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Revitalization of Pico-Hydro Pelton Turbines for Operation at Low Head: An Experimental Study and Efficiency Analysis

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Abstract

The transition to clean energy in Indonesia by 2025 is a key issue in national energy policy, with a target renewable energy mix ranging from 17–20%, adjusted from the previous target of 23%. One energy source with development potential is the pico-hydro power generation system with a capacity below 5 kW, particularly for remote areas not yet connected to the main power grid. This study aims to design and experimentally test a modified Pelton turbine capable of operating effectively under low-head conditions (<10 m) with a relatively constant flow rate. The research variables include variations in water flow rate between 0.5–2.0 L/s, head in the range of 2–8 m, and changes in generator load. Turbine design development was carried out by modifying the nozzle, varying the runner diameter between 100–250 mm, adjusting the water jet angle, and altering the number of blades on the runner to achieve optimal performance. This study is expected to yield performance data on the hydraulic and mechanical efficiencies of the Pelton turbine under low-head conditions, with a target efficiency of over 50% and an output power of up to 5 kW. The findings of this study are expected to contribute scientifically to the development of small-scale water turbine technology and support the utilization of renewable energy for rural electrification, in line with Sustainable Development Goals (SDGs) 7 and 13.

Keywords Renewable Energy; Pico-hydro; Pelton Turbine; Low Head; Turbine Efficiency; Micro-hydro Power Plant

INTRODUCTION

The utilization of small-scale renewable energy is a key strategy in supporting national energy security, particularly in remote areas not yet connected to the main power grid. Micro-hydro power generation systems (PLTMH) and pico-hydro systems hold great potential in Indonesia due to the country's geographical conditions, which are characterized by small rivers with relatively stable flow rates throughout the year. A report from the Ministry of Energy and Mineral Resources of the Republic of Indonesia emphasizes that the development of new and renewable energy (EBT) is a priority in the national energy mix through 2030 (Ministry of Energy and Mineral Resources, 2023). Globally, pico-hydro systems (<5 kW) are also recognized as an economical and sustainable solution for rural electrification. Water turbines are the primary component in hydro systems that determine the level of energy conversion efficiency. Based on their operating principles, water turbines are classified into reaction turbines and impulse turbines. Pelton turbines are a type of impulse turbine designed for high-head and low-flow conditions. Under ideal conditions, Pelton turbines can achieve efficiencies above 85%. However, under low-head conditions (<20 m), the performance of Pelton turbines tends to decline due to the low kinetic energy of the resulting water jet.

Various Scopus-indexed studies have addressed the optimization of Pelton turbines through both experimental and numerical approaches. A study published in Renewable Energy shows that bucket geometry significantly affects pressure distribution and momentum transfer efficiency (Zhang et al., 2018). Another study in Energy Reports revealed that the ratio of jet velocity to runner circumferential velocity (speed ratio) is a key parameter in improving the power coefficient of small-scale turbines. Additionally, a publication in the Ain Shams Engineering Journal confirmed that variations in nozzle diameter directly affect the system's power performance and efficiency (Elbatran et al., 2015).

At the national level, research on Pelton turbines has also been widely published in Sinta-indexed journals. A study in the Journal of Mechanical Engineering reports that variations in the number of blades affect efficiency and shaft torque, with an optimal configuration at a specific number of blades (Wicaksana & Adiwibowo, 2023). Another study in Teknosia showed that the bowl depth and blade deflection angle have a positive correlation with power increase on a laboratory scale (Tonadi, 2022). Furthermore, an experimental study in the Journal of Mechanical Engineering revealed that the ratio of jet width to bucket width significantly affects energy conversion efficiency (Prasetyo et al., 2021).

Although these various studies have addressed the design optimization of Pelton turbines, most research has focused on developing new designs. In reality, however, in many pico-hydro installations in the field, the turbines used are simple fabricated products with relatively low actual efficiency. A revitalization or retrofit approach to existing turbines is a more economical alternative compared to a complete system replacement. A study in Sustainability reports that a retrofit approach for small hydro turbines can increase efficiency by up to 10–15% without modifying the main civil structure (Bianchi et al., 2021).

