

Development of a Water Impulse Turbine for Pico-Hydro Energy Generation in Off-Grid Rural Areas

Ahmad Aiman Johaimi¹, Khairul Anwar Ibrahim¹, Mohd Farriz Basar¹,
Nurul Ashikin Mohd Rais¹, Kamaruzzaman Sopian²

¹Faculty of Electrical Technology and Engineering, Universiti Teknikal Malaysia Melaka (UTeM), Melaka, Malaysia

²Department of Mechanical Engineering, Universiti Teknologi PETRONAS (UTP), Seri Iskandar, Malaysia

Email: khairulanwar@utem.edu.my

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Abstract

Pico-hydro is a low cost and clean power generation system that harnesses the energy from flowing low head and low flow streams and rivers. Pico-hydro plays a key enabler to address the lack of electricity in remote areas, particularly in forested regions, where conventional grid extension is expensive, complex, and limited, relying on varying water flows such as river flow and waterfall flow for its operation. This project designs a versatile water impulse turbine (Pelton turbine) on an ultra-low head condition. The design incorporates a flat surface base to ensure system stability when subjected to vibrations during the rotational movement of the turbine. The actual prototype employs hollow mild steel as the material for the turbine casing. The turbine is fabricated using 3D printing using PETG material for the 24 Pelton turbine buckets and one rotational disk. The project was tested under ultra-low head of 1 m water head height with different pipe sizes from 15 mm to 32 mm, different number of turbine bucket from 6-buckets to 24-buckets and different flow rates. The quantity of energy produced by the pico-hydro generating system is influenced by two key factors which are head and water flow. This project achieved its highest speed at 89.8 RPM, with turbine efficiency reaching up to 88.14%.

Keywords

Renewable Energy, Hydroelectric, Pico Hydro, Water Turbine, Pelton Turbine

1. Introduction

According to UN, the global electricity access rate increased from 87% in 2015

to % in 2021, serving close to an additional 800 million people [1]. This increase of energy will subsequently contribute to the increasing of carbon footprint, if the energy sources are produced by the burning of fossil fuels. Clean energy, such as geothermal, solar, and wind energy, can be harvested using various technologies in order to increase the use of green and sustainable energy resources to meet the ever-increasing energy demand and alleviate the environmental crisis [2]. In recent years, growth rate of energy from the renewables gradually gains momentum over the years and was reported at 7% in 2018 compared to 6% in 2017. The renewables, overall, contributed to 26% of the global electricity, 19% of which was large and medium hydropower and other renewable energy besides solar and wind [3].

Although hydropower is considered to be a renewable energy resource, its sustainability is sometimes questioned because of the high cost as well as impacts of dams on the environment, which is a major barrier for the deployment of large or mid-sized hydropower projects [4]. Large and medium hydropower typically costs millions to billions of dollars, making it not feasible to poor and least developed countries. To worsen the scenario, according to 2023 SDG report by UN, financial flows in support of clean energy in developing countries have been on a decreasing trend; they amounted to \$10.8 billion in 2021, down by nearly 12 per cent from 2020 [5]. Thus, it affected its rapid development. Therefore, as an alternative, lower cost of hydro power is needed.

Pico Hydro refers to the smallest systems for generating hydroelectric power, typically producing less than 5 kW of electricity [6]. In contrast to larger power plants, Pico Hydro plants are relatively compact and significantly lower cost than large and medium hydro power [7]. They are commonly utilized in isolated communities to supply electricity for essential purposes like lighting, radios, and various household appliances [8]. These power plants are designed to be small and suitable for rural or remote areas and communities, resulting in lower manufacturing and maintenance costs. Moreover, the materials required for their construction are easily obtainable and do not require hard-to-find components. For example, Pico Hydro Turbines can be created using scrap metal or simple metals readily available in the market. The manufacturing materials, including generators, batteries, and turbines, are relatively affordable and accessible. Additionally, these power plants can be seamlessly integrated into existing irrigation networks, serving a dual purpose [9].

Interest in using Pico hydropower resources is increasing, and the technology is being developed worldwide because of its advantages in terms of its small scale, short construction and deployment time, and lowest impact on the environment [10]. To date, most published literature focuses mainly on small hydropower technologies that use low hydraulic heads between 2 m and 30 m or on hydrokinetic energy conversion technology. Nevertheless, little attention has been paid to water-energy development in situations where the hydraulic head is less than 3 m (*i.e.* ultra-low head, ULH) because of the poor economic benefits of these resources [11] [12]. Thus, this project aims to design a small-scale prototypical Pico

Hydro system which is capable of harnessing energy from a 1 m head using impulse Pelton water turbine. By optimizing impulse turbine efficiency under micro-flow conditions, the project could potentially offer a scalable, low-cost solution tailored to remote areas with limited infrastructure, where conventional hydro-power is impractical and supporting UN Sustainable Development Goal 7 (Affordable and Clean Energy).

2. Methodology

This section highlights the methodical design process employed to achieve the objectives. The design incorporates the water reaction mechanism, which is carefully engineered to maximize power generation efficiency. Following the design phase, a prototype of a Pico hydro power plant is constructed. This involves fabricating the necessary components, such as the water turbine, generator, control system, and water reaction mechanism. Testing of the prototype system will be conducted to ensure the functionality, reliability, and performance of the system.

2.1. Tools, Equipment and Material

The performance of Pico hydro turbines is governed by fundamental design parameters, which include hydraulic head, discharge rate, turbine efficiency, and mechanical losses. Optimizing these variables is essential for viable small-scale energy production. Turbine type and design parameters will be carefully selected based on the site conditions to optimize power generation efficiency.

