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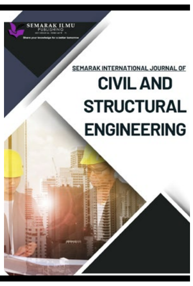

Exploratory Results of Building-Integrated Small Hydro Pumped Storage (SHPS) Systems

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ABSTRACT

Waterpower, a form of renewable energy, has been used for irrigation since a thousand years ago with the construction of water turbines or mills. This project addresses energy management challenges in urban buildings by creating a small-scale hydro-pumped storage system using Pelton turbines. It consists of two phases: the initial conceptual stage and the subsequent implementation and analysis stage. In the first phase, thorough research defines the problem and gathers relevant data. Solidworks software is used to meticulously design system components, considering factors like water flow rates and head height. The second phase involves the preliminary result of the system and rigorous on-site testing to measure Pelton turbine performance metrics, including power output, torque, and water flow velocity. A comprehensive feasibility study evaluates the system's impact within a building context. Expected outcomes include a holistic system design, turbine selection, and seamless integration within the building infrastructure.

1. Introduction

Renewable energy derives from natural processes with consistent energy flows in the local environment. It persists even after harnessing through specialized equipment, like solar panels (sunlight), rain, tides, geothermal heat, and wind [1]. Various bodies of water offer energy sources, from vast oceans to rivers and tiny streams. Recent advances have enabled harnessing multiple types of waterpower, including hydroelectric energy, dam-less hydro systems [2], ocean energy [3], tidal power, wave power, and deep lake water conditioning [1,4-7]. One method of harnessing water energy involves directing a moving stream onto the blades or vanes of a horizontally oriented water wheel [1]. Integrating a generator into the system converts mechanical energy, primarily rotational, into electrical energy.

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In contrast, small-scale hydroelectric projects, often with low dams and limited reservoirs, are near small waterways. These facilities face challenges due to seasonal variations in water flow affecting electricity production. They are often impractical in such settings due to space constraints and infrastructural limitations. Thus, SHPS presents a compelling solution by offering a scalable and adaptable energy storage method suitable for urban environments.

SHPS systems operate on the same basic principles as conventional pumped storage hydroelectric systems but are tailored to the scale and needs of urban buildings. During peak demand, the stored water is released back to the lower reservoir, passing through turbines to generate electricity. This cyclical process effectively balances supply and demand, enhancing the stability and reliability of the urban grid [1,4,5].

Implementing SHPS in buildings involves several critical technical and logistical challenges that need to be addressed to ensure viability and effectiveness:

i. Space Optimization: Urban environments often have limited available space. Innovative architectural solutions are required to integrate water reservoirs into building structures, such as utilizing rooftops, basements, or other unused spaces without compromising the building’s functionality or aesthetics.
ii. Water Management: Effective water management is crucial for SHPS systems. Strategies must be developed to minimize water loss through evaporation or leakage and ensure the availability of a reliable water source. The system's design must also consider the water quality and potential treatment needs.
iii. Structural Integrity: Buildings must be structurally capable of supporting the additional weight of water reservoirs and associated infrastructure. This necessitates thorough engineering assessments and potential reinforcements to ensure safety and durability.
iv. Economic Feasibility: The economic viability of SHPS systems is a critical factor. While the initial investment may be significant, long-term benefits such as energy savings, reduced reliance on external power sources, and potential revenue from energy sales can justify the costs. Comprehensive cost-benefit analyses are essential to demonstrate the financial attractiveness of SHPS projects.

1.1 Case Studies and Real-World Applications

Several projects and case studies have demonstrated the practical application of SHPS in buildings. Examples from densely populated cities such as Japan [8], United States [9], and Pacific Rim Economics Countries [10] highlight how innovative engineering solutions can overcome spatial constraints and integrate SHPS systems into urban architecture. These projects provide valuable insights and lessons for future implementations, showcasing the potential for SHPS to become a mainstream solution in urban energy management.

SHPS enables energy storage from intermittent renewable sources and excess electricity from continuous base-load sources, thereby contributing to grid stability and the incorporation of renewables. The round-trip energy efficiency of PSH ranges from 70% to 80% [10], with some sources claiming an efficiency of up to 87% [1]. SHPS has benefits such as energy storage, enhancement of grid stability, support for renewable energy penetration, and reduction of greenhouse gas emissions.

SHPS in buildings represents a groundbreaking approach to urban energy management. By adapting the principles of traditional hydroelectric power to the unique challenges and opportunities of urban environments, SHPS can play a vital role in the transition to sustainable cities. This paper delves into the technical aspects, design challenges, and potential impacts of SHPS, offering a comprehensive understanding of its role in the future of urban energy systems.

In the context of growing energy demands and environmental concerns, SHPS offers a promising pathway toward more resilient, sustainable, and efficient urban energy landscapes. This innovative approach not only supports the goals of renewable energy integration but also enhances the overall sustainability and livability of urban areas.