Theoretically, the efficiency of a Pelton turbine is influenced by the jet velocity (Vj), the runner peripheral velocity (U), the flow inlet and outlet angles, and losses due to friction and splashing (Dixon & Hall, 2014). Under low-head conditions, the kinetic energy of the jet decreases, making it difficult to achieve the optimal velocity ratio. Numerical research published in the Journal of Mechanical Science and Technology indicates that modifying the splitter bucket angle can improve pressure distribution and reduce energy losses under suboptimal conditions (Kim et al., 2019). This suggests that geometric modifications have the potential to enhance the performance of Pelton turbines at low heads.

Pelton turbines fall into the category of impulse turbines that operate by converting the kinetic energy of a water jet into mechanical energy through the momentum of the flow's change in direction as it strikes the buckets on the runner. This basic principle makes the Pelton turbine ideal for conditions of high-pressure, low-flow water, where the water's potential energy is converted into kinetic energy through a nozzle before striking the turbine buckets (Pelton Wheel, 2026). The theoretical efficiency of a Pelton turbine depends on the ratio of the jet velocity to the circumferential velocity of the runner, which ideally results in maximum momentum change and optimal power output.

Several experimental studies have evaluated the performance of Pelton turbines under varying operating parameters such as nozzle diameter, head, and flow rate. Other studies have confirmed that turbine design and configuration parameters, as well as the mechanical transmission system, have a significant impact on the performance of energy conversion systems in applied mechanical engineering applications, highlighting the importance of geometric evaluation and configuration adjustments to improve turbine efficiency under specific operating conditions. Research by Alomar et al. shows that nozzle diameter and head conditions affect turbine output and efficiency, with a smaller nozzle diameter combined with a specific head capable of producing higher efficiency across a wide range of runner speeds (Alomar, Abd, Salih, & Ali, 2021). These findings confirm that the selection of nozzle geometry and operating conditions are critical factors in optimizing Pelton turbine performance. Furthermore, a numerical study by Židonis revealed that the application of Computational Fluid Dynamics (CFD) has emerged as a vital tool for predicting performance and optimizing Pelton turbine designs, particularly for understanding the complex flow around the buckets—a phenomenon that is difficult to analyze using conventional methods (Židonis, 2015). This CFD approach allows for a more detailed evaluation of variations in operating conditions and bucket geometry that can significantly impact hydraulic efficiency.

In the context of pico-hydro applications, the performance of impulse turbines such as the Pelton and Turgo has been evaluated due to their ability to handle variations in jet velocity and specific velocity ratios. A study by Cobb and Sharp compared the performance characteristics of the Turgo and Pelton turbines, showing that while both types exhibit high efficiency, design parameters such as the velocity ratio and the precision of jet alignment play a crucial role in achieving peak efficiency in pico-hydro systems (Cobb & Sharp, 2013). These findings are relevant to revitalization research because they highlight the limitations and opportunities for optimizing impulse turbines outside of high-head conditions.

Turbine design parameters—including nozzle diameter, number of nozzles, and bucket geometry—have been shown to have a significant impact on Pelton turbine performance. Several empirical studies, such as those described by Setyawan et al., indicate that increasing the number of nozzles can directly affect turbine efficiency, although this relationship is not always linear and depends on operating conditions and turbine configuration (Setyawan et al., 2024). Meanwhile, other research shows that variations in bucket geometry and runner configuration can provide opportunities to increase torque and power output, particularly in small-scale turbines operated outside their optimal design parameters.

Based on the above discussion, there is a research gap in the form of a lack of experimental studies specifically examining the revitalization of pico-hydro Pelton turbines at low head using an integrated approach (simultaneous modification of the nozzle and runner). Therefore, this study aims to analyze the improvement in the efficiency of pico-hydro-scale Pelton turbines through the revitalization of key components and to evaluate system performance before and after modifications under varying low-head conditions. This study is expected to provide practical contributions to the development of small-scale renewable energy systems in Indonesia and to enrich both national and international literature.

Specifically, the contributions of this study include: (1) providing experimental data on Pelton turbine performance at low head, (2) evaluating the effectiveness of geometric modifications on system efficiency, and (3) providing practical revitalization design recommendations for pico-hydro implementation in rural areas. Thus, this research is not only oriented toward the development of impulse turbine theory but also toward the application of appropriate technology to support a sustainable energy transition.