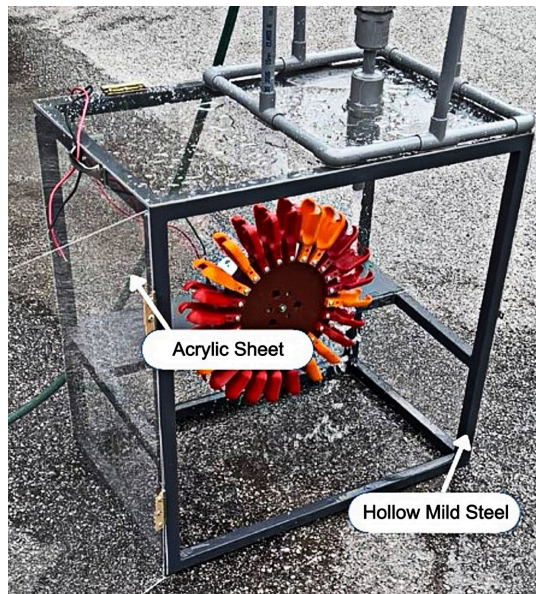


Figure 1. Hollow mild steel for turbine casing.

The turbine components were fabricated using Polyethylene Terephthalate Glycol (PETG) through 3D printing, selected for its excellent durability, high impact resistance (Izod impact strength ~ 3.5 kJ/m²), and high tensile strength (~ 50

MPa) [13]. These properties ensure the runner can withstand the dynamic hydraulic forces and mechanical stress in a wet environment. Furthermore, PETG is a recyclable material, aligning with the sustainable ethos of the project. The turbine casing frame was constructed from low-carbon steel hollow sections, valued for their high strength-to-weight ratio, excellent weldability, and cost efficiency. Its high yield strength (~250 MPa) provides a rigid and stable support structure capable of damping vibrations during operation, which is crucial for maintaining alignment and protecting generator bearings in field deployments [14].

The tools and equipment used in the project include computer-aided design (CAD) software for turbine design and modeling, engineering and measurement tools such as measuring tape and rulers for accurate measurements, electrical components such as generators and control systems, testing and measurement instruments like multimeters, wattmeters and tachometers for evaluating turbine performance. (see **Table 1**). **Figure 1** shows the physical construction of the Pico hydro turbine casing.

Table 1. Tools and equipment.

No.	Tools and equipment
1.	Digital multimeter
2.	Digital tachometer
3.	High precision digital TURBINE flow meter generator Generator rated power = 300 W Rated speed = 900 rpm
4.	Engine = three-phase permanent magnet generator Rated voltage = 12 V - 24 V (DC/AC) Rated current = 25 A/12.5A
5.	3D printer
6.	PETG material for 3D printer
7.	Acrylic transparent sheet for turbine casing
8.	Hollow mild steel for turbine casing
9.	PVC ball water valve non-threaded
10.	PVC Pipes and fittings
11.	CAD software

2.2. Turbine Design and Governing Equations

Hydropower operates on the fundamental principle of utilizing water pressure to initiate the rotation of a mechanical shaft in a hydro turbine. This rotational motion is then harnessed to drive a generator that transforms the energy into electrical power. Both head and water flow rate are critical parameters in a hydropower system. Head refers to the measurement of falling water at the turbine, representing the vertical distance from the top of the penstock to the turbine at the bottom. On the other hand, water flow rate indicates the volume of water that passes through

the system within one second. Consequently, precise measurement of the head becomes crucial since a higher head result in increased power and higher rotational speed of the turbine [15].

The design of Pico hydro turbines is guided by fundamental fluid mechanics and energy conversion equations, including Euler's turbine equation, continuity, and Bernoulli's principle. These governing equations establish the relationship between hydraulic head, flow rate, and mechanical power output, ensuring optimal turbine performance, which is discussed in the following sub-section.

2.2.1. Water Velocity and Flowrate

Water flow calculation involves determining the volume of water passing through a specific point per unit of time. It is a crucial aspect of hydropower system design, requiring consideration of factors such as the cross-sectional area of the penstock and the velocity of the water. The flow rate is a key parameter for optimizing power generation efficiency. Various methods can be used, including flow meters and mathematical formulas, to accurately calculate and control water flow within the hydropower system, ensuring that the turbine receives the necessary water volume to generate the desired electrical output. Equation (1) represents to determine the velocity of water and while Equation (2) is to determine the water flow rate [16].

$$v_2 = \sqrt{2gH} \quad (1)$$

$$Q = v_2 A \quad (2)$$

where:

v_2 = velocity of water, m/s

H = water head, m

g = gravity, m/s²

Q = flowrate of water, m³/s

A = area of penstock, m²

2.2.2. Number of Pelton Buckets

The number of Pelton buckets in a Pelton turbine is determined based on the specific characteristics of the hydropower site, including water flow, head, and desired turbine speed. These curved buckets, situated around the rotating wheel or runner, interact with a high-velocity water jet, converting kinetic energy into mechanical energy to drive a generator for electricity production. Higher number of buckets may enhance overall efficiency. The number of Pelton buckets or drive can be determined by Equation (3).

$$n_b = 15 + \frac{D_r}{2d_j} \quad (3)$$

where:

n_b = number of Pelton bucket

D_r = diameter of runner, m

d_j = diameter of jet, m

2.2.3. Penstock Geometrical Area and Mass

The geometrical area of a penstock, (which is the pipeline conveying water from the source to the turbine in a hydropower system), is calculated based on factors such as the required flow rate and the desired velocity of the water. The cross-sectional area of the penstock is determined to ensure that sufficient water is delivered to the turbine to generate the desired power. Area of penstock can be determined by the Equation (4) below. Penstock mass calculation involves assessing the material and structural requirements of the penstock to withstand the pressure exerted by the flowing water. Factors such as the material's tensile strength, wall thickness, and diameter contribute to the mass calculation which is using the Equation (5).

$$A = \pi r^2 \quad (4)$$

$$m = \rho Q \quad (5)$$

where:

A = area of penstock, m²

r = radius of penstock, m

m = mass, kg

ρ = density of water, kg/m³

Q = flowrate of water, m³/s

2.2.4. Theoretical Power Generated by Pelton Turbine

The theoretical power output of a Pelton turbine is determined by the potential energy of the water available at a given head. When water of density ρ falls under gravity g with a volumetric flow rate Q and an effective head H , the maximum theoretical hydraulic power can be expressed as Equation (6):

$$P_{th} = \rho g Q H \eta \quad (6)$$

where:

P_{th} = theoretical power output, W

ρ = density of water, kg/m³

g = gravity, m/s²

Q = flowrate of water, m³/s

H = water head, m

η = efficiency of the Pico-hydro, %

Equation (7) provides a means to assess the turbine-only efficiency of the system, which measures how effectively the turbine converts the hydraulic power of water into mechanical shaft power. The generator's efficiency is not accounted for in this calculation.

$$\eta_t = \frac{P_{act}}{P_{th}} \times 100\% \quad (7)$$

where:

η_t = turbine-only efficiency, %

P_{act} = actual power output from turbine, W

P_{th} = theoretical hydraulic power, W

2.2.5. Design and Construction of Pelton Bucket

The design of a Pelton bucket for a pico-hydro system with a low head of 1 m requires careful consideration of geometry and control features to ensure efficiency and reliability. Key factors include the use of a cut-out mechanism for emergency flow stoppage and speed regulation, as well as the bucket's shape. A sharp splitter enhances jet division, a shallower bucket depth suits compact low-head operation, and a smaller pitch circle diameter helps achieve higher rotational speeds. These features collectively improve energy conversion from the water jet into torque and rotation.

The bucket was modeled using CAD software (Figure 2), with the integrated cut-out system as a central feature. This mechanism ensures stable operation and rapid flow interruption during emergencies, offering a safer and more efficient alternative to earlier designs that relied on external, less effective flow-control methods. Figure 3 shows the finished actual prototype of the turbine bucket. The inclusion of a splitter is a critical design feature for optimizing performance. The sharp edge of the splitter cleanly cleaves the water jet, directing it symmetrically across the bucket curvature to maximize momentum transfer. This efficiently accelerates the turbine, enhancing energy extraction and overall power production. In contrast, buckets without a splitter allow the jet to disperse more uniformly upon impact, resulting in less effective force application and a comparative reduction in efficiency.

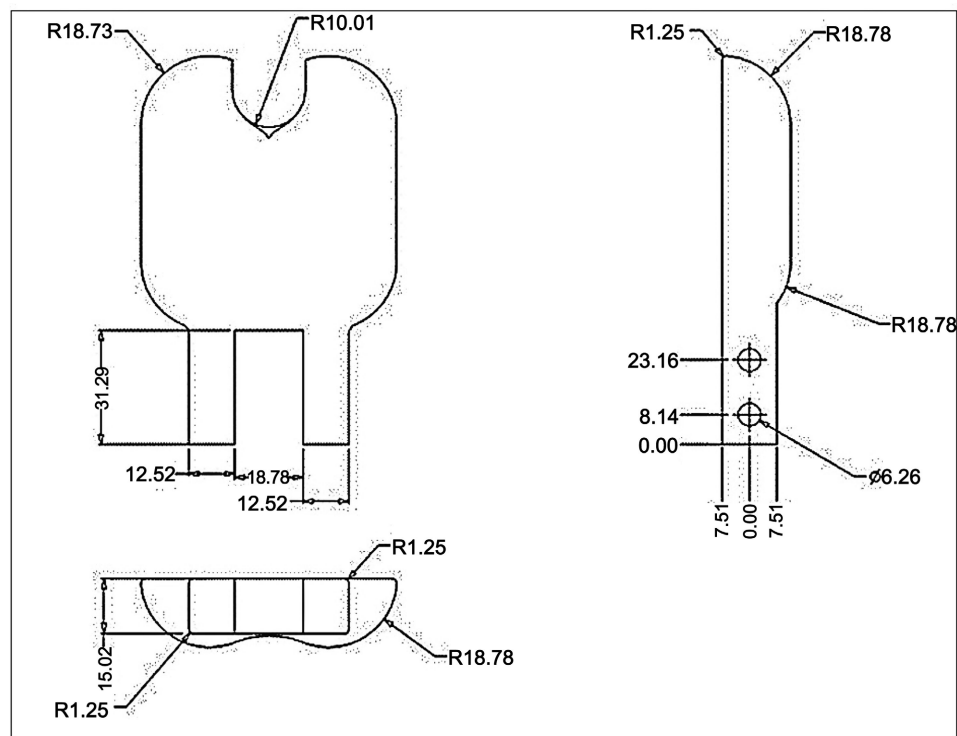


Figure 2. Pelton buckets CAD design.

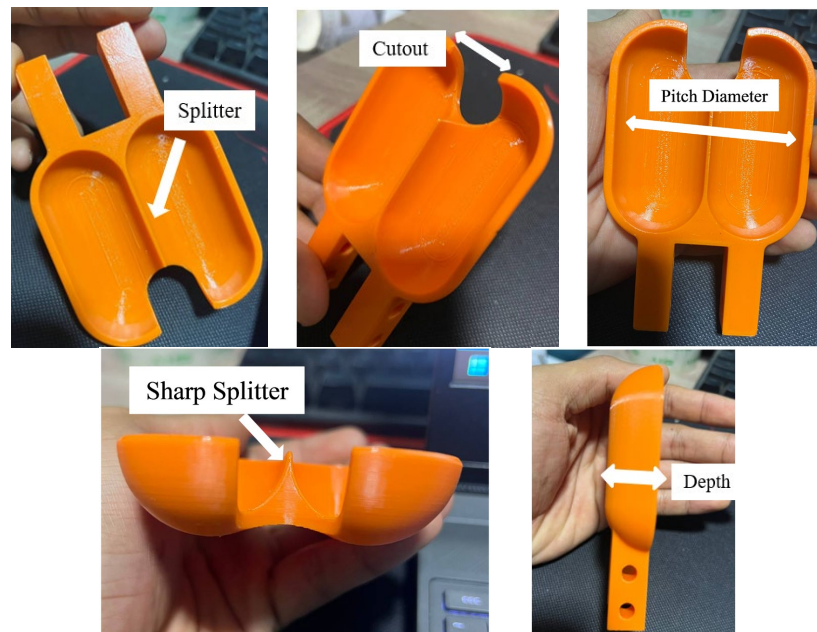


Figure 3. Finished design of the Pelton bucket using 3D printer.