1.2 Design of Pelton Turbine

In a hydroelectric power facility, the turbine is one of the system's primary components, converting rotational or mechanical energy into electricity via the generator. Generally, the classification of water turbines is based on flow direction, water pressure, and the geometry or orientation of the turbine [11]. Specifically, hydraulic turbines can be categorized based on the pressure change that occurs within the rotor [12]. This classification includes impulse turbines, such as the Pelton turbine.

A Pelton turbine may have one or more nozzles that direct water jets at the buckets on the turbine runner. This type of turbine is commonly used in locations with medium to high heads. For micro-hydro systems with lower heads, Pelton turbines have smaller runner diameters and need to spin quickly [13]. In this case, the velocity of the water jet striking the buckets will be estimated for system design shown in Eq. (1) – Eq. (3) [13,14].

$$V_{jet} = C_v \times \sqrt{2gH_n} \tag{1}$$

$$A_{jet} = \frac{\pi d_{jet^2}}{4} \tag{2}$$

$$Q = A_{jet} V_{jet} \tag{3}$$

where V_{jet} is the jet velocity, C_v is the coefficient of velocity for the nozzle, $g = 9.81 \text{ m/s}^2$, A_{jet} is the cross-sectional area of each jet (m^3), d_{jet} is the diameter of jets (m), and Q is the volume flow rate. Another important parameter is the turbine speed. Eq. (4) and Eq. (5) illustrate the relationships necessary for designing the turbine.

$$N_s = 85.49 \times \frac{\sqrt{n_j}}{H_{n^{0.243}}} \tag{4}$$

$$N = N_s \times \frac{H_{n^{\frac{5}{4}}}}{\sqrt{P_{ti}}} \tag{5}$$

where N_s is the specific speed, n_j is the number of turbine nozzles (jets), N is the turbine speed, and P_{ti} is the power turbine input (W).

An essential part of the turbine design is the nozzle. Eq. (6) – Eq. (10) detail critical aspects of nozzle design, where n_b represents the number of buckets on the runner, L_{ab} is the length of the bucket's moment arm, and R_{br} is the radius from the bucket center to the center of the runner.

$$D_r = 38.6 \times \frac{\sqrt{H_n}}{N} \tag{6}$$

$$X_{nb} = 0.625 \times D_r \tag{7}$$

$$n_b = 15 + \frac{D_r}{\left(2 \times d_{jet}\right)} \tag{8}$$

$$L_{ab} = 0.195 \times D_r \tag{9}$$

$$R_{br} = 0.47 \times D_r \tag{10}$$

1.3 Power of the Turbine

Within the African area, several countries, such as Zimbabwe and Zambia, have implemented the pico-hydro system specifically in rural sections of their respective countries [10]. This hydro system offers an alternative to the significant financial burden that the extension of the energy networks would cause. The pico-hydro system is utilized to supply power for the residential needs of the local community [6]. The power from the pico-hydro system can be expressed in Eq. (11) and Eq. (12) [10].

$$P_{ti} = \rho_{water} \times Q \times g \times h_{gross} \tag{11}$$

$$P_{to} = \rho_{water} \times Q \times g \times h_{gross} \times \eta_{total} \tag{12}$$

where, P_{ti} = 214.295 W, ρ_{water} is the density of water (1000 kg/m3), Q is the flow rate in penstock pipe (m3/s), h_{gross} is the total vertical drop from intake to turbine (m), P_{to} = 192.866 W, and η_{total} is the efficiency of all components of the system. The main components of the pico-hydro system generally consist of the following [4]:

i. Intake water diversion (forebay tank) - includes diversion gate valve and settling basin.
ii. Penstock - water conveyance that channels the water from the forebay tank to the powerhouse designed based on the pressure exerted by the water.
iii. Hydro turbines - based on impulse or reaction principles were utilized according to the power output expected.
iv. Generator - common types used include synchronous or induction.

The continuity equation is examined in the context of hydroturbine systems, highlighting its application in design and optimization. It also provides a foundation for understanding the subject, informing the design and implementation of a small-scale hydro-pumped storage system to enhance sustainable energy solutions and off-grid electrification.

2. Methodology

In this research, the initial phase involves the computation of turbine dimensions, penstock specifications, and the theoretical output energy of the generator. Subsequently, a thorough analysis will be conducted, comparing the theoretical data with real-scenario results. The ensuing discussion will delve into the disparities between the calculated and observed values, providing valuable insights into the performance and efficiency of the system. Figure 1 outlines the research framework, highlighting that the theoretical study is conducted initially, followed by real-time experimental work. Figure 1 illustrates the comprehensive research methodology of the project, commencing with a theoretical analysis prior to proceeding with real-time experiments. The feasibility study evaluates system performance through data obtained from both theoretical models and experimental results.