Furthermore, studies on flow characteristics and the thermophysical properties of fluids in energy conversion systems indicate that changes in operating parameters can significantly affect system performance. The review study confirms that variations in viscosity and fluid heat transfer characteristics directly affect energy efficiency in engineering applications. These findings indicate that the analysis of flow characteristics and hydrodynamic parameters is also a crucial aspect in the revitalization of Pelton turbines at low heads to maximize energy conversion efficiency.

METHODS

This study employs an experimental and engineering redesign approach, focusing on the revitalization of a Pelton turbine that has experienced a decline in performance. The methods used include an evaluation of the existing conditions, the redesign of key components, and post-repair performance testing.

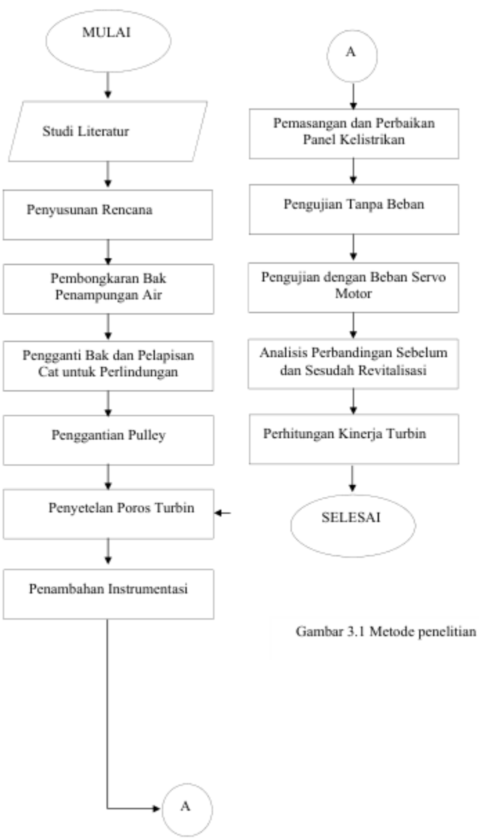

Figure 1. Research Flowchart

This study was conducted through several systematic stages to evaluate and improve the performance of a Pico-Hydro Pelton turbine operating under low-head conditions. The first stage involved problem identification, which included observing the existing condition of the Pelton turbine, identifying damage to critical components such as the buckets, nozzle, and transmission system, and evaluating the losses in efficiency and power output. This preliminary assessment provided the basis for determining the necessary improvements to enhance turbine performance.

The second stage consisted of technical data collection. During this stage, essential operational parameters were measured, including the effective head, water flow rate, turbine rotational speed, and generator power output before the revitalization process. These data served as the baseline for assessing the effectiveness of the redesign and subsequent performance improvements. The third stage focused on the redesign of the turbine system. Engineering modifications were carried out by improving the bucket geometry to increase water impact efficiency, adjusting the nozzle spray angle to optimize jet direction, optimizing the runner diameter for low-head operation, and aligning the coupling and shaft system to minimize mechanical losses. These design modifications were intended to improve energy conversion efficiency and overall turbine performance.

Following the redesign process, the fourth stage involved fabrication and installation. New buckets were manufactured according to the redesigned specifications, worn or damaged components were replaced, and the entire turbine system was reassembled and installed. This stage ensured that all redesigned components functioned properly as an integrated system before performance testing. The final stage consisted of testing and evaluation. The revitalized turbine was tested by measuring its rotational speed (rpm), generator output power, and overall operating performance. The efficiency of the turbine before and after the revitalization process was then compared to determine the effectiveness of the engineering modifications in improving power generation under low-head operating conditions.

The performance evaluation of the revitalized Pico-Hydro Pelton turbine was based on several key engineering parameters. These included the effective head (H), which represents the available hydraulic energy; the water flow rate (Q), indicating the volume of water passing through the turbine per unit time; the rotational speed (n) of the turbine runner; and the turbine power output (Pt) generated during operation. In addition, the study analyzed the overall system efficiency (η), which was calculated as the ratio of the actual output power produced by the generator to the theoretical hydraulic power available from the water source. These parameters were analyzed comparatively before and after the revitalization process to determine the extent to which the design modifications improved the operational efficiency and power output of the Pelton turbine.