The hydraulic performance of a Pelton bucket is strongly influenced by its depth. A deeper profile increases jet interaction time and energy capture, enhancing speed and power output. However, in this low-head (1 m) pico-hydro application, a shallower bucket depth was selected to achieve better efficiency under low-pressure flow, while maintaining a compact design. The pitch circle diameter (PCD) also plays a crucial role. Larger diameters favor torque and power but reduce rotational speed. For this project, a smaller PCD was chosen to deliver higher rotational speeds compatible with standard generators, while also reducing size and manufacturing cost. This choice accepts a controlled trade-off in peak torque in favor of practicality and efficiency.

Overall, the final design integrates key features tailored to the project's constraints: a cut-out system for stability and emergency shutdown, a sharp splitter for effective jet division, a shallow bucket depth for low-head flow adaptation, and a small PCD for compactness and higher rotational speed. These combined design strategies ensure reliable, efficient, and cost-effective performance in low-head pico-hydro generation.

2.2.6. Design of Turbine Casing, Piping and Test Rig

The design of the turbine casing, piping, and test rig are critical for transforming the Pelton runner's theoretical performance into a functional, measurable pico-hydro system. This sub-chapter details the engineering of these supporting components, which ensure structural integrity, direct hydraulic flow, and provide a controlled environment for performance evaluation.

The turbine casing is made of Hollow mild steel and transparent acrylic sheet. This hollow steel offers a high strength-to-weight ratio and weldability for cost-effective frameworks. The acrylic provides optical clarity, UV resistance, and im-

compact strength for glazing and displays. Both are valued for their durability, lightweight properties, and versatility in construction and fabrication. Finally, for the piping system, Polyvinyl chloride (PVC) components were selected due to their durability, corrosion resistance, and cost-effectiveness.



Figure 4. Different sizes of PVC pipes use in the project.

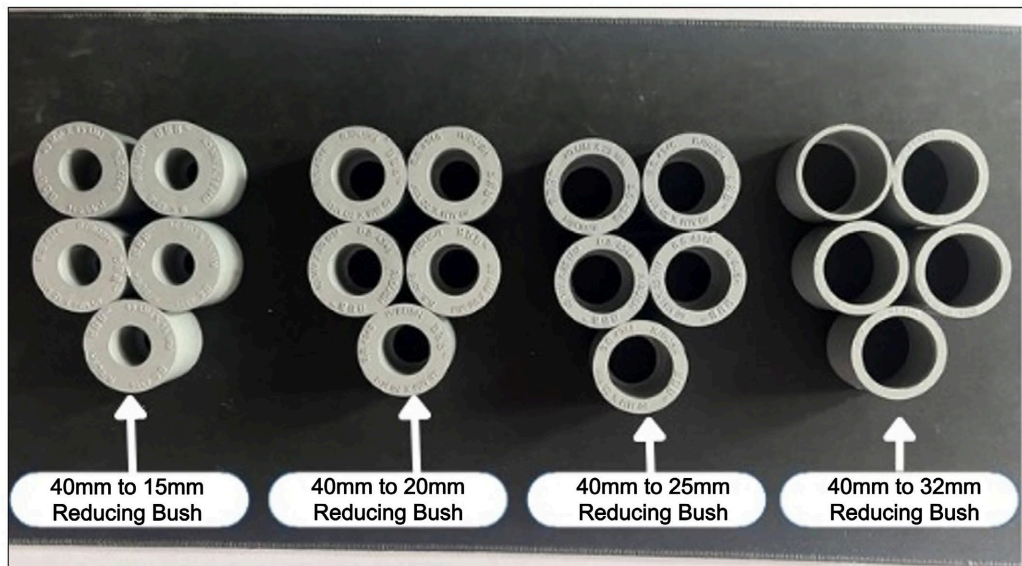


Figure 5. Different sizes of PVC reducing bush.

The piping system utilized 1-meter-long pipes with four diameters (15 mm, 20 mm, 25 mm, and 32 mm) to analyze the effect of conduit size under a 1-meter

water head (See **Figure 4**). These pipes were interconnected using PVC reducing bushes—tapered fittings that create secure, leak-resistant transitions between different diameters—specifically sized at 40 mm-to-32 mm, 40 mm-to-25 mm, 40 mm-to-20 mm, and 40 mm-to-15 mm (See **Figure 5**). Flow to the entire apparatus was controlled by a 40 mm non-threaded PVC ball valve, which provides reliable on/off control via a 90-degree turn of its handle and is designed for permanent solvent-welded connections. **Figure 6** shows the overall view of the fully assembled prototype Pico hydro turbine, casing and piping.