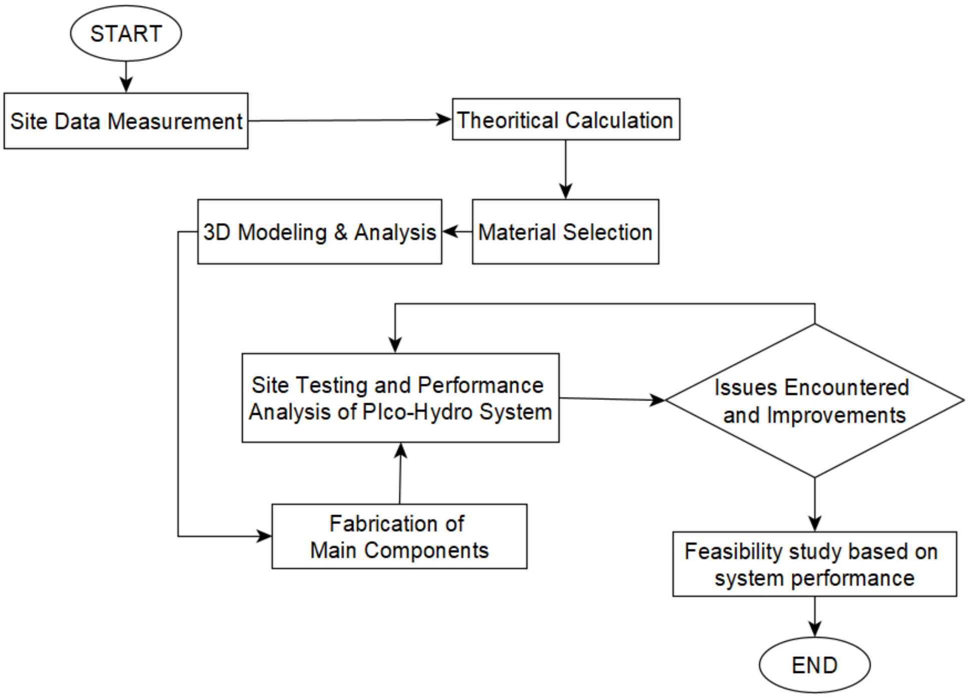

Fig. 1. Flow of the study

The round water tank depicted in Figure 2 is utilized for water storage. Water from outside the building is pumped into this tank, which has a capacity of 500 gallons, before being distributed to houses or small areas. This tank plays a critical role in the turbine system.

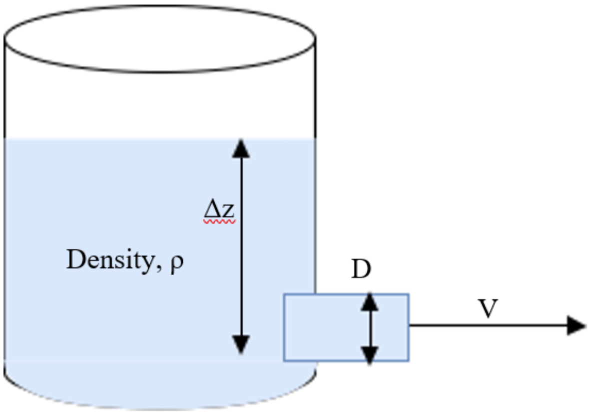

Fig. 2. Round-type water tank 500 gallons with dimensions: 1727mm (L) x 1727mm (W) x 1321mm (H)

The parameter constants mentioned in Table 1 are crucial for the tank's flow dynamics and effective water dispensing. Theoretical calculations for a Pelton turbine are integral to optimizing its performance. The parameter constant in Table 1 is used for Eq. (1) – Eq. (3) for the design process providing key parameters essential for assessing the turbine's efficiency and effectiveness. The element of jet velocity, the cross-sectional area of the jet along with its diameter can determine the flow rate of the water. The jet velocity and volume flow rate are tabulated in Table 2.

Table 1
Parameter Constant

Height of nozzle, *Hn*	1.321 m
Fluid density, r	1000 kg/l
Diameter of the jet, D	0.0762 m
Coefficient of velocity, Cv	0.98

Table 2
Jet velocity and volume flow rate

Velocity of jet, V_{jet}	The nozzle area, A_{jet}	Volume Flowrate, Q
$5.09\ m/s$	$4.56 \times 10^{-3} m^2$	$0.02322\ m^3 s^{-1}$

The velocity of the jet is a critical parameter in fluid dynamics as it directly influences the flow rate, which is the amount of fluid passing through a given area per unit of time. Table 3 shows the value of turbine speed. The specific speed, denoted as N_s, is a fundamental parameter in fluid dynamics and turbomachinery design, and in this context, it's calculated to be 85.49 rpm. Meanwhile, the actual turbine speed, denoted as *N*, is measured at 184.675 rpm.

Table 3
Turbine speed

Specific speed, N_s	Turbine speed, N
85.49 rpm	184.675 rpm

The specific speed is an essential factor for characterizing the performance of a turbine, providing insights into its design and efficiency. The fact that the specific speed is significantly lower than the actual operating speed (Ns < N) suggests that the turbine is designed for a relatively low-speed application. Table 4 provides the values used for the nozzle and bucket dimensions.