FINDINGS AND DISCUSSION

Turbine Condition Before Revitalization

The initial evaluation revealed that the Pico-Hydro Pelton turbine experienced a significant decline in performance due to several mechanical and hydraulic problems. One of the primary issues was the wear of the turbine buckets, which reduced their ability to effectively capture and redirect the kinetic energy of the water jet. As a result, the conversion of hydraulic energy into mechanical energy became inefficient, leading to a lower turbine rotational speed. In addition, the nozzle was found to produce an inaccurate water jet direction, preventing the jet from striking the bucket at its optimal impact point. The runner also experienced rotational imbalance, which increased mechanical losses and reduced operational stability. These conditions collectively resulted in suboptimal generator output power and decreased overall system efficiency.

Design Changes and Implementation

Following the initial assessment, several engineering modifications were implemented to improve the turbine's performance. The bucket geometry was redesigned to increase the water deflection angle, enabling more efficient momentum transfer from the water jet to the runner. Furthermore, the nozzle position and spray angle were carefully adjusted to ensure that the water jet struck the center of each bucket with greater precision. The transmission system, including the shaft and coupling alignment, was also rebalanced to minimize vibration and mechanical losses during operation. These improvements enhanced the interaction between the water jet and the turbine buckets, resulting in greater torque generation, smoother rotational motion, improved energy conversion efficiency, and increased generator power output under low-head operating conditions.

Figure 2. Disassembly of the bucket

Figure 3. Replacing the pulley bar

The image above shows the process of dismantling the reservoir and replacing the pulley bar in a pico-hydro Pelton turbine system. These steps were carried out as part of a mechanical revitalization process to address the system's declining performance due to component wear and misalignment of the power transmission system. The reservoir was dismantled to provide full access to the shaft system, runner, and transmission mechanism, which were previously enclosed by a protective structure. Inspection results revealed that the pulley bar exhibited wear on the belt contact surface, which could potentially cause slippage and mechanical power loss. This condition directly resulted in a decrease in generator speed and a reduction in the system's overall efficiency. Therefore, the pulley bar was replaced with a new component featuring better dimensional precision and an optimized contact surface. In addition, the replacement process was accompanied by realignment between the turbine shaft and the generator shaft to minimize vibration and mechanical losses caused by misalignment. With these measures in place, it is expected that power transmission from the turbine to the generator will be more effective, thereby supporting improved system performance following the revitalization.

Figure 4. Installation of a pressure gauge

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The figures above show the process of setting up the distribution piping and installing a flow meter as an instrument for measuring flow rate in the Pelton pico-hydro turbine system. The piping was reconfigured to ensure a stable water flow toward the nozzle, minimize secondary turbulence, and reduce head losses caused by connections and changes in flow direction. The flow meter was installed to obtain quantitative, real-time data on actual flow rate (Q), enabling more accurate calculations of hydraulic power and system efficiency. Precise flow measurement is a fundamental parameter in evaluating the performance of impulse turbines, as hydraulic power is directly proportional to flow rate and effective head. With a more controlled installation configuration, the test system better represents actual operating conditions and supports the validity of post-revitalization efficiency analyses.

Table 1. Material and Component Requirements for Revitalization

No	Component Group	Qty	Unit Price (Rp)
1	Drive System (Servo, Pulley, V-Belt)	3	35,000–420,000
2	Measurement System (Pressure Gauge)	1	157,000
3	Piping System (Pipes, Elbows, Tees, Couplings, Reducers, Ball Valves, Faucets)	9	3,500–45,000
4	Installation Materials (Adhesive, Sealing Tape)	3	5,000–8,000
5	Structural & Fasteners (Bolts, Screws, Threaded Rods)	8	3,000–12,000
6	Finishing & Electrical (Paint, Switches)	3	3,000–20,000

No-Load Testing

No-load testing was conducted to determine the basic rotational characteristics of the turbine resulting from variations in the nozzle angle without an electrical load. The water flow rate was maintained at a constant 24 liters for 30 seconds at each angle variation. The results showed that at a 0° angle, the rotational speed was only 20 RPM, then increased significantly at a 5° angle to 130 RPM. However, at angles of 10° and 15°, the rotational speed decreased to 62 RPM and 59 RPM, respectively. This indicates the presence of an optimal nozzle angle (5°) that results in the most effective momentum transfer of the water jet. The decrease in RPM at larger angles is caused by the misalignment of the flow direction relative to the blades, resulting in kinetic energy not being absorbed to its fullest extent.