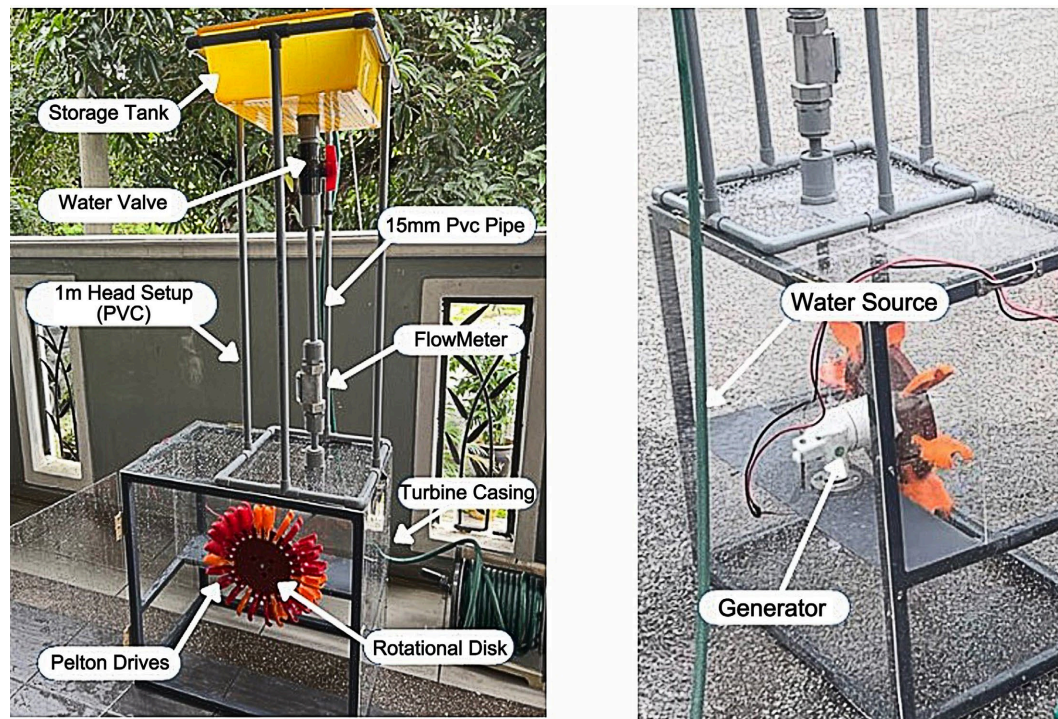


Figure 6. Pico hydro test rig for testing turbine performance.

A constant water head (H) of 1.0 m was maintained by a gravity-fed reservoir. Head losses in the PVC penstock were minimized by eliminating unnecessary bends and fittings. The net head was verified by measuring the static pressure immediately upstream of the turbine nozzle to ensure accuracy in the theoretical power calculations.

3. Results and Discussion

3.1. Overall Results

In this study, a tachometer was used to measure the turbine's speed, while a multimeter was used to measure the voltage and current generated by the generator, in order to calculate the power generated. Each configuration (pipe size and bucket number combination) was tested three (3) times to ensure result consistency. The values presented in **Tables 3-7** represent the average of these repeated runs. The measured parameters showed minimal variation, with standard

deviations of ± 2.1 RPM for speed and ± 0.15 W for power output, indicating high measurement reliability.

A flowmeter was utilized to measure the water flow in PVC pipes of different sizes, which 15 mm, 20 mm, 25 mm, and 30 mm. The data collection involved variations in the number of buckets, specifically 6, 8, 12, 18, and 24 buckets. Following the measurements, the task involves computing the average flow rate for each pipe size. **Table 2** displays the collected data on flow rate through different pipe sizes.

Table 2. Flow rate through different pipe sizes.

Pipe size	Flow rate (m ³ /s)					Average
	6 buckets	8 buckets	12 buckets	18 buckets	24 buckets	
15 mm	0.000767	0.000758	0.000758	0.00076	0.000753	0.000759
20 mm	0.000697	0.000705	0.0007	0.000698	0.00070	0.00070
25 mm	0.000632	0.000632	0.00063	0.000627	0.000628	0.00063
32 mm	0.000503	0.000497	0.0005	0.000505	0.000505	0.000502

A tachometer is used to measure the turbine's speed, while a multimeter was used to measure the voltage and current generated by the generator, in order to calculate the power generated by the generator. Furthermore, flow Rate, speed, voltage, current, and actual power generated by the generator are obtained based on different Pelton bucket numbers and pipe sizes on a 1m water head. The turbine efficiency is then calculated based on the theoretical power of the turbine. The complete results are shown from **Tables 3-7**.

Table 3. Performance of 6 Pelton bucket on 1 m water head.

Pipe size	Data	Flow rate (m ³ /s)	Speed (r/min)	Voltage (V)	Current (A)	Pact (W)	Pth (W)	η_t (%)
15 mm		0.000767	66.6	3.9	0.534	2.0826	5.267	39.54
20 mm		0.000697	59.8	3.4	0.469	1.5946	4.786	33.32
25 mm		0.000632	55.5	2.9	0.403	1.1687	4.349	26.87
32 mm		0.000503	51.4	2.7	0.354	0.9558	3.454	27.67

Table 4. Performance of 8 Pelton bucket on 1 m water head.

Pipe size	Data	Flow rate (m ³ /s)	Speed (r/min)	Voltage (V)	Current (A)	Pact (W)	Pth (W)	η_t (%)
15 mm		0.000758	70.7	4.2	0.609	2.5578	5.205	49.14
20 mm		0.000705	62.4	3.6	0.554	1.9944	4.841	41.2
25 mm		0.000632	58.6	3.2	0.437	1.3984	4.349	32.15
32 mm		0.000497	54.5	2.9	0.399	1.1571	3.412	33.91

Table 5. Performance of 12 Pelton bucket on 1 m water head.

Pipe size \ Data	Flow rate (m ³ /s)	Speed (r/min)	Voltage (V)	Current (A)	Pact (W)	Pth (W)	η_t (%)
15 mm	0.000758	78.6	4.6	0.762	3.5052	5.205	67.34
20 mm	0.000700	70.3	4.1	0.574	2.3534	4.807	48.96
25 mm	0.000630	66.2	3.5	0.528	1.848	4.326	42.72
32 mm	0.000500	63.2	3.3	0.498	1.6434	3.434	47.86

Table 6. Performance of 18 Pelton bucket on 1 m water head.

