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Heca Journal of Applied Sciences

Vol. 3, No. 2, 2025



Utilization Strategy of Discharged Seawater from Power Plant Cooling System to Reduce Energy Consumption: A Process Engineering Approach

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Article History

Received 27 March 2025
Revised 11 June 2025
Accepted 15 June 2025
Available Online 23 June 2025

Keywords:

Steam power plant efficiency
Cooling water reutilization
Hydropower generation
Energy conservation
Environmental sustainability

Abstract

Steam power plants are among the primary sources of electricity generation; however, they face significant challenges in terms of energy efficiency and environmental impact due to their high consumption of coal. Innovative strategies are required to reduce emissions and improve system efficiency. One potential approach is the reutilization of condenser cooling water to drive a hydropower turbine before being discharged into the sea. By harnessing the head and flow rate of this water, the kinetic energy from the waste stream can be converted into additional electricity. This study examines a process engineering approach to integrating a hydropower generation system with a steam power plant, encompassing technical analysis, energy efficiency, as well as economic and environmental impacts. Simulation results indicate that the system is capable of generating between 14.2 and 49.5 kW of power, depending on operating conditions and water availability. The electricity produced can be utilized for internal Steam power plant needs, such as cooling pumps and lighting, thereby reducing dependence on coal combustion. This strategy not only improves energy efficiency and reduces operational costs but also supports environmental conservation and the long-term sustainability of power plant operations.



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1. Introduction

Steam power plants are a primary source of electricity generation in many countries. However, energy efficiency in steam power plant systems remains a major challenge, particularly due to high fossil fuel consumption and its environmental impact [1]. The use of coal as the primary fuel leads to greenhouse gas emissions, including carbon dioxide (CO₂), sulfur dioxide (SO₂), and nitrogen oxides (NO_x), which contribute to climate change and air pollution. Therefore, innovative strategies are needed to

improve energy efficiency, reduce fuel consumption, and minimize environmental impact [2].

Steam power plants generally use seawater as a cooling medium in condensers to convert exhaust steam from turbines back into water [3, 4]. However, an innovative approach to reusing seawater can transform this challenge into an opportunity to enhance energy efficiency in steam power plants [5]. In 2024, Biedunkova et al. published a study demonstrating the reuse of cooling water by predicting total alkalinity and total hardness levels, effectively reducing overall water

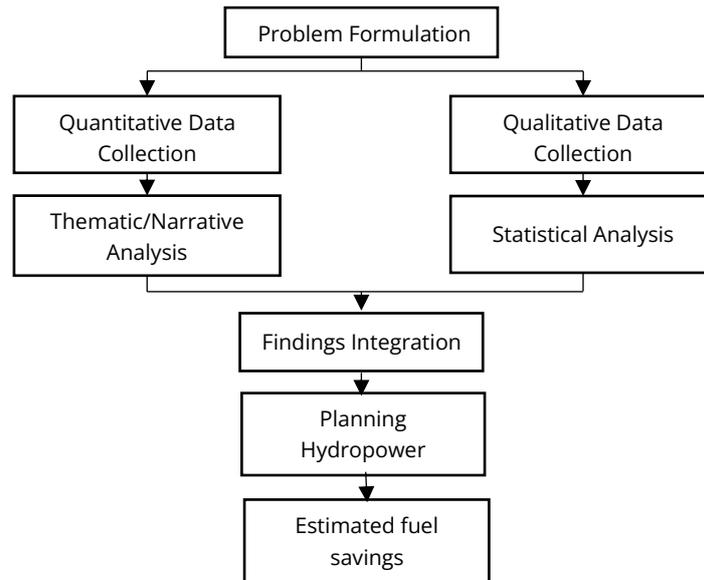


Figure 1. Methodological framework.

consumption [6]. One strategy that can be implemented is utilizing seawater from the condenser to drive turbines in a hydropower plant system before the water is returned to the sea [7]. By harnessing the pressure difference and water flow generated in this process, the kinetic energy of the water can be converted into additional electricity [8]. This approach enables seawater, previously considered a waste by-product, to contribute to electricity production, thereby enhancing the overall efficiency of the power generation system [9].

The implementation of this strategy provides significant benefits in optimizing energy consumption in steam power plants [10, 11]. The electricity generated from seawater utilization can be used for internal plant consumption, ultimately reducing the need for electricity from primary sources such as coal combustion [12]. As a result, this strategy not only enhances energy efficiency but also reduces fossil fuel consumption and carbon emissions from the electricity generation process [13–15]. Besides the energy efficiency benefits, seawater from the condenser is first utilized in the hydropower plant system before being discharged back into the sea.