Table 4
Nozzle and bucket dimension

Runner circle diameter, D_r	$0.209\ m$
Distance between nozzle and bucket, X_{nb}	0.131 m
Number of buckets on the runner, n_b	$15.01 \approx 15$
Length of moment arm of bucket, L_{ab}	$0.041\ m$
Radius of bucket center to center of runner, R_{br}	$0.098\ m$

The initial design of the turbine in Fig. 3 incorporates 15 buckets positioned around the periphery of the disc. This disc has an overall diameter of 0.209 m, equivalent to 20.9 cm. These 15 buckets are strategically placed with a moment arm, or the distance from the center of the disc to the point where the buckets are attached, measuring 4 cm. Additionally, the radius of each bucket, indicating the distance from the disc's center to the bucket's outer edge, is approximately 9.8 cm.

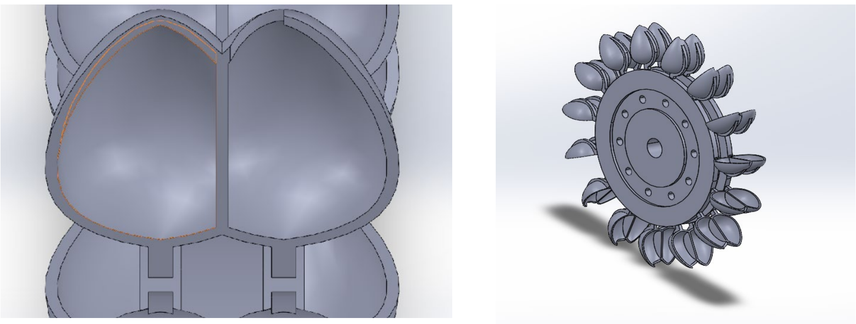

Fig. 3. 3D design Pelton turbine

2.1 Actual Design

The proposed system's layout is illustrated in Figure 4. As indicated in the design, the penstock of the pico-hydro system originates from the point of water intake and extends to the turbine. The SHPS is designed to provide a dual function by offering a water outlet from the turbine. The water emanating from this outlet is used for turbine rotation and can be repurposed for various domestic activities.

Fig. 4. Penstock actual design

The area of the water jet in Design 2 is 12.759 cm^2 (see Figure 5). In this design is closed on one side to ensure that the turbine moves in one direction.

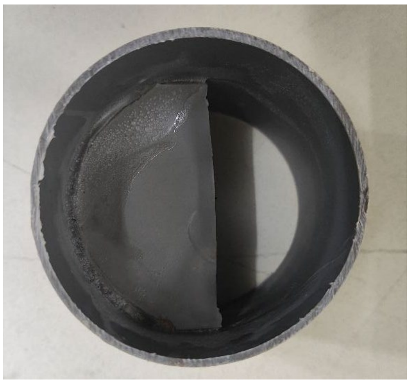

Fig. 5. Water jet actual design

In SHPS, a 12V motor is affixed to a T-pipe configuration (see Figure 6). As water flows into the T-pipe's edge, it propels the turbine inside, converting the water's kinetic energy into electrical power.

The redirected water then exits through the downward pipe, ensuring a continuous and efficient energy generation process. This simple and effective mechanism harnesses the water's force within the existing infrastructure, making SHPS a practical solution for utilizing the building's water flow to generate electricity.

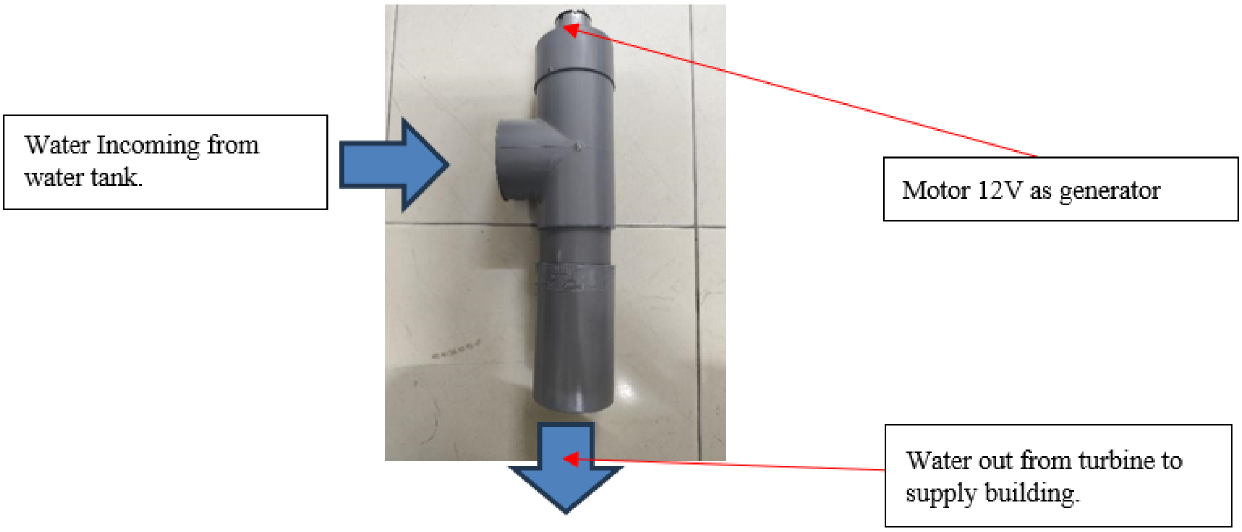

Fig. 6. The flow power generates

3. Results

In this actual design, a 12V motor is affixed to a T-pipe configuration. As water flows into the T-pipe's edge, it propels the turbine inside, converting the water's kinetic energy into electrical power. The redirected water then exits through the downward pipe, ensuring a continuous and efficient energy generation process. This simple and effective mechanism harnesses the water's force within the existing infrastructure, making Actual Design a practical solution for utilizing the building's water flow to generate electricity.