Pipe size \ Data	Flow rate (m ³ /s)	Speed (r/min)	Voltage (V)	Current (A)	Pact (W)	Pth (W)	η_t (%)
15 mm	0.000760	82.2	5	0.811	4.055	5.219	77.7
20 mm	0.000698	75.3	4.3	0.637	2.7391	4.793	57.15
25 mm	0.000627	69.1	3.8	0.584	2.2192	4.306	51.54
32 mm	0.000505	65.3	3.5	0.535	1.8725	3.468	53.99

Table 7. Performance of 24 Pelton bucket on 1 m water head.

Pipe size \ Data	Flow rate (m ³ /s)	Speed (r/min)	Voltage (V)	Current (A)	Pact (W)	Pth (W)	η_t (%)
15 mm	0.000753	89.8	5.4	0.844	4.5576	5.171	88.14
20 mm	0.000700	79.1	4.6	0.659	3.0314	4.807	63.06
25 mm	0.000628	70.4	4.1	0.639	2.6199	4.312	60.76
32 mm	0.000505	68.8	3.7	0.579	2.1423	3.468	61.77

3.2. Performance Analysis and Discussion

3.2.1. Turbine Speed

Turbine speed performance was evaluated at a constant 1 m head across various pipe sizes and bucket numbers (See **Table 8** and **Figure 7**). Results demonstrate that rotational speed (RPM) is significantly influenced by both parameters. Smaller pipe diameters yielded higher RPM, with the 15 mm pipe achieving the maximum speed of 89.8 RPM (24 buckets). Conversely, the 32 mm pipe produced the lowest speeds, ranging from 51.4 RPM (6 buckets) to 68.8 RPM (24 buckets). This trend is attributed to the higher jet velocity generated by smaller pipes under low-head conditions, which increases the impulse force on the turbine buckets. Increasing the bucket count from 6 to 24 also enhanced turbine speed across all pipe sizes, with the most substantial gains occurring between 6 and 12 buckets. Performance improvements diminished beyond 18 buckets, likely due to increased flow interference and frictional losses. The 15 mm pipe showed the highest relative gain (34.8%), though all sizes exhibited significant improvements (20% - 35%).

The optimal configuration for maximizing RPM under low-head conditions was the 15 mm pipe with 18 - 24 buckets. Larger pipes underperformed due to

reduced jet velocity and potential spreading losses, highlighting the critical role of nozzle optimization in pico-hydro Pelton turbine design.

Table 8. Data table for turbine speed analysis for different pipe sizes and bucket count.

Pipe size	Turbine speed (RPM)				
	6 buckets	8 buckets	12 buckets	18 buckets	24 buckets
15 mm	66.6	70.7	78.6	82.2	89.8
20 mm	59.8	62.4	70.3	75.3	79.1
25 mm	55.5	58.6	66.2	69.1	70.4
32 mm	51.4	54.5	63.2	65.3	68.8

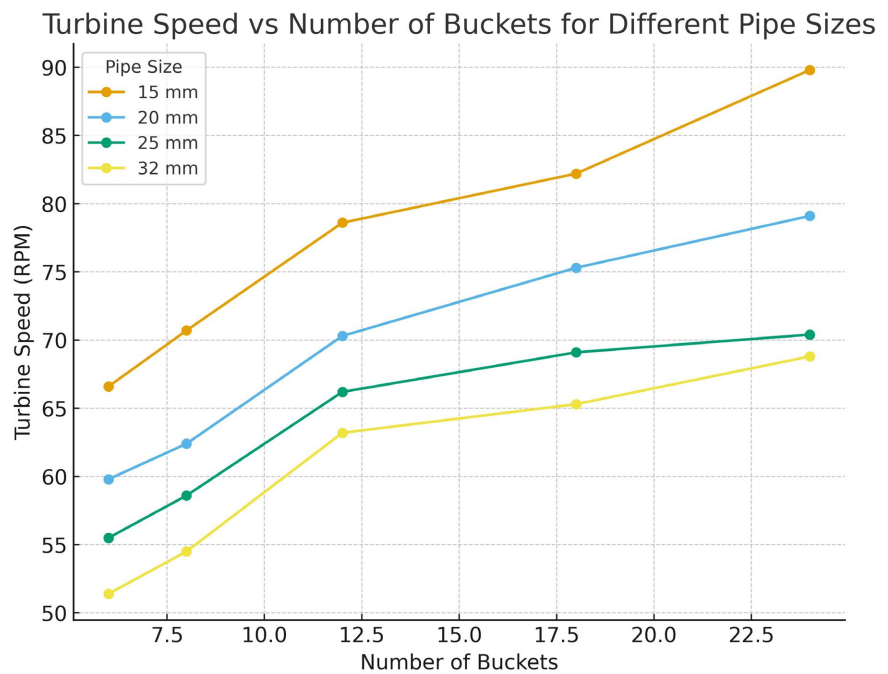


Figure 7. Pelton turbine speed vs bucket count at 1 m head for different pipe size.

3.2.2. Turbine Power Output and Efficiency

The power output of a Pelton turbine-driven generator was measured across a range of pipe diameters and bucket numbers (See **Table 9** and **Figure 8**). Results indicate that power output is highly sensitive to pipe size, with smaller diameters (e.g., 15 mm) yielding significantly higher output compared to larger diameters (e.g., 32 mm), across all bucket configurations. For instance, with 24 buckets, the 15 mm pipe produced 4.56 W, while the 32 mm pipe produced only 2.14 W—a reduction of over 53%. Additionally, increasing the number of buckets consistently improved performance, with the most substantial gains observed in smaller pipes. The 15 mm pipe exhibited a power increase of 2.48 W when moving from 6 to 24 buckets, compared to a gain of only 1.19 W for the 32 mm pipe. These findings underscore the importance of optimizing both hydraulic design (pipe diameter) and mechanical design (bucket count) to maximize energy extraction in

micro-hydro systems.

Table 9. Data table for output power.

