evaluating small-to-medium-scale micro-hydropower systems, as it accounts for energy conversion losses in turbine and generator components.

Annual Energy Production

Annual electricity generation is estimated based on the actual power output and operational capacity factor [1], [6]:

$$E_{annual} = P_{averagel} x\ CF\ x\ 8760 \tag{5}$$

where:
E_{annual} = annual electricity production (MWh/year)
CF = capacity factor (0-1)
8760 = total hours in one year

This formulation assumes steady-state operating conditions, representing the normal operational pattern of the CFPP.

Economic Feasibility Analysis

The economic feasibility of the project is evaluated using a discounted cash flow (DCF) approach, considering a project lifetime of n years and a discount rate r [3], [11].

1) Net Present Value (*NPV*)

$$NPV = -I_O \sum_{t=1}^{n} \frac{CF_t}{(1+r)^t} \tag{6}$$

where:
I_O= initial investment
CF_t= cash flow in year t
r = discount rate

The project is considered financially feasible if: $NPV > 0$.

2) Internal Rate of Return (IRR)
The IRR is obtained by solving the following equation:

$$0 = - I_O \sum_{t=1}^{n} \frac{CF_t}{(1 + IRR)^t} \tag{7}$$

Investment is considered feasible if:$IRR > r$
3) Payback Period (PP)

$$PP = \frac{I_O}{CF_{annual}} \tag{8}$$

This indicator provides a simplified estimate of the capital recovery period.

4) Levelized Cost of Energy (*LCOE*)
The LCOE is calculated using the standard formulation [1], [3]:

$$LCOE = \frac{\sum_{t=0}^{n} \frac{I_t + O_t}{(1 + r)^t}}{\sum_{t=0}^{n} \frac{E_t}{(1 + r)^t}} \tag{9}$$

where:
I_t= investment cost
O_t= operation and maintenance cost
E_t = annual electricity production

The resulting $LCOE$ is compared with the internal electricity tariff to evaluate the economic competitiveness of the proposed system.

Environmental Impact Analysis
Carbon emission reduction is estimated using the electricity system emission factor [1], [2]:

$$ER = E_{annual}\ x\ EF \tag{10}$$

where:
ER= emission reduction (ton CO_2/year)
EF = emission factor (ton CO_2/kWh)

This approach is consistent with IPCC methodologies and international energy efficiency evaluation standards.

Sensitivity Analysis

A one-variable-at-a-time (OVAT) sensitivity analysis is conducted to evaluate the robustness of the economic model. Key parameters, including capital expenditure (CAPEX), capacity factor (CF), discount rate (r), and operation and maintenance (O&M) cost, are varied within ±10–20% while other variables are held constant. The analysis assesses the impact on Net Present Value (NPV), Internal Rate of Return (IRR), Levelized Cost of Energy (LCOE), and present worth of benefits (PW) to identify the most influential parameters affecting project economic feasibility [3], [6], [11], [14], [15].

Integrated Evaluation Framework

The feasibility of the micro-hydropower system is determined based on the following multidimensional criteria:

- $P > 0$ and no interference with the main plant operation (non-interference);
- $NPV > 0$,
- $IRR > r$, and LCOE< internal electricity tariff.
- significant carbon emission reduction

This framework positions the MHP system as an asset-based efficiency enhancement strategy, rather than merely an additional power generation project.