3.1 Theoretical Experiment

The percentage of water use in Madison, USA [14], provides valuable insights into consumption patterns (see Figure 7). By extrapolating this percentage, it can serve as an illustrative example of hourly water consumption at home. This data aids in understanding and managing water usage, fostering sustainability efforts for responsible resource utilization.

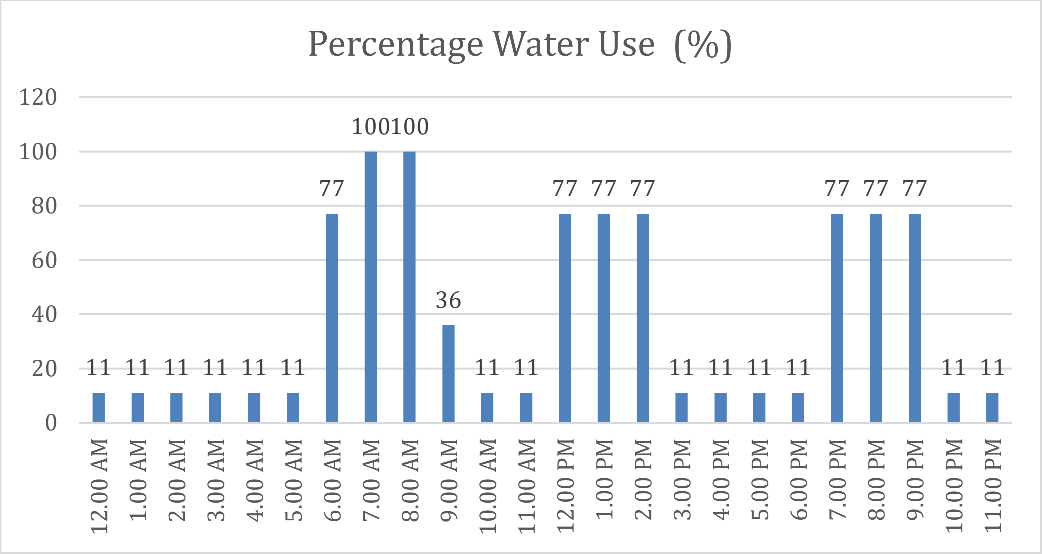

Fig. 7. The percentage of use data is obtained through estimates of consumption

3.1.1 Open circuit test

Theoretical open circuit tests were conducted to determine the relationship between the turbine speed and the open circuit voltage generated. These tests involved operating the turbine without any electrical load while varying the rotational speed. The results will be presented as a graph showing the open circuit voltage as a function of turbine speed. Theoretical predictions are calculated using Microsoft Excel. Figure 8 and 9 shows the flow rate water, and power in and power out, respectively.