Although various studies have demonstrated the efficiency of managing cooling water systems for energy savings in steam power plants, this study specifically examines the integration process of a hydropower system that utilizes condenser water as an additional energy source. The research gap lies in the lack of process engineering approaches that directly utilize condenser water to drive water turbines, thereby enhancing the overall efficiency of the power generation system. This study introduces a novel concept through the innovative use of condenser wastewater as an energy source within

the operational cycle of a steam power plant. It applies a process engineering approach to optimize pressure differences and water flow, thereby driving the turbine. This research only provides a theoretical calculation of the potential power that could be generated, as well as the possible impacts if implemented. The objectives of this study are to analyze the potential utilization of condenser water as an additional energy source through the integration of a hydropower system, to examine the technical aspects and efficiency of the integrated system from coal-based to water-based energy, and to propose an efficient solution to reduce dependence on fossil fuels.

2. Materials and Methods

2.1 Research Approach

This study employs a mixed-method approach, combining qualitative and quantitative data. Both types of data play a crucial role in process analysis and optimization, as illustrated in Figure 1 [16]. The qualitative data include descriptive aspects such as the operational conditions of the power plant, environmental characteristics of the discharge area, and sustainability factors, as well as the ecological impacts of reusing wastewater. Meanwhile, the quantitative data include technical parameters such as the water flow rate from the Circulating Water Pump (CWP), the available head, and the turbine's efficiency in converting kinetic energy into electricity.

The measurement of the flow rate was conducted using an ultrasonic sensor installed on the condenser inlet pipe, providing real-time, per-second accuracy. The flow rate data were averaged daily from January to May. The

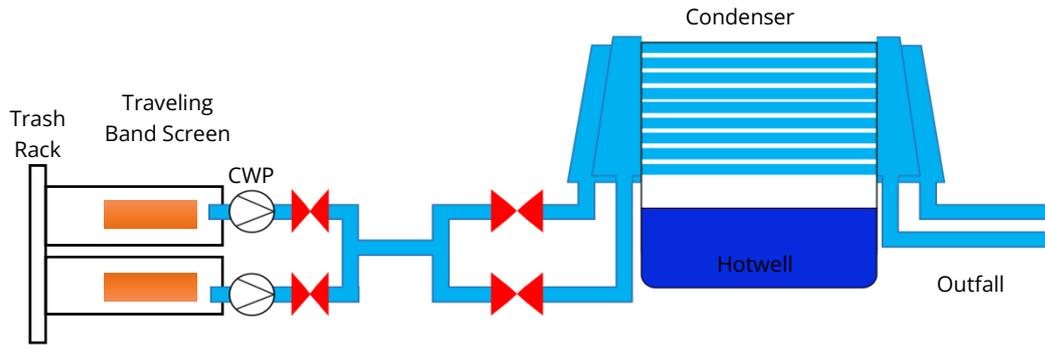


Figure 2. Cooling system condenser.

head was obtained through manual field measurements, considering the minimum turbine height.

The combination of these two types of data was used to determine the optimal system design, estimate potential energy savings, and evaluate the economic and environmental feasibility of implementing this strategy in power plants.

2.2 Data Collection

The data collection in this study focuses on measuring the flow from the CWP in Units 1 and 2, which depends on the operational and maintenance conditions of the power plant. This data is used to determine the discharge flow rate returning to the sea and the variations in flow caused by changes in operational load. Additionally, the location of the power plant building is a key factor in determining the design of the storage pond, which serves as a temporary reservoir before the water is directed into the hydropower generation system [17]. By considering the head generated from elevation differences and water pressure, this study aims to optimize the utilization of wastewater's kinetic energy, enabling its efficient conversion into electricity.

2.3 Process Engineering Approach

The process engineering approach in utilizing discharged water from the power plant's cooling system aims to convert the kinetic energy and pressure of the returning water into electricity. The design of a small-scale hydropower generation system involves selecting suitable turbines, such as Pelton or Kaplan, to optimize energy conversion from the discharged water flow [18].