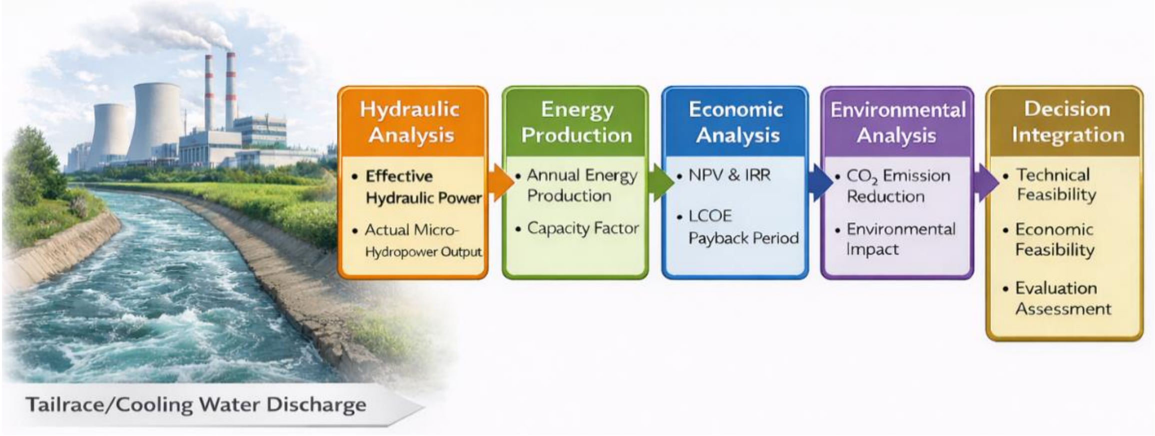

Figure 1. Integrated Evaluation Framework for the Micro-Hydropower System

Figure 1 illustrates the systemic evaluation model integrating hydraulic potential analysis, annual energy production estimation, economic feasibility assessment, and environmental impact analysis into a unified decision-making framework. The effective power obtained from the hydraulic analysis forms the basis for estimating annual electricity production, which subsequently feeds into the economic evaluation through NPV, IRR, Payback Period, and LCOE calculations. In parallel, environmental benefits are assessed through estimated carbon emission reductions.

This integrated approach enables a multidimensional feasibility assessment while maintaining the non-interference principle with the primary power plant operation. The study extends conventional micro-hydropower evaluation approaches by simultaneously integrating technical, economic, and environmental aspects within the operational boundaries of an active power plant, thereby contributing to the literature on waste energy recovery through internal system optimization.

RESULT AND DISCUSSION

This section presents the comprehensive findings of the hydraulic, energy, economic, and environmental analyses of the proposed micro-hydropower (MHP) system utilizing condenser cooling water discharge from a coal-fired power plant (CFPP). The evaluation is conducted based on actual operational data and the integrated techno-economic assessment (TEA) framework described in the methodology.

The results include hydraulic performance assessment, estimation of actual power output, annual energy production, and economic feasibility indicators such as Net Present Value (NPV), Internal Rate of Return (IRR), Payback Period (PP), and Levelized Cost of Energy (LCOE). In addition, environmental benefits are quantified through carbon emission reduction analysis, while system robustness is evaluated using sensitivity analysis.

Unlike conventional micro-hydropower studies that rely on natural hydrological conditions, this study is based on a controlled and continuous industrial discharge flow, enabling a more stable and predictable system performance. Therefore, the discussion not only focuses on numerical results but also emphasizes interpretation of system behavior, comparison with existing studies, and practical implications for energy efficiency improvement in thermal power plants.

The integration of technical, economic, and environmental perspectives provides a multidimensional understanding of feasibility, positioning the proposed system as an embedded energy recovery solution within existing infrastructure rather than a standalone power generation unit.

Hydraulic Performance and Effective Energy Potential

Field measurements indicate an average condenser discharge of 1.20 m^3/s with an effective head of 8.73 m, producing a theoretical hydropower potential of 103.16 kW based on standard equations [1], [2]. As shown in Table 2, discharge variation between 1.08 and 1.48 m^3/s results in theoretical power outputs ranging from 92.18 to 126.49 kW, reflecting operational fluctuations in plant load and cooling demand.

Considering an overall system efficiency of 75%, the corresponding actual power output ranges from 69.13 to 94.87 kW, with an average of 77.37 kW. This performance is consistent with reported efficiency levels for low-head crossflow turbines in similar applications [3], [4]. The relatively stable head and moderate discharge variability contribute to predictable and steady power generation behavior.