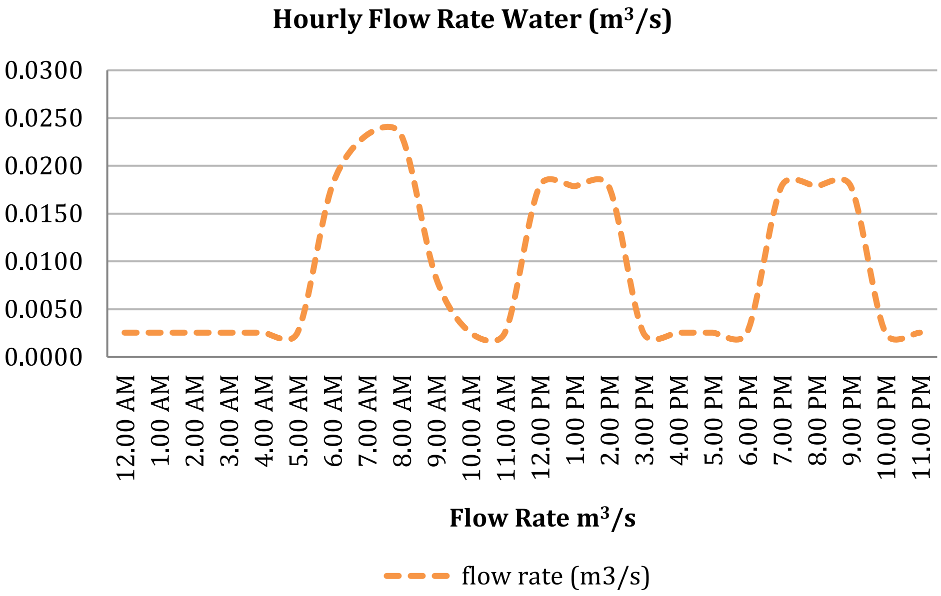

Fig. 8. Flow rate water

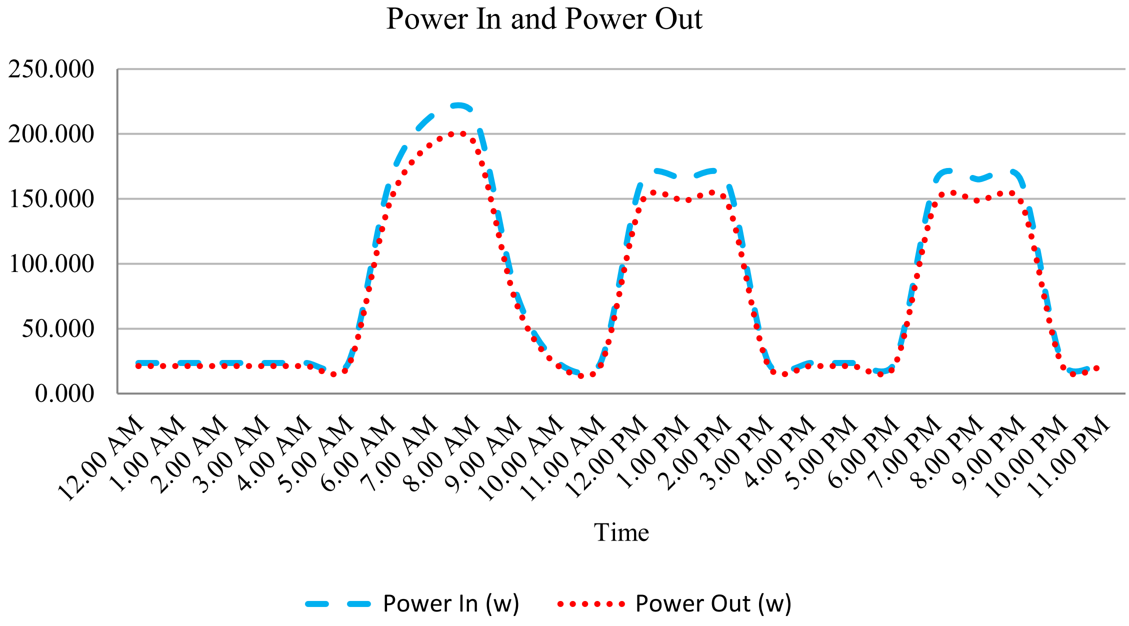

Fig. 9. Power in and power out

During the morning, starting at 6 am, there is a noticeable increase in both power output and water flow rate. This can be attributed to the fact that people typically wake up from sleep during this time and begin using water for various purposes. The peak power output of 192.866 W occurs at 12 pm, likely due to the highest water consumption happening around that time. Conversely, the lowest power output is observed from 12 am to 5 am, which coincides with a period of lower water usage, estimated to be around 11% of the peak water consumption [14]

3.1.2 The maximum power delivered test

This comprehensive test systematically records the speed, energy input, and energy output for various water flow rates. By meticulously analyzing these parameters, researchers gain crucial insights into the efficiency and performance of Pico-hydro systems, informing advancements in sustainable energy generation and utilization. Table 5 shows the Bucket dimension.

Table 5
Bucket dimension

Flow Rate (m3/s)	Speed (rpm)	Power In (w)	Power Out (w)
0.002554	9.4039	23.5725	21.2153
0.008358	30.7764	77.1464	69.4318
0.017877	65.8273	165.0076	148.5068
0.023217	85.4900	214.2956	192.8660

From Figure 10, it is assessed that the flow rate of water into turbine is directly proportional to the power output of the turbine. With increment in the flow rate, the power into the turbine also increases.