Furthermore, process simulation and optimization are conducted to ensure that the integration of the hydropower generation system does not interfere with the main operations of the power plant, taking into account operational and maintenance parameters. The economic evaluation includes an analysis of potential energy savings, while the sustainability aspect is assessed

based on the reduction of coal waste and its environmental impact. This approach is expected to enhance the energy efficiency of the power plant and mitigate the adverse effects of discharging hot water into the sea.

Figure 2 shows that pressurized seawater from the CWP reaches the condenser, where it serves as a cooling medium to condense exhaust steam from the steam turbine [19]. The hot steam entering the condenser releases its heat to the cooling water, causing the steam to revert to a liquid form (condensate) and flow into the hotwell, which is then pumped back into the power cycle for reheating [20]. During this process, the cooling water temperature rises as it absorbs heat from the exhaust steam. To maintain optimal thermal efficiency, the system must ensure a sufficiently high and stable cooling water flow rate [21].

After passing through the condenser, the heated cooling water is discharged back into the sea via a discharge channel or outfall [22]. Before being released, the water temperature is typically monitored to ensure it does not exceed environmental limits, preventing negative impacts on marine ecosystems [23]. Some systems incorporate additional cooling towers or heat exchangers to reduce the water temperature before discharge. This cycle continues as seawater is reintroduced into the system by the Cooling Water Pump, repeating the cooling process within the power plant or industrial system [24].

2.3.2. Small-Scale Hydropower Plant Technology

2.3.2.1. Water Flow Rate and Head

The energy output of the system is determined based on the CWP flow rate and water head, which serve as sources of kinetic energy. In hydropower plant calculations, the head refers to the height difference between the water intake point (head pond) and the outlet point (turbine), which determines the potential energy of the water before it is converted into electricity [25]. Head significantly influences the power output of a

hydropower plant, as a higher head results in greater water pressure entering the turbine, thereby increasing power generation efficiency [26]. Field observations indicate that this measurement represents the gross head, while the net head is determined from the head pond to the power station. The distance from the storage pond to the power station is a height difference of 3 meters.

2.3.2.2. Turbine and Generator

Selecting the appropriate water turbine type for a hydropower plant depends on several key factors, including head height, water flow rate, and power demand [27]. Water turbines are generally classified into two main categories: Impulse Turbines (e.g., Pelton Turbine) – suitable for high head (>50 meters) and low flow rates. These turbines convert water energy into high velocity before impacting the turbine blades [28]. Reaction Turbines (e.g., Francis, and Kaplan) are better suited for medium to low head applications (Francis: 10–300 meters, Kaplan: <50 meters) with higher flow rates, as they operate based on pressure changes and water velocity as it passes through the turbine blades [29]. The selection of a Kaplan turbine was based on the system design characteristics, which involve low head conditions, where this type of turbine is known for its efficiency in converting water energy into electricity under high flow and low elevation scenarios.

Generators in hydropower plants generally use alternators (AC generators) that produce alternating current (AC) electricity [30]. The main components of a generator include the stator (a stationary copper wire coil), the rotor (a rotating magnetic field), and a cooling system. The size and capacity of the generator depend on the power generated by the turbine. Once electricity is produced, the voltage is typically increased by a transformer before being transmitted to the power grid for consumer use [31]. The use of an AC generator with a capacity exceeding 1 kW in steam power plants is expected to effectively support energy supply, considering that most electrical loads in the plant are inductive.

2.3.2.3. Power Output of a Hydropower Plant

The basic formula for calculating the power generated is according to Equation 1:

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

Where P (Watts) is electrical power generated, η is total system efficiency (56% from turbine, generators, and penstock), including turbine, generator, and transmission efficiency, ρ (kg/m³) is seawater density, typically 1030 kg/m³, g is gravitational acceleration typically 9.81 m/s², Q

(m³/s) is water flow rate to the turbine, H (meters) is water head or height difference [32].

From this formula, it is evident that the generated power depends on the head and the water flow rate [33]. The higher the head or the greater the water flow rate, the more energy can be converted into electricity. However, not all energy can be perfectly converted due to system losses caused by friction, turbulence, and the mechanical efficiency of the turbine and generator [34]. Therefore, the efficiency factor (η) is crucial in determining the actual power output of the hydropower plant [35].