Table 2. Monthly Estimated Potential Power Output

No	Head Effective	Debit (m^3/s)	P_Theoretical (kW)	P_Actual (kW)
1	8,73	1,19	101,84	76,38
2	8,73	1,48	126,49	94,87
3	8,73	1,21	103,67	77,75
4	8,73	1,18	100,73	75,55
5	8,73	1,16	99,58	74,69
6	8,73	1,24	106,46	79,84
7	8,73	1,14	97,33	73,00
8	8,73	1,20	103,06	77,30
9	8,73	1,20	102,72	77,04
10	8,73	1,19	102,13	76,59
11	8,73	1,14	97,32	72,99
12	8,73	1,28	109,51	82,13
13	8,73	1,22	104,86	78,65
14	8,73	1,17	99,93	74,95
15	8,73	1,18	101,15	75,86
16	8,73	1,16	99,20	74,40
17	8,73	1,13	96,70	72,53
18	8,73	1,26	107,95	80,96
19	8,73	1,15	98,47	73,85
20	8,73	1,21	103,69	77,77
21	8,73	1,23	105,25	78,94
22	8,73	1,19	101,80	76,35
23	8,73	1,20	103,06	77,30
24	8,73	1,19	101,64	76,23
25	8,73	1,21	103,43	77,57
26	8,73	1,19	102,02	76,52
27	8,73	1,08	92,18	69,13
28	8,73	1,31	111,81	83,86
29	8,73	1,20	102,54	76,90
30	8,73	1,27	108,45	81,34
Average	8,73	1,20	103,16	77,37
Minimum	8,73	1,08	92,18	69,13
Maximum	8,73	1,48	126,49	94,87

Figure 2 illustrates the relationship between discharge and power output, highlighting the consistent gap between theoretical and effective power due to system efficiency losses. The theoretical power $P_t = pgQH$ represents the ideal maximum energy conversion without losses, whereas the effective power $P = pgQH_{ef}\eta_{total}$ accounts for hydraulic, mechanical, and electrical losses. With an assumed total efficiency of 75%, the effective power is consistently reduced by approximately 25% relative to the theoretical value.

The results show a clear linear dependence of power on discharge. At the minimum flow rate of 1.08 m³/s, the effective power reaches 69.13 kW, representing the lower operational limit. Conversely, at the maximum discharge of 1.48 m³/s, the effective power increases to 94.87 kW, indicating higher energy potential but also implying the need for adequate design margins to prevent system overload. The average condition (1.20 m³/s) yields 77.37 kW and represents the most stable and dominant operating point.

The linear trend observed in Figure 2 confirms the fundamental hydropower principle that output power is directly proportional to flow rate and effective head. The relatively smooth variation indicates stable hydraulic behavior, supporting reliable and continuous energy production. These characteristics reinforce the operational feasibility of the proposed micro-hydropower system, where average conditions guide turbine-generator design, while minimum and maximum values define safe operational boundaries and system flexibility.

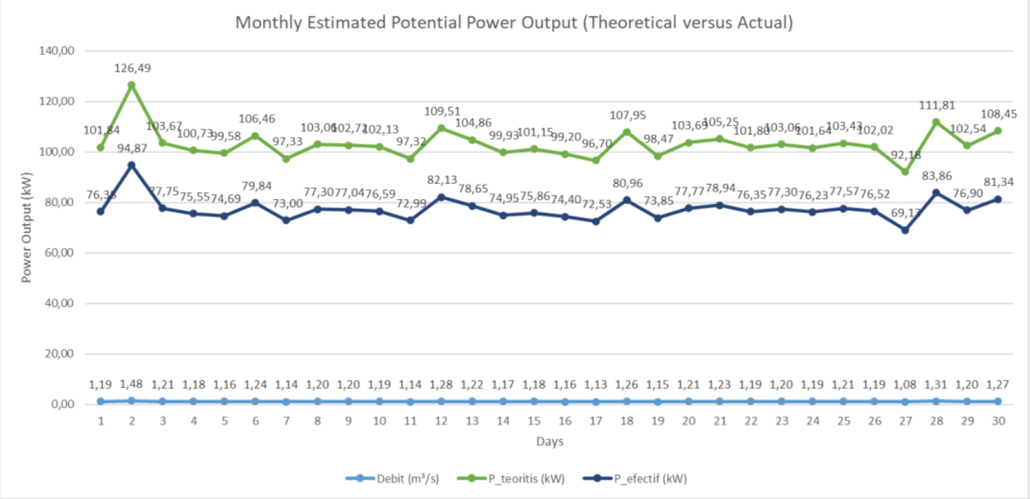

Figure 2. Monthly Estimated Potential Power Output (Theoretical versus Actual)