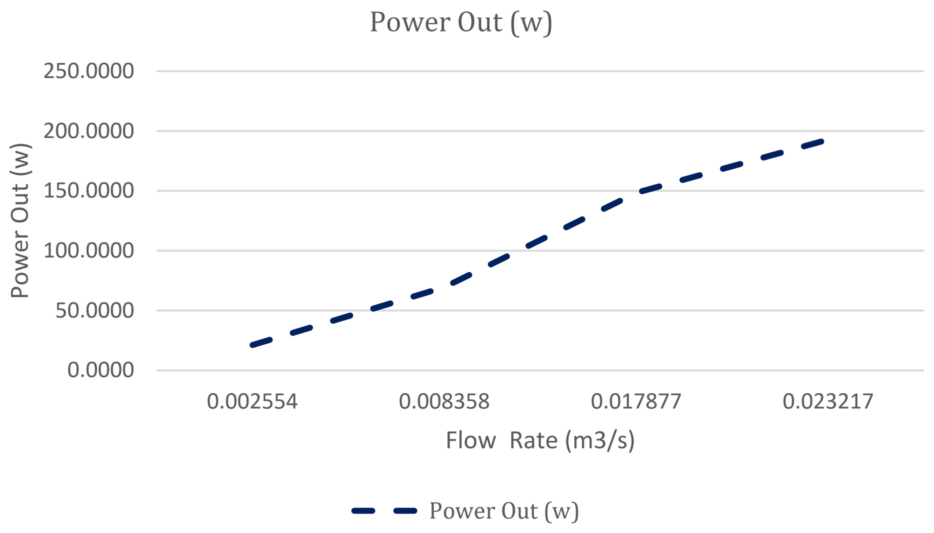

Fig. 10. Power Out

3.2 Actual Experiment

Before the test can be done. The water flow rate needs to be measured. The water flow rate is measured using a bucket with a capacity of 5 gallons equal to 18.927 liters. Equations below are entered into the table to be calculated. The variable in this experiment is the opening rate of the water tap based on the theoretical percentage of water consumption. Table 6 shows the Flow rate tap water

flow rate (l/m)=(Bucket capacity (l))/(Full water time (m)) (13)

Table 6
Flow rate tap water

Pipe Open	Bucket Capacity (l)	Time to full (m)	Flow Rate (l/m)
11%	18.927	1.35	14.020
36%	18.927	1.22	15.514
77%	18.927	1.14	16.603
100%	18.927	1.06	17.856

3.2.1 Open circuit test

The test at Pauh Putra College involved the use of a multimeter to measure both voltage and current. This essential procedure aids in assessing electrical components' behavior under no-load conditions, providing valuable insights into their characteristics. The multimeter serves as a versatile tool for accurate measurements, ensuring precise evaluations of electrical parameters during the test. Figure 11 and Figure 12 shows the flow rate water and power out, respectively.