Pipe size	Power (W)				
	6 buckets	8 buckets	12 buckets	18 buckets	24 buckets
15 mm	2.0826	2.5578	3.5052	4.055	4.5576
20 mm	1.5946	1.9944	2.3534	2.7391	3.0314
25 mm	1.1687	1.3984	1.848	2.2192	2.6199
32 mm	0.9558	1.1571	1.6434	1.8725	2.1423

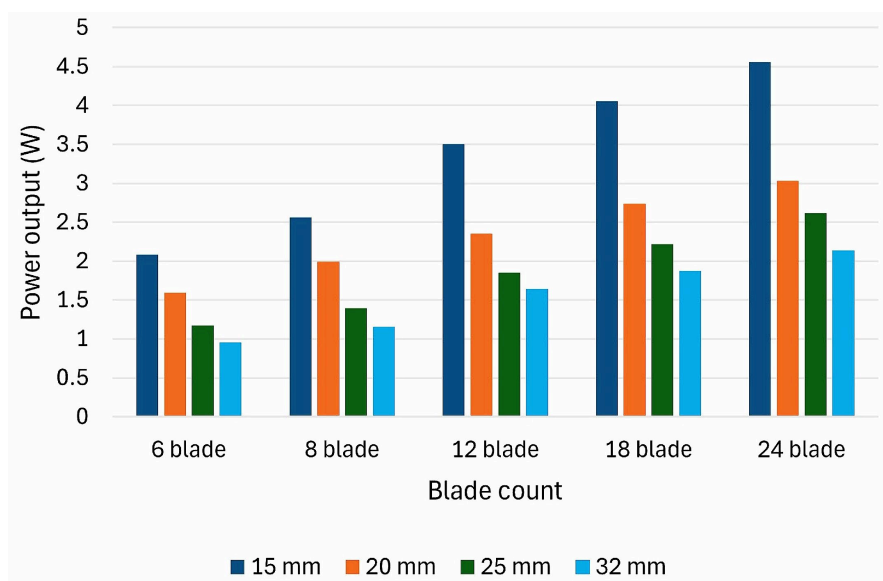


Figure 8. Power output vs different pipe size and bucket count.

The analysis for turbine efficiency is shown in **Table 10** and **Figure 9**. For a smaller pipe diameter, the 6-bucket impeller achieved a peak efficiency of 78%, outperforming the 24-bucket design, which registered only 62%, a 16% reduction attributed to excessive frictional losses and flow restriction in a constrained environment. Conversely, for the largest pipe diameter, this relationship inverted dramatically; the 24-bucket turbine achieved a maximum efficiency of 92%, substantially outperforming the 6-bucket variant's efficiency of 75%, a 17% difference resulting from insufficient fluid guidance and energy capture in an unconstrained flow. The 12-bucket impeller frequently emerged as a robust compromise, maintaining efficiencies above 80% across most pipe sizes, yet the data conclusively shows that no single bucket count is universally optimal. This non-linear response surface underscores the necessity of a system-level design approach, where a 20% increase in efficiency is attainable solely by optimizing the bucket-to-conduit ratio, a finding with profound implications for the customization and energy output of micro-hydro and fluidic systems. With an efficiency of 88.14% under a 1 m head, this turbine's performance is favorable compared to the typical range for pi-

co-hydro installations [17]. It also suggests potential for efficiency gains in the ultra-low head category, building on the groundwork established by earlier specialized turbines, such as the Z-Blade design presented in reference [11].

Table 10. Data table for turbine efficiency.

Pipe size	Turbine efficiency (%)				
	6 buckets	8 buckets	12 buckets	18 buckets	24 buckets
15 mm	39.54	49.14	67.34	77.7	88.14
20 mm	33.32	41.2	48.96	57.15	63.06
25 mm	26.87	32.15	42.72	51.54	60.76
32 mm	27.67	33.91	47.86	53.99	61.77

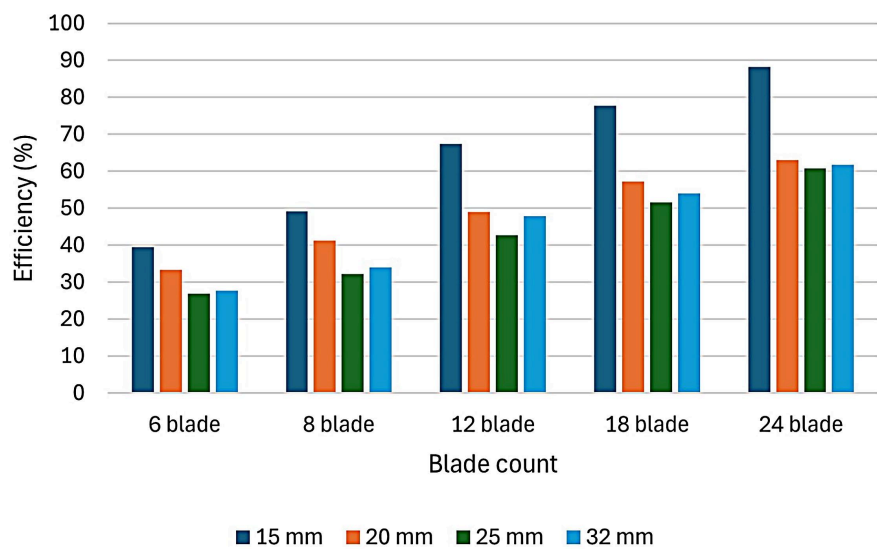


Figure 9. Turbine efficiency vs different pipe size and bucket count.