Table 2. No-Load Testing

No	Nozzle Angle	RPM	Water Flow Rate	Time
1	0	20	24 L	30 Seconds
2	5°	130	24 L	30 Seconds
3	10°	62	24 L	30 Seconds
4	15°	59	24 L	30 Seconds

Servo Load Testing

Load testing was conducted by mounting a magnetic servo motor on the turbine shaft. The water flow rate was maintained at a constant 24 L for 30 seconds, with the observed parameters being RPM and output voltage. At an angle of 0°, the rotation was low (20 RPM) with a voltage of 0.45 V. An angle of 5° yielded the best performance with 128 RPM and a maximum voltage of 4.50 V. However, at angles of 10° and 15°, the RPM dropped to 60 RPM and 54 RPM, respectively, with the voltage decreasing to 3.45 V and 3 V. These results indicate that an angle of 5° represents the most optimal operating condition.

Table 3. Testing with a Load

No	Nozzle Angle	RPM	Water Flow Rate	Time	Voltage (V)
1	0	20	24 L	30 Seconds	0.45
2	5°	130	24 L	30 Seconds	4.50
3	10°	62	24 L	30 Seconds	3.45
4	15°	59	24 L	30 Seconds	3

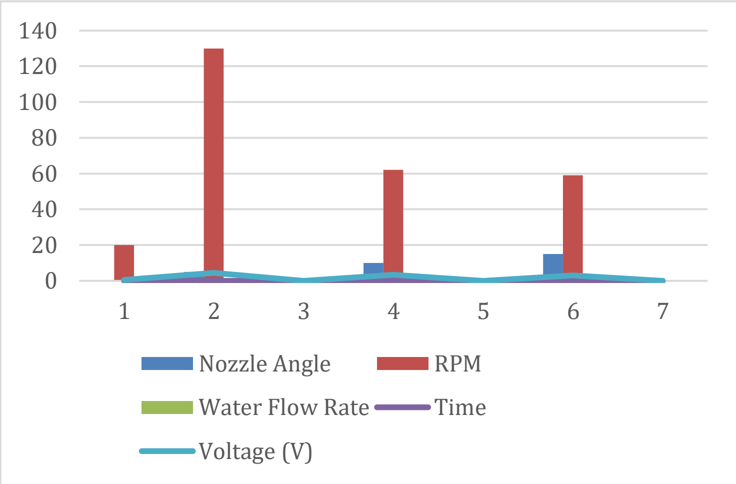

Figure 6 Relationship between turbine RPM and nozzle angle

Calculation of Turbine Power and Efficiency

The performance of the revitalized Pico-Hydro Pelton turbine was evaluated by calculating the flow rate, hydraulic power, electrical power, turbine efficiency, and angular velocity under optimal operating conditions. The water flow rate (Q) was determined by dividing the measured water volume by the discharge time. A water volume of 24 liters (0.024 m^3) was collected over 30 seconds, resulting in a flow rate of 0.0008 m^3/s. The theoretical hydraulic power (Ph) was then calculated using the equation Ph=ϱgQHP, where the water density (ϱ\rhoϱ) was 1000 kg/m^3, gravitational acceleration (9.81 m/s^2), flow rate (0.0008 m^3/s), and effective head (2 m). Based on these parameters, the available hydraulic power was calculated to be approximately 15.7 W. The electrical power output (Pe) generated by the system was calculated using the equation Pe=V×IP_e = V \times IPe=V×I. Under the optimal nozzle angle of 5°, the generator produced an output voltage of 4.50 V with a current of 0.30 A, resulting in an electrical power output of 1.35 W.

The turbine efficiency (η) was determined by comparing the electrical output power with the available hydraulic power using the equation η=(Pe/Ph)×100%. The calculation showed that the turbine achieved an efficiency of 8.59%, indicating that approximately 8.6% of the available hydraulic energy was successfully converted into electrical energy. Although the efficiency remains relatively low, the result demonstrates the operational capability of the revitalized turbine under low-head conditions and provides a basis for further optimization.

The rotational performance of the turbine was also analyzed by calculating its angular velocity. At the optimal nozzle angle of 5°, the turbine reached a rotational speed of 128 rpm. Using the relationship $\omega=2\pi n/60$, the corresponding angular velocity was calculated to be approximately 13.40 rad/s. This result indicates that the revitalized turbine was capable of maintaining stable rotational motion, contributing to improved torque generation and more consistent electrical power production. Overall, the hydraulic and mechanical performance analysis confirms that the implemented design modifications enhanced the operational characteristics of the Pico-Hydro Pelton turbine operating under low-head conditions.