Installed Capacity and Energy Production

Although the average actual power output is 77.37 kW, an installed capacity of 100 kW is recommended to accommodate discharge variability and maintain operational flexibility. To estimate the annual energy generation under more realistic operating conditions, a capacity factor (CF) of 0.9 is applied to account for potential downtime, maintenance, and operational fluctuations. The annual energy output is therefore calculated as:

$$E = 77.37 \ x \ 8760x \ 0.9 \ = 610.01 \ MWh/year$$

With an installed capacity of 100 kW, this output corresponds to a capacity factor of approximately 77%, which remains within the typical operating range of continuous micro-hydropower systems in industrial installations [2], [6]. The generated electricity is utilized to supply auxiliary loads within the coal-fired power plant (CFPP), thereby improving the overall energy utilization of the plant without increasing primary fuel consumption [5], [7].

Economic Performance and Investment Feasibility

The economic feasibility of the proposed micro-hydropower (MHP) system was evaluated using standard discounted cash flow (DCF) indicators—Net Present Value (NPV), Internal Rate of Return (IRR), Payback Period (PP), and Levelized Cost of Energy (LCOE)—as defined in Section Economic Feasibility Analysis [8], [9]. The analysis adopts base-case assumptions consisting of an initial investment of IDR 3.0 billion, a project lifetime of 20 years, a discount rate of 10%, an electricity value of IDR 1,500/kWh, and annual O&M costs of IDR 90 million.

Using the annual energy production of 610.01 MWh (Equation (5), the net annual cash flow is estimated at approximately IDR 825 million. By applying the DCF formulations in Equations (6)– (9), the resulting economic indicators are summarized in Table 3.

As shown in Table 3, the project yields an NPV of approximately IDR 4 billion, indicating a positive net economic benefit over the project lifetime. The IRR is calculated at around 27%, significantly exceeding the discount rate (10%), confirming strong investment attractiveness. The payback period of 3.6 years further indicates rapid capital recovery, while the LCOE of IDR 725/kWh is substantially lower than the internal electricity cost of IDR 1,500/kWh, demonstrating clear cost competitiveness.

Table 3. Economic Feasibility Indicators

Indicator	Value
Initial investment	Rp3,000,000,000
NPV (10%)	±Rp 4 billion
IRR	±27%
LCOE	±Rp725/kWh
Payback Period	3.6 years

These results are directly derived from the integration of energy production estimation and DCF-based evaluation, confirming the internal consistency between the methodological framework and the economic outcomes presented in Table 3. Moreover, the favorable economic performance is primarily driven by the absence of fuel costs and the utilization of existing infrastructure, which collectively reduce both capital and operational expenditures.

Environmental Impact and Carbon Reduction Potential

The annual electricity generation of 610.01 MWh results in estimated emission reductions based on an electricity system emission factor of 0.85 kg CO_2/kWh, which is consistent with typical emission factors for fossil-fuel-based power systems [11]. The annual emission reduction is calculated as:

$$ER = 610.01x\ 0.85 = 518\text{-ton } CO_2/\text{year}$$

Over the 20-year project lifetime, the cumulative emission reduction is estimated to reach approximately 10.327,31 tons of CO_2 equivalent. This contribution supports energy sector decarbonization efforts through the utilization of secondary energy resources without increasing primary energy consumption [5], [12].

Although the absolute reduction is relatively small compared to total emissions of a coal-fired power plant, its significance lies in the mechanism of reduction. The system operates without additional fuel consumption and utilizes existing condenser discharge flow, thereby achieving emission reduction through internal energy efficiency improvement rather than new power generation capacity [8], [10].

This finding highlight that the proposed system represents an efficiency-based decarbonization strategy, where residual hydraulic energy is recovered and converted into useful electricity within the existing infrastructure. Such an approach aligns with recent studies emphasizing the role of waste energy recovery and system optimization as cost-effective pathways for reducing emissions in industrial energy systems [8], [12].

From a broader perspective, while large-scale renewable deployment remains essential, incremental solutions such as this provide low-cost, low-risk, and scalable contributions to energy transition efforts, particularly in existing thermal power plants [1], [2].