2.4 Energy Efficiency and Environmental Assessment

The assessment of energy efficiency and environmental impact in the strategy of utilizing discharged seawater from power plants focuses on reducing coal consumption and emissions from combustion. By converting the kinetic energy of discharged water into electricity through a small-scale hydropower generation system, the power plant can reduce its reliance on fossil fuels, thereby lowering the cost of coal purchases. Additionally, reducing coal consumption directly contributes to a decrease in greenhouse gas emissions, such as carbon dioxide (CO₂) and sulfur dioxide (SO₂), which are produced during combustion [36]. This positive impact not only enhances the operational efficiency of the power plant but also supports environmental sustainability by reducing the carbon footprint and air pollution.

3. Results and Discussion

The implementation of utilizing condenser cooling water for hydropower generation demonstrates that wastewater from the condenser can serve as an additional energy source before being discharged back into the environment. By leveraging the height difference (head) and sufficient water flow rate, this system can drive a small-scale hydro turbine. Simulations indicate that the generated power depends on parameters such as the condenser wastewater head, water flow rate, and the efficiency of the turbine and generator. Under optimal conditions, this system can generate additional electricity sufficient to meet the internal needs of the steam power plant, such as powering cooling pumps or operational lighting.

As shown in Figure 3, wastewater from the cooling systems of Units 1 and 2 undergoes a merging process before being further directed. These two flows are channeled into a head pond, which serves as a control point before the water is distributed further, with a head height of 3 meters. The head pond stabilizes the flow and helps regulate the pressure and water volume sent to the

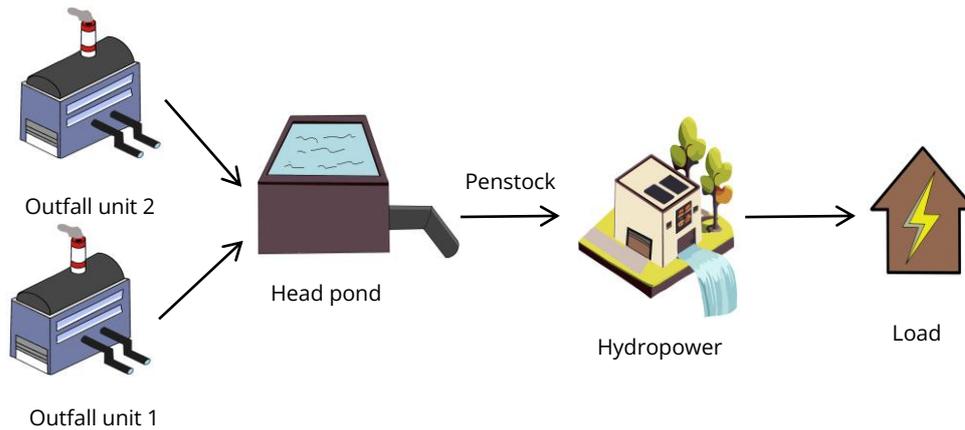


Figure 3. Wastewater recovery strategy.

next process. This pond allows for more effective management of wastewater, preventing sudden surges in flow that could disrupt the system [37].

The water stored in the head pond is then channeled to the turbine through a penstock. The penstock plays a crucial role in converting the potential energy of water at a height into kinetic energy as it flows toward the turbine. This energy transformation occurs because the penstock is designed to accelerate the water flow, increasing both pressure and velocity to efficiently drive the turbine. The increase in kinetic energy generated by the penstock has a significant impact on the turbine's efficiency [38]. The higher the water flow velocity entering the turbine, the greater the mechanical energy that the turbine can produce.

In designing and constructing the penstock, it is essential to consider factors such as length, diameter, and pipe material to minimize energy losses during the flow. Additionally, the use of an inner lining made of rubber or corrosion-resistant material is highly recommended to protect the pipe from damage caused by corrosion and abrasion [39]. The rubber lining process involves attaching rubber sheets to the inner surface of the pipe, providing protection against chemical reactions and reducing wear due to fluid flow.

The water flowing through the penstock toward the turbine plays a crucial role in driving the hydropower generation system. The turbine is designed to convert the kinetic energy of the flowing water into mechanical energy, which is then used to rotate the generator. To ensure durability and operational efficiency, the turbine is made of corrosion-resistant materials such as high-quality stainless steel [40]. The use of stainless steel not only provides resistance to corrosion but also ensures a long service life for the equipment.

Once the turbine rotates, the mechanical energy generated is transferred to the generator, which is directly coupled to the turbine. The generator then converts this mechanical energy into electrical energy [41]. The amount of electricity generated depends on the water flow rate (flow) and the available water head (height). The greater the flow rate and water head, the more electricity the hydropower system can produce.