Interpretation of Results

The calculation results indicate that the 5° nozzle angle produced the highest electrical power output and turbine efficiency compared to the other nozzle angle configurations tested. This finding is consistent with the experimental results obtained under both loaded and unloaded operating conditions, where the maximum rotational speed (RPM) was consistently achieved at the 5° nozzle setting. The improved performance at this angle can be attributed to the more precise alignment of the water jet with the center of the Pelton bucket, allowing more effective momentum transfer and maximizing the conversion of hydraulic energy into mechanical energy. Consequently, the turbine generated higher torque, resulting in greater rotational speed and improved electrical power output.

Despite the observed performance improvement, the overall efficiency of the turbine remained relatively low. Several factors contributed to this limitation. First, the turbine operated under a low effective head, characteristic of pico-hydro systems, which inherently provides limited hydraulic energy for power generation. Second, mechanical losses within the transmission system, including friction in the shaft, bearings, and coupling components, reduced the amount of mechanical energy transferred to the generator. Third, hydraulic losses caused by turbulence, water splash, and imperfect jet-bucket interaction decreased the efficiency of hydraulic energy conversion. Finally, the relatively low efficiency of the generator further reduced the electrical output because not all mechanical energy produced by the turbine could be converted into electrical energy efficiently. These findings suggest that although optimizing the nozzle angle significantly improves turbine performance, further enhancements are required to increase overall system efficiency. Future improvements should focus on minimizing mechanical and hydraulic losses, optimizing bucket geometry, improving nozzle design, and employing higher-efficiency generators. Such engineering modifications would enable pico-hydro Pelton turbines to produce greater electrical power and operate more effectively under low-head conditions.

Table 4 Performance of the revitalized turbine

Parameter	Symbol	Value	Unit	Description
Number of buckets	–	22	pieces	Turbine runner design
Water volume	V	0.024	m^3	Test volume
Flow time	t	30	s	Sampling time
Flow rate	Q	0.0008	m^3/s	Calculation Results
Effective head	H	3	m	Pump head
Water density	ϱ	1000	kg/m^3	Standard assumption
Acceleration due to gravity	g	9.81	m/s^2	Constant
Hydraulic power	P_id	23.54	W	Theoretical water power
Turbine speed (optimum)	n	128	RPM	Nozzle angle 5°
Angular velocity	ω	13.4	rad/s	Calculation results
Shaft torque	T	0.5	Nm	Operating value
Mechanical power of the turbine	Pm_e	6.7	W	Shaft power
Output voltage	V	4.5	Volts	Measurement results
Equivalent resistance	R	10	Ohms	System load
Electric current	I	0.45	Amperes	Calculation Results
Electric power	P_e	2.03	W	Generator power

CONCLUSION

This study aimed to revitalize a Pico-Hydro Pelton turbine operating under low-head conditions and evaluate its performance through experimental testing and efficiency analysis. The findings demonstrate that the revitalization process successfully improved the turbine's operational performance. The optimized system achieved a maximum rotational speed of 128 RPM at the optimal nozzle angle of 5°, confirming that nozzle configuration plays a critical role in maximizing turbine efficiency and power generation. Among all tested nozzle angle variations, the 5° angle consistently produced the highest rotational speed, output voltage, and overall system performance, indicating more effective momentum transfer between the water jet and the turbine buckets.

The performance analysis further revealed that the available hydraulic power was successfully converted into mechanical and electrical power, demonstrating the feasibility of the redesigned turbine for low-head pico-hydro applications. In addition, the use of 22 turbine buckets contributed to smoother rotational continuity and improved torque stability during operation. Although the overall efficiency remains relatively low because of hydraulic, mechanical, and generator losses, the revitalization significantly enhanced the operational characteristics of the system. These findings indicate that the proposed design modifications provide a practical and cost-effective approach for improving the performance of Pico-Hydro Pelton turbines. The developed system also has strong potential as an educational and experimental platform for renewable energy research. Future studies should investigate alternative bucket geometries, nozzle configurations, and high-efficiency generators to further improve energy conversion efficiency under low-head operating conditions.

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