Sensitivity Analysis on Key Economic Parameters

1) Sensitivity to Capital Expenditure (CAPEX)

As presented in Table 4, the sensitivity analysis of CAPEX (±10–20%) shows that investment cost significantly influences both NPV and IRR. A reduction in CAPEX increases IRR and NPV, while higher CAPEX reduces both indicators. However, IRR remains above the discount rate in all scenarios, confirming strong financial robustness.

Table 4. Sensitivity of NPV and IRR to CAPEX Variation

Scenario	CAPEX (IDR)	NPV (IDR)	IRR (%)
Base Case (*CAPEX*)	Rp3.000.000.000	±Rp 3,99 miliar	≈ 25–26%
CAPEX -10%	Rp2.700.000.000	±Rp 4,32 miliar	≈ 26–27%
CAPEX -20%	Rp2.400.000.000	±Rp 4,59 miliar	≈ 28–29%
CAPEX +10%	Rp3.300.000.000	±Rp 3,69 miliar	≈ 23–24%
CAPEX +20%	Rp3.600.000.000	±Rp 3,39 miliar	≈ 21–22%

This behavior reflects the capital-intensive nature of micro-hydropower systems, where initial investment strongly determines overall profitability [4], [6], [14].

2) Sensitivity to Discount Rate (Cost of Capital)

Table 5 shows that increasing the discount rate significantly reduces NPV, with a decrease of more than IDR 1.8 billion observed between 8% and 12%. This confirms the strong sensitivity of long-term projects to financing conditions.

Table 5. Sensitivity of NPV to Discount Rate Variation

Discount Rate (%)	Present Worth of Benefit (IDR)	*NPV (IDR)*
8%	Rp8.062.985.973	Rp5.062.985.973
10% (Base Case)	Rp6.991.618.887	Rp3.991.618.887
12%	Rp6.134.153.081	Rp3.134.153.081

This occurs because higher discount rates reduce the present value of future cash flows in the DCF framework. Despite this, all NPV values remain positive, supported by an IRR of ~27%, indicating robust feasibility [3], [11], [12].

3) Sensitivity to Electricity Value (Energy Tariff)

As shown in Table 6, the electricity tariff is the most dominant parameter affecting NPV. A ±20% variation in tariff results in approximately ±39% change in NPV, indicating strong dependence on revenue.

Table 6. Sensitivity of NPV to Electricity Tariff Variation

Scenario	Tariff (Rp/kWh)	Annual CF (IDR)	PW Benefit (IDR)	NPV (IDR)	Change vs Base
-20%	1.200	642.016.842	5.465.851.291	2.465.851.291	↓ 38,9%
-10%	1.350	733.518.947	6.244.860.294	3.244.860.294	↓ 19,5%
Dasar	1.500	825.021.052	6.992.768.172	3.992.768.172	—
10%	1.650	916.523.157	7.802.878.301	4.802.878.301	↑ 19,4%
20%	1.800	1.008.025.263	8.581.887.304	5.581.887.304	↑ 38,8%

This linear relationship arises because revenue directly scales with electricity price, while costs remain largely fixed. Although the project remains feasible under all scenarios, this highlights exposure to tariff and regulatory risks [1], [2].

4) Sensitivity to ELCO

The quantitative results of the sensitivity analysis on Levelized Cost of Energy (LCOE) are presented in Table 7 and illustrated in Figure 3. The analysis evaluates ±10% variations in key economic and operational parameters

Table 7. Sensitivity Analysis of Levelized Cost of Energy (LCOE)

No	Parameter	−10% (IDR/kWh)	Base LCOE (IDR/kWh)	+10% (IDR/kWh)	Deviation −10	Deviation +10%	Max Deviation
1	Energi	805,74	725,16	659,24	-65,92	+80,57	80,57
2	CAPEX	652,65	725,16	797,68	-72,52	+72,52	72,82
3	Discount Rate	676,31	725,16	769,35	−48,85	+44,19	48,85
4	O&M	710,41	725,16	739,92	-14,75	+14,75	14,75

As shown in Table 7, energy production is the most influential parameter on LCOE, with the highest maximum deviation (80.57 IDR/kWh). This is followed by CAPEX (72.52 IDR/kWh), discount rate (48.85 IDR/kWh), and O&M cost (14.75 IDR/kWh). The asymmetry observed in the energy and discount rate scenarios reflects the nonlinear response of LCOE to variations in energy output and discounting effects.