The electricity generated from hydropower can be integrated with a steam power plant in a hybrid system to supply the internal electricity demand of the steam power plant [42]. The integration of hydropower and steam power in a hybrid system allows optimal utilization of both energy sources. In this configuration, the electricity generated by the hydropower plant can be used to supply the internal power needs of the steam power plant, such as cooling systems and facility lighting. Thus, this system not only produces electricity for distribution to the general grid but also supports the internal operations of the power plant, ensuring all equipment functions properly and efficiently.

A hydropower Plant utilizes water energy to generate electricity, relying heavily on water height and flow rate as its primary driving sources. In its operation, the available water flow is significantly influenced by the supply from the CWP and the predetermined maintenance schedule. If one of the Steam Power Plant units undergoes an operational shutdown due to planned annual equipment maintenance, the water flow available for the hydropower Plants will decrease. This reduction can impact the efficiency of electricity production, making proper planning and coordination between water resource management and the maintenance schedule of power generation units essential to ensure an optimal water supply for sustaining hydropower performance [43]. Table 1 shows the results of the power that can be generated based on

Table 1. Average condenser outlet flow and power generated in 2025

Day	January				February				March			
	Flow			Power	Flow			Power	Flow			Power
	Unit 1	Unit 2	Total		Unit 1	Unit 2	Total		Unit 1	Unit 2	Total	
1	3.1	0.0	3.1	30.9	2.5	0.1	2.5	25.4	3.1	0.5	3.6	36.2
2	3.1	0.0	3.1	31.1	1.9	1.5	3.4	34.1	3.5	0.4	3.9	39.1
3	2.4	0.0	2.4	23.7	2.1	1.2	3.3	33.1	3.1	0.5	3.6	35.8
4	1.5	0.0	1.5	15.2	3.1	0.0	3.1	31.0	3.1	1.0	4.1	41.6
5	1.4	0.0	1.4	14.2	3.0	0.0	3.0	30.7	3.4	0.5	3.9	39.6
6	1.4	0.0	1.4	14.2	3.0	0.0	3.0	30.2	3.4	0.5	3.9	39.5
7	1.4	0.0	1.4	14.2	3.0	1.1	4.1	40.9	3.4	0.5	3.9	39.7
8	1.4	1.1	2.5	24.8	3.1	1.4	4.5	45.7	3.5	0.5	4.0	40.3
9	1.4	1.1	2.5	25.0	3.0	1.3	4.4	43.8	2.4	0.5	2.9	29.2
10	1.5	1.2	2.7	27.4	2.9	1.1	4.1	40.9	1.8	1.0	2.8	28.0
11	1.6	0.0	1.6	15.9	3.0	1.3	4.3	43.2	1.7	0.2	1.9	19.0
12	1.6	0.0	1.6	15.9	3.4	1.3	4.8	47.8	2.6	0.2	2.8	28.6
13	2.4	0.0	2.4	24.3	3.4	1.4	4.8	48.2	3.1	0.2	3.4	33.8
14	2.9	0.0	2.9	29.1	3.4	0.0	3.4	34.0	3.4	0.5	3.9	39.2
15	3.2	0.0	3.2	32.0	3.4	1.3	4.7	47.8	3.4	1.1	4.5	45.1
16	2.8	0.0	2.8	28.6	3.4	1.3	4.7	47.2	3.4	0.2	3.6	36.5
17	2.9	0.0	2.9	29.5	3.1	0.2	3.2	32.7	3.4	0.3	3.7	37.1
18	3.2	0.0	3.2	32.2	3.0	1.9	4.8	48.6	3.4	0.2	3.6	35.8
19	3.0	0.0	3.0	29.7	3.1	0.0	3.1	31.5	3.4	0.3	3.7	37.3
20	3.0	0.0	3.0	29.7	3.4	0.0	3.4	34.5	3.4	0.4	3.8	38.7
21	2.9	0.0	2.9	29.6	3.0	1.3	4.3	43.6	3.3	0.6	3.9	39.3
22	3.0	1.4	4.3	43.7	3.4	0.1	3.5	34.9	3.4	0.4	3.8	38.6
23	3.5	1.4	4.9	49.5	3.4	0.1	3.5	35.1	3.4	0.5	3.9	39.5
24	3.2	1.1	4.3	43.4	3.0	0.1	3.1	31.1	3.4	1.0	4.4	44.6
25	2.6	0.0	2.6	26.6	3.0	0.8	3.8	37.9	3.4	0.4	3.8	38.4
26	3.2	0.0	3.2	32.5	2.9	0.5	3.4	34.0	3.4	0.0	3.4	34.5
27	2.8	0.0	2.8	27.9	1.8	0.4	2.2	22.2	3.4	0.4	3.9	38.8
28	1.9	0.0	1.9	18.6	2.5	0.5	3.0	30.6	3.4	0.0	3.4	34.5
29	2.9	0.0	2.9	29.2	0.0	0.0	0.0	0.0	3.5	1.0	4.4	44.7
30	3.6	0.0	3.6	36.7	0.0	0.0	0.0	0.0	3.5	0.0	3.5	34.9
31	3.1	0.0	3.1	30.8	0.0	0.0	0.0	0.0	3.4	0.0	3.4	34.2