4. Conclusions

This study evaluated a Pelton turbine at a 1 m head, finding that both a smaller pipe diameter and a higher bucket count significantly enhance performance. The 15 mm pipe with 24 buckets achieved the maximum rotational speed (89.8 RPM) and power output (4.56 W), attributed to higher jet velocity providing greater impulse force. In contrast, the 32 mm pipe performed poorly (e.g., 2.14 W at 24 buckets), suffering from reduced jet velocity. While increasing buckets from 6 to 24 improved output across all configurations, gains diminished beyond 18 buckets due to flow interference. The results conclusively demonstrate that optimizing both the nozzle (pipe) size and bucket count is critical for maximizing energy extraction in low-head pico-hydro systems. For future work, several recommendations are proposed:

- Increased Water Head: Testing under higher heads (e.g., 4 - 5 m) is essential to significantly improve pressure and power output.

- **Design Optimization:** The turbine casing and structural framework should be redesigned for compactness and reduced weight to enhance portability.
- **Advanced Modeling:** Employing Computational Fluid Dynamics (CFD) software would provide deeper insights into fluid-structure interactions, optimize bucket geometry, and reduce reliance on physical prototyping.
- **Structural Integrity:** Future designs must prioritize robust sealing and assembly to prevent water leakage and minimize vibrations, especially when operating at higher pressures.

In summary, this project provides a validated foundation for the development of small-scale, low-head pico-hydro systems. Addressing the identified limitations through the proposed future work will be crucial for enhancing the efficiency, durability, and practical viability of such systems for decentralized renewable energy generation.

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Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

References

- [1] United Nations (UN) (2023) The Sustainable Development Goals Report 2023.
- [2] Su, H., Nilghaz, A., Liu, D., Dai, L., Tian, J., Razal, J.M., *et al.* (2023) Harnessing the Power of Water: A Review of Hydroelectric Nanogenerators. *Nano Energy*, **116**, Article ID: 108819. <https://doi.org/10.1016/j.nanoen.2023.108819>
- [3] Tang, K.H.D. (2020) Hydroelectric Dams and Power Demand in Malaysia: A Planning Perspective. *Journal of Cleaner Production*, **252**, Article ID: 119795. <https://doi.org/10.1016/j.jclepro.2019.119795>
- [4] Zhou, D. and Deng, Z. (2017) Ultra-Low-Head Hydroelectric Technology: A Review. *Renewable and Sustainable Energy Reviews*, **78**, 23-30. <https://doi.org/10.1016/j.rser.2017.04.086>
- [5] United Nations SDG Committee (2017) Resolution adopted by the United Nations General Assembly on 6 July 2017.
- [6] Lahimer, A.A., Alghoul, M.A., Sopian, K., Amin, N., Asim, N. and Fadhel, M.I. (2012) Research and Development Aspects of Pico-Hydro Power. *Renewable and Sustainable Energy Reviews*, **16**, 5861-5878. <https://doi.org/10.1016/j.rser.2012.05.001>
- [7] Klein, S.J.W. and Fox, E.L.B. (2022) A Review of Small Hydropower Performance and

- Cost. *Renewable and Sustainable Energy Reviews*, **169**, Article ID: 112898.
<https://doi.org/10.1016/j.rser.2022.112898>
- [8] Zainuddin, H., Yahaya, M.S., Lazi, J.M., Basar, M.F.M. and Ibrahim, Z. (2009) Design and Development of Pico-Hydro Generation System for Energy Storage Using Consuming Water Distributed to Houses. *World Academy of Science, Engineering and Technology, International Journal of Electrical, Computer, Energetic, Electronic and Communication Engineering*, **3**, 1922-1927.
- [9] Edenhofer, O., Pichs-Madruga, R., Sokona, Y., *et al.* (2011) IPCC Special Report on Renewable Energy Sources and Climate Change Mitigation. *Cambridge University Press*, Cambridge.
https://rael.berkeley.edu/old_drupal/sites/default/files/IPCC%202011-%20Special%20Report%20on%20Renewable%20Energy%20Sources%20and%20Climate%20Change%20Mitigation.pdf
- [10] Kadier, A., Kalil, M.S., Pudukudy, M., Hasan, H.A., Mohamed, A. and Hamid, A.A. (2018) Pico Hydropower (PHP) Development in Malaysia: Potential, Present Status, Barriers and Future Perspectives. *Renewable and Sustainable Energy Reviews*, **81**, 2796-2805. <https://doi.org/10.1016/j.rser.2017.06.084>
- [11] Ashikin, N., Rais, M., Farriz Basar, M., Ikram, M. and Rizan, M.N. (2025) An Innovative Water Reaction Turbine of the Ultra Z-Blade Designed for Water Conditions of Low-Head and Ultra-Low Flow. *International Journal of Integrated Engineering*, **17**, 367-380.
- [12] Jawahar, C.P. and Michael, P.A. (2017) A Review on Turbines for Micro Hydro Power Plant. *Renewable and Sustainable Energy Reviews*, **72**, 882-887.
<https://doi.org/10.1016/j.rser.2017.01.133>
- [13] Dey, A. and Yodo, N. (2019) A Systematic Survey of FDM Process Parameter Optimization and Their Influence on Part Characteristics. *Journal of Manufacturing and Materials Processing*, **3**, Article 64. <https://doi.org/10.3390/jmmp3030064>
- [14] Karimi, M. (2023) Review of Steel Material Engineering and Its Application in Industry. *Journal of Engineering in Industrial Research*, **4**, 61-67.
- [15] van Dijk, M., Loots, I., Van Vuuren, S.J., Barta, B. and Bonthuys, G.J. (2016) Energy Generation Using Low Head Hydro-Power Technologies.
- [16] Kamran, M. (2021) Hydro Energy. In: Kamran, M. and Fazal, M.R., Eds., *Renewable Energy Conversion Systems*, Elsevier, 193-219.
<https://doi.org/10.1016/b978-0-12-823538-6.00007-5>
- [17] Klein, S.J.W. and Fox, E.L.B. (2022) A Review of Small Hydropower Performance and Cost. *Renewable and Sustainable Energy Reviews*, **169**, Article ID: 112898.
<https://doi.org/10.1016/j.rser.2022.112898>