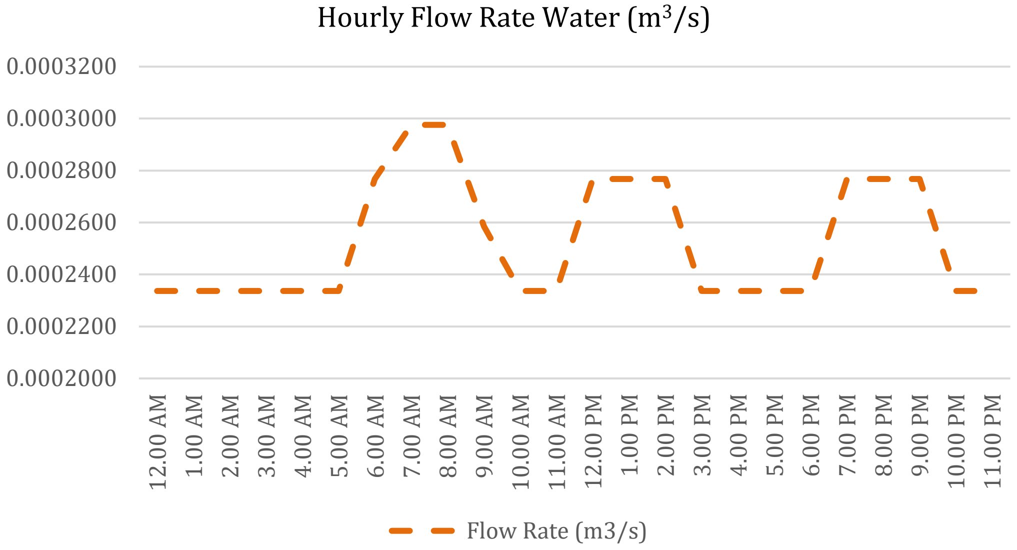

Fig. 11. Flow rate water

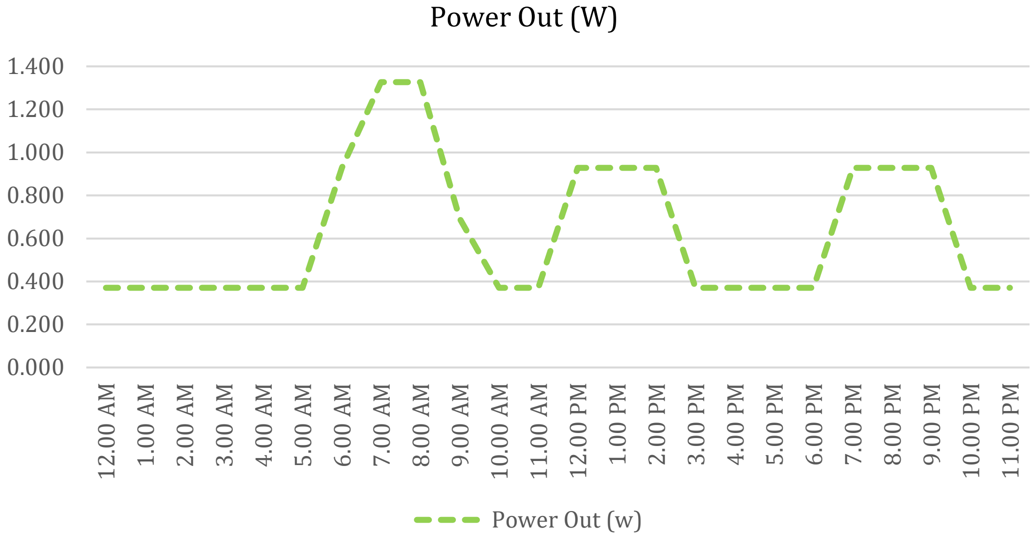

Fig. 12. Power out

The observed power output in the practical test is notably diminished, primarily attributed to the diminutive size of the turbine and the low energy consumption of the generator, as depicted in Figure 13. The discrepancy is evident when comparing the actual maximum power release of 1.327 watts to the theoretical potential of 192.8660 watts. This stark contrast underscores the practical limitations of the system, emphasizing the need for enhancements in turbine size and generator efficiency to optimize power generation. Achieving a closer alignment between theoretical and actual power output is crucial for enhancing the overall efficacy of the pico hydro system.

3.2.2 The maximum power delivered test

Table 7 shows the data from actual maximum power delivered

Table 7
Data from actual maximum power delivered

Flow Rate (l/m)	Flow Rate (m^3/s)	Speed (rpm)	Voltage (V)	Current (A)	Power In (W)	Power Out (W)
14.0201	0.0002337	272.8	1.95	0.19	0.4117	0.3705
15.5140	0.0002586	501.4	2.89	0.24	0.7707	0.6936
16.6027	0.0002767	1426.7	3.57	0.26	1.0313	0.9282
17.8558	0.0002976	1608.5	4.02	0.33	1.4740	1.3266

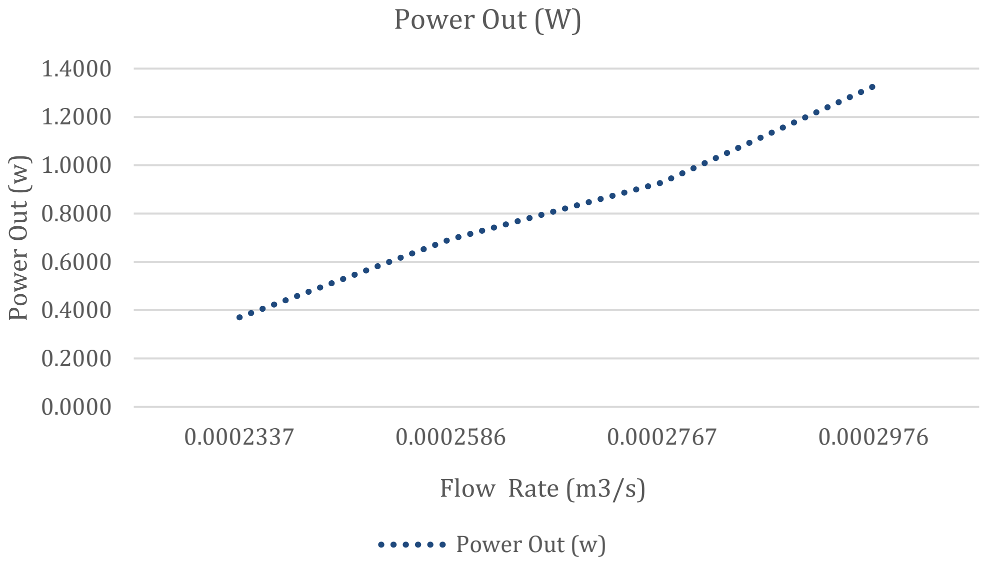

Fig. 13. Relationship between water flow rate into the turbine and power output

From Figure 13, it's observed that, while the actual final value is relatively low compared to the theoretical, there's a clear proportional relationship between water flow rate into the turbine and power output. As the flow rate increases, the power supplied to the turbine rises accordingly. Despite the final value disparity, this correlation underscores the significance of optimizing water flow rates for enhanced Pico-hydro turbine performance. This finding guides further research and practical applications, aiming to maximize power generation efficiency in Pico-hydro systems.

4. Conclusions

The successful development of a small-scale hydro-pumped storage system within a building utilizing an Impulse turbine has yielded valuable insights through calculations, theoretical analyses, and open circuit tests. These findings provide a comprehensive understanding of the system's performance and feasibility. Examination of the turbine dimensions demonstrated the effective design of the Impulse turbine for the given head and flow rate, including parameters like nozzle diameter and bucket dimensions. Open circuit tests established a clear relationship between turbine speed and voltage generation, confirming the model's accuracy. Moreover, maximum power delivery tests offered insights into power output under various low rate, showcasing the system's potential for optimal performance. Overall, these results suggest that the small-scale hydro-pumped storage system employing a Impulse turbine has the potential to be an efficient and sustainable energy solution for buildings. This is especially true in areas with access to a suitable water source characterized by a favorable head and flow rate. The system's advantages include energy storage capabilities for harnessing excess energy during low-demand periods and electricity generation during peak-demand times.

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