the periodic maintenance planning and operating conditions in 2025.

Based on the data presented in [Table 1](#), the average daily water discharge generated from the cooling condenser serves as a key parameter in calculating the potential electrical power that can be generated. This water discharge is the result of the cooling process in the condensation system, which is then channeled into the hydropower generation system [44]. The consistency and fluctuation of the water discharge largely depend on the normal operation of the power generation units, so any changes in operational patterns can affect the amount of water available for hydropower generation.

In [Figure 4a](#), the average water flow is shown when Unit 2 is undergoing maintenance, and unit testing is being conducted. Meanwhile, Unit 1 is in a shutdown state; however, the CWP remains operational to maintain the equipment at optimal temperature conditions. The operation of the CWP in this situation is crucial for

ensuring that inactive equipment remains within a safe temperature range, thereby preventing overheating that could potentially damage components. Next, in [Figure 4b](#), Unit 1 has resumed normal operation, while Unit 2 is still under repair. In this condition, the CWP is still used to support additional work related to Unit 2's maintenance. The use of the CWP in this phase is intended to ensure that the equipment undergoing repairs remains at the appropriate temperature, allowing the maintenance process to proceed smoothly without technical issues caused by overheating. [Figure 4c](#) illustrates that Unit 1 continues to operate normally, while Unit 2 is still undergoing maintenance. However, Unit 2 still requires a small water flow from the CWP for its cooling process. This indicates that even when a unit is not fully operational, an adequate cooling system is still necessary to maintain equipment temperature stability within a safe range.

In the planning of hydropower plants, the height of the head pond and the presence of water flow are crucial

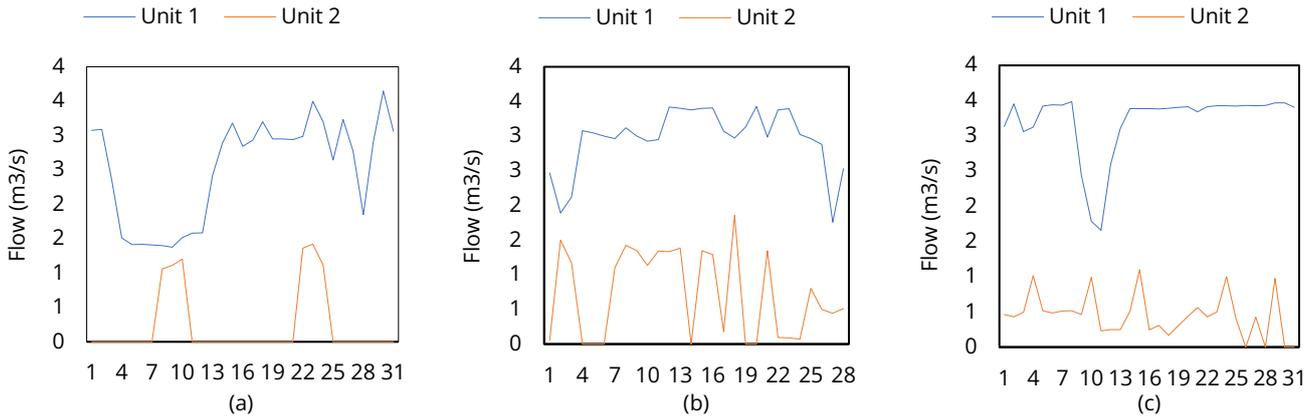


Figure 4. Average condenser outlet flow Unit 1 and Unit 2 in (a) January 2025 (b) February 2025 (c) March 2025.