Figure 3 further confirms this ranking, where energy production exhibits the largest impact on LCOE variation, followed by CAPEX and discount rate, while O&M cost shows minimal influence.

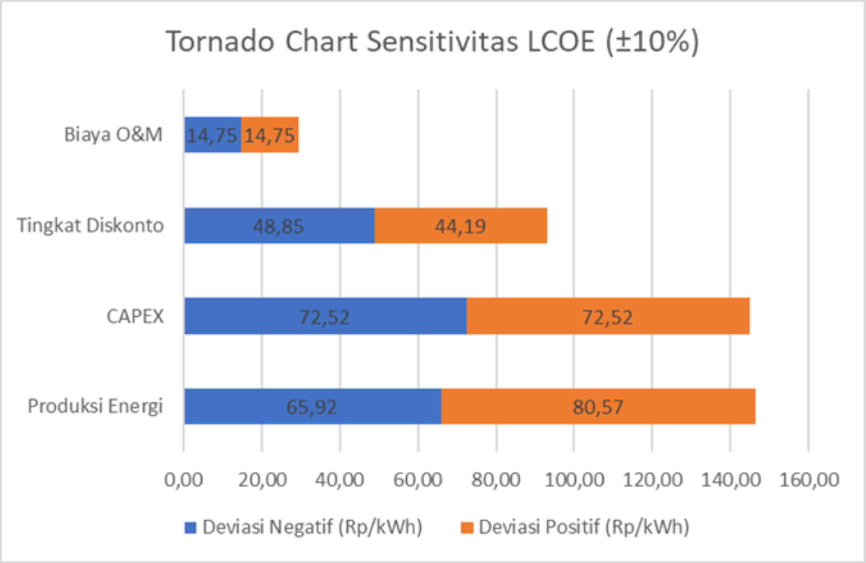

Figure 3. LCOE sensitivity analysis for ±10% variations in key economic and operational parameters.

This behavior is consistent with the LCOE formulation, where energy production appears in the denominator, making it highly sensitive to variations in annual energy output. CAPEX and discount rate also significantly affect LCOE due to their direct influence on capital recovery and discounted cash flows, respectively [8], [9], [10].

Comparative Analysis with Previous Studies

The feasibility of the proposed micro-hydropower (MHP) system is assessed using the integrated framework defined in the methodology, combining technical, economic, and environmental criteria.

Technically, the system satisfies $P > 0$, delivering 77.37 kW under stable condenser discharge conditions, while maintaining a non-interference operation with the main plant system. This confirms that the available hydraulic potential can be effectively converted into useful energy under low-head conditions [7], [14].

Economically, all indicators meet feasibility thresholds: NPV ≈ IDR 3.9–4.0 billion, IRR ≈ 27% (>10%), and LCOE ≈ IDR 725/kWh (< internal tariff), confirming strong financial performance within the discounted cash flow (DCF) framework [3], [6], [11]. The favorable economic performance is primarily driven by the absence of fuel costs and the utilization of existing infrastructure, which reduces capital and operational uncertainties [2], [10].

From an environmental perspective, the system achieves an emission reduction of 518 tons CO_2/year, without additional fuel consumption. This reflects the role of efficiency-based energy recovery in supporting incremental decarbonization within existing energy systems [1], [9], [12].

The integrated evaluation results are summarized in Table 8.

Table 8. Integrated Feasibility Evaluation of the Proposed MHP System

Aspect	Criterion	Result	Status
Technical	P > 0	77.37 kW	✓ Feasible
	Non-interference	No disruption	✓ Feasible
Economic	NPV > 0	~IDR 3.9–4.0 billion	✓ Feasible
	IRR > r (10%)	~27%	✓ Feasible
	LCOE < tariff	725 < 1,500 IDR/kWh	✓ Feasible
Environmental	Emission reduction	518 tons CO_2/year	✓ Feasible

All criteria are satisfied, confirming that the system is technically viable, economically competitive, and environmentally beneficial. This integrated validation demonstrates that the proposed approach extends conventional micro-hydropower assessment by framing it as an infrastructure-based energy efficiency strategy, rather than a standalone generation system, consistent with recent studies on system-level efficiency improvement and waste energy recovery [8], [9], [12].

Implications and Limitations of the Proposed System

The obtained results are consistent with fundamental hydropower theory, where power output is directly proportional to flow rate and effective head, as well as with techno-economic principles in which annual energy production strongly influences LCOE through cost distribution. The relatively stable performance observed in this study is primarily attributed to the controlled and continuous nature of condenser cooling water discharge, which minimizes hydrological variability compared to conventional river-based systems. This finding aligns with previous studies highlighting the advantages of infrastructure-based hydropower systems in improving operational reliability and reducing uncertainty [6], [10]. Furthermore, the dominance of energy production and CAPEX in influencing LCOE and NPV is consistent with established techno-economic analyses of small hydropower systems [3], [11].

From a practical perspective, these results indicate strong potential for replication in industrial facilities with continuous discharge systems, supporting broader implementation of waste energy recovery strategies for efficiency improvement and incremental decarbonization. However, several limitations should be acknowledged. The system is inherently dependent on the operational conditions of the host power plant, and the low-head characteristics constrain the maximum achievable power output. In addition, the analysis is based on steady-state assumptions, which may not fully capture transient operational variations. Despite these limitations, the proposed approach offers a reliable, low-risk, and scalable solution for enhancing energy utilization within existing thermal power plant infrastructure, consistent with recent studies emphasizing the role of system-level efficiency improvements in industrial energy transitions [8], [12].

CONCLUSION

This study evaluates the feasibility of utilizing residual hydraulic energy from condenser cooling water discharge in a coal-fired power plant (CFPP) through the integration of a micro-hydropower (MHP) system within existing operational boundaries. The proposed approach frames energy recovery as an asset-based efficiency strategy, enabling additional electricity generation without interfering with primary plant operations, consistent with current energy efficiency and decarbonization pathways [1], [2], [9].

The results demonstrate that an average discharge of 1.20 m^3/s and an effective head of 8.73 m can produce an actual power output of 77.37 kW, corresponding to an annual energy generation of 610.01 MWh. Based on the discounted cash flow (DCF) framework, the system exhibits strong economic performance, with an NPV of approximately IDR 3.9–4.0 billion, an IRR of ~27%, an LCOE of ~IDR 725/kWh, and a payback period of 3.6 years, confirming financial feasibility and cost competitiveness [3], [6], [11].

Sensitivity analysis indicates that capacity factor (annual energy production) and discount rate are the most influential parameters affecting LCOE and NPV, respectively, reflecting the mathematical structure of the economic model and the capital-intensive nature of the system. Despite parameter variations, the project remains financially robust, supported by stable flow conditions and low operational costs [2], [11].

From an environmental perspective, the system achieves an emission reduction of approximately 518 tons CO_2/year, or about 10,300 tons CO_2 over the project lifetime, without additional fuel consumption or land-use changes. Although modest in absolute terms, this reduction highlights the role of efficiency-driven decarbonization through internal energy optimization [1], [12].

Comparative analysis shows that, relative to conventional river-based micro-hydropower systems, the proposed approach offers higher operational stability, lower resource dependency, and reduced investment risk, primarily due to the use of continuous industrial flow and existing infrastructure [6], [10], [14].

Overall, the study confirms that integrating micro-hydropower into condenser cooling systems is a technically feasible, economically attractive, and low-risk solution for improving energy efficiency and supporting incremental decarbonization in thermal power plants.

Future work should focus on dynamic operational modeling using long-term plant data and probabilistic, multi-variable risk analysis to enhance the robustness and scalability of implementation under varying operational and financial conditions.

The findings are consistent with fundamental hydropower theory and established techno-economic behavior, particularly in the strong influence of flow conditions on energy output and the sensitivity of economic performance to energy production and capital cost. Compared to conventional micro-hydropower systems, the use of controlled industrial discharge enhances system reliability and reduces uncertainty, supporting more predictable performance. However, the system remains dependent on power plant operation and is constrained by low-head conditions, which limit maximum power generation. These findings reinforce the role of infrastructure-based energy recovery as a practical and scalable approach to improving energy efficiency and supporting incremental decarbonization in existing thermal power plants.

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