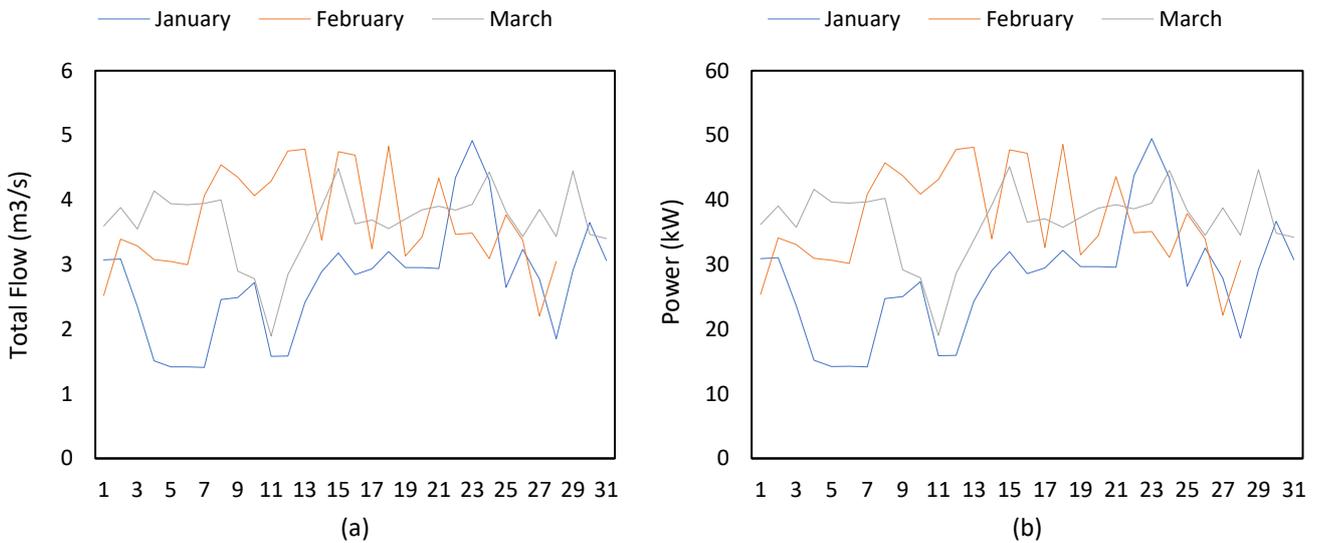


Figure 5. Comparison of (a) Average total flow 2025 (b) Power generated 2025.

Table 2. Estimate saved energy cost based on kWh.

Power generate kWh	Coal T/h	Cost USD /T
14.2	0.01	0.507
49.5	0.035	1.77

factors in determining the type of turbine to be used. The Kaplan turbine is chosen due to its ability to operate optimally under relatively low water head conditions while still maintaining a sufficiently large flow rate [45]. Considering the variations in water discharge from the cooling condenser, selecting the appropriate turbine is essential to ensure optimal energy conversion efficiency from water to electricity. Therefore, the design planning of the generation system must align with the water flow characteristics produced by the Steam Power Plant cooling system.

Figure 5 illustrates the distribution of water flow and the power that can be generated. Figure 5a shows that even when a unit is under maintenance, such as repairing the CWP experiencing high vibration, there is still sufficient water flow to drive the turbine due to the available head

of 3 meters. This indicates that, despite operational limitations, the existing water flow can still contribute to power generation, albeit at a reduced capacity. Figure 5b presents the calculated power output based on the recorded flow and head data, resulting in a power generation range of 14.2 to 49.5 kW, as shown in Table 1. In reality, this power output could be significantly higher if both units operated simultaneously under normal conditions, achieving a total water flow of 7 m³/s. This highlights the potential for increased energy production when both units operate optimally, thereby maximizing efficiency in the hydropower generation process.

One of the major factors influencing the amount of power that can be generated is the maintenance schedule, which is determined based on the water flow pattern [46, 47]. When one of the Steam Power Plant units undergoes periodic maintenance, the available water discharge decreases, ultimately affecting the electricity output of the hydropower plant. The power generated by the Micro Hydropower Plant is designed to minimize interference with the main operations of the Steam Power Plant,

ensuring that energy distribution remains balanced and does not compromise the efficiency of the main system. With the presence of hydropower Plants, energy needs for supporting facilities can be met independently, reducing reliance on the main system while enhancing overall efficiency and sustainability in power plant operations [48].

The condenser wastewater recovery strategy plays a crucial role in improving energy efficiency in Steam Power Plants. By optimizing the reuse of condenser wastewater, the thermal load on the cooling cycle can be reduced [49]. Since Steam Power Plants have an efficiency of approximately 30-45%, meaning that only 30-45% of the energy in coal is converted into electricity. At the same time, the rest is lost as heat, this heat loss results in energy wastage [50]. Therefore, the presence of hydropower Plants provides a positive impact in terms of cost efficiency.

The reduction of heat loss in this system also contributes to an overall increase in thermal efficiency, allowing for a decrease in fossil fuel consumption, such as coal. Studies have shown that implementing this strategy can save energy derived from coal combustion in the range of 14.2 kW to 49.5 kW, which directly impacts improvements in power plant efficiency and reductions in operational costs. Table 2 provides an estimate of energy savings and costs that can be optimized if the hydropower plant operates efficiently without any damage. This reduction in operational costs also depends on the calorific value of coal and its price in the global market.

From an environmental perspective, condenser wastewater recovery helps mitigate the negative impact of Steam Power Plants on aquatic ecosystems by reducing the amount of discharged water into the environment. This can lower the risk of thermal pollution, which often disrupts the balance of aquatic ecosystems. Additionally, by decreasing coal consumption, this strategy directly reduces greenhouse gas emissions such as carbon dioxide (CO₂), sulfur dioxide (SO₂), and nitrogen oxides (NO_x), which are major contributors to air pollution and climate change [51]. Therefore, the implementation of the condenser wastewater recovery strategy not only enhances energy efficiency but also contributes to environmental sustainability by minimizing the ecological impact of steam power generation.

As a comparative context, various waste utilization approaches have been explored in desalination and cooling systems to improve energy efficiency. For instance, a study by Rostamzadeh et al. demonstrated that a hybrid HDH-RO system utilizing waste heat from

wind turbine generators for seawater desalination had significant drawbacks in terms of economic viability and thermal efficiency compared to a standalone RO system [52]. Meanwhile, in a study conducted in Isfahan, Iran, Assareh et al. performed a multi-objective optimization of a solar-based integrated system to improve exergy efficiency and reduce system costs. However, the system's performance was significantly influenced by fluctuations in ambient temperature [53]. On the other hand, a paper authored by Shafieian and Khiadani describes a desalination and air-conditioning system powered by waste heat from submarine diesel engines, which successfully reduced fuel consumption and lightened the vessel load through multifunctional system integration [54].

In comparison to these approaches, the strategy proposed in this study, utilizing discharged seawater from a power plant's condenser cooling system, offers a unique advantage by converting residual thermal energy into electricity generated from hydropower. This approach enhances the overall efficiency of the power plant while minimizing its environmental impact. It presents a viable and energy-efficient solution that supports efforts to reduce coal energy consumption in thermal power generation.

4. Conclusions

The utilization of condenser cooling system wastewater as an additional energy source through a small-scale hydro turbine demonstrates a practical approach to improving energy efficiency and sustainability in Steam Power Plants. By leveraging the height difference (head) and water flow rate, this system can generate between 14.2 kW and 49.5 kW of electricity, resulting in an estimated reduction in coal consumption, lower operational costs, and minimized emissions if implemented. The system is expected to consume between 0.01 and 0.035 tons of coal per hour. The integration of a head pond further ensures stable flow management and system reliability. Future research can explore the application of other technologies, such as thermoelectric generators for direct heat-to-electricity conversion or advanced energy storage systems, to optimize electricity utilization. Additionally, integrating artificial intelligence and machine learning for predictive maintenance and efficiency optimization could further enhance the performance of wastewater energy recovery systems in power plants.

Author Contributions: Conceptualization, E.Y. and C.A.; methodology, E.Y. and C.A.; validation, E.Y.; formal analysis, E.Y.; investigation, E.Y.; resources, E.Y.; data curation, E.Y.; writing—original draft preparation, E.Y. and C.A.; writing—review and editing, E.Y., C.A., O.L., R.S., A.T., and R.A.; visualization, E.Y.;

supervision, E.Y. and C.A.; project administration, C.A.; All authors have read and agreed to the published version of the manuscript

Funding: This study does not receive external funding.

Ethical Clearance: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: All data supporting the findings of this study are included within the paper.

Acknowledgments: The authors would like to thank their respective universities

Conflicts of Interest: All the authors declare no conflicts of interest.

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