Development of A Water-Recycling Pico Hydropower System

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Abstract

This paper presents a groundbreaking Pico water-recycling hydropower system designed to transform the kinetic energy of water into clean, affordable electricity. Unlike conventional hydropower systems, the innovative closed-loop design continuously recycles water, making it an ideal solution for areas with limited water resources while maintaining a minimal environmental impact. The system was designed and constructed to have 10 buckets, a net head of 2 m, and a flow rate of 0.0041 0.000124 m^3/s, and a return flow rate of 0.000124 m^3/s. The turbine achieves an impressive 80% efficiency, thereby generating 24 W of usable electrical output. The results demonstrate that this technology is technically viable, offering an alternative to diesel generators and solar panels in remote settings. The system's zero-emission production while conserving water through continuous recycling can provide a significant environmental benefit and can contribute to achieving multiple sustainable development goals simultaneously.

Keywords: *Pico hydropower, water recycling, Pelton turbine, off-grid energy, sustainable electrification, renewable energy, kinetic energy.*

1.0 Introduction

Hydroelectric power is a clean and renewable energy source that generates electricity by utilizing the kinetic energy of flowing water. Recognized as one of the most efficient and economical renewable energy options, it has been employed for hundreds of years to supply power to residential, commercial, and industrial sectors. Implementing standalone power generation systems that rely on renewable resources is a highly viable and essential approach to electricity production [1],[2]. Recent studies highlight their economic viability, with levelized costs of energy (LCOE) as low as $0.02–0.05/kWh for large-scale projects, outperforming solar and wind in baseload reliability [3]. Small-scale hydro turbines (<10 MW) are particularly cost-effective in rural areas, with payback periods of 5–8 years [4]. The technological advancements in materials and modular designs make hydroelectric power highly efficient, 75–90% conversion rate, reduced installation costs by 30%, and low maintenance costs.

Pico hydro is a type of hydro turbine with a maximum electrical output of five kilowatts (5kW). Hydro power systems of this size benefit from different design, planning, and installation approaches that are simpler and more cost-effective than those used in larger hydro power systems. Recent innovations in pico-hydro technology have made it a feasible power source even in some of the world's poorest and most remote areas. Developments such as modular turbine designs (e.g., inexpensive 3D-printed parts) and smart microgrid integration now allow deployment in ultra-low-head streams (< 3 meters), cutting installation costs by up to 40% (Oluwajuwon et al., 2024; Energy for Sustainable Development). Foundational research by [5] and [2] confirmed the technical and economic viability of small-scale hydro systems, while more recent studies by [6] have focused on the development aspects of pico-hydro power. The use of water-recycling components has been extensively studied by [7] and [8], who showed significant improvements in system efficiency and water conservation. Optimization of turbine design for pico-hydro applications has been a key research area, with notable contributions from [9], [10], and [11], who compared the performance of Pelton, Turgo, and cross-flow turbines under different flow conditions. Materials research by [12] has advanced corrosion-resistant components for water-recycling systems. Case studies in Nepal [13] and Nigeria [14] provided valuable data on system performance, complemented by economic analyses from [15] and [16]. As [17] explores hybrid renewable system integration by demonstrating improved reliability, [18] reviews energy system models and spatial explicit modeling tools for hybrid renewable energy systems in rural electrification projects in developing countries. A work by [19] has focused on smart grid integration and IoT-based monitoring, while sustainability assessments by [20] and [21] have confirmed the environmental benefits of these systems. Despite these advances, challenges remain in standardization [22],

financing models [23], and long-term maintenance [24], as identified in comprehensive reviews by [25].

A Pico hydro system as an alternative power source can produce alternating current (AC) electricity, enabling the use of electrical appliances. Common examples of devices that can be powered by pico-hydro are light bulbs, radios, and televisions [26]. Generally, a pico-hydropower system is found in rural or hilly areas [27].

Pico hydro plants offer some advantages over traditional large-scale hydroelectric power plants. For one, they are more cost-effective and easier to install. Additionally, Pico hydro plants can be installed in remote areas that lack access to traditional power grids, making them ideal for communities in developing countries [28].

1.1 Working principle of the Pico water-recycling hydro turbine system

A Pico hydro system typically operates using an upper water reservoir, which is a few meters high above ground. From the reservoir, water flows downhill through the piping system. Figure 1 illustrates the basic principle of converting gravitational energy from water into electricity via turbine rotation. It shows a reservoir at a higher elevation connected via a penstock (pipe) to a nozzle and turbine wheel at a lower level. Water flows from the upper reservoir through the penstock, driving the turbine to generate electricity. A pump is included, suggesting the system can also return water to the upper reservoir. The hydropower principle demonstrates how gravitational potential energy is converted into kinetic energy, enabling both energy storage and on-demand electricity generation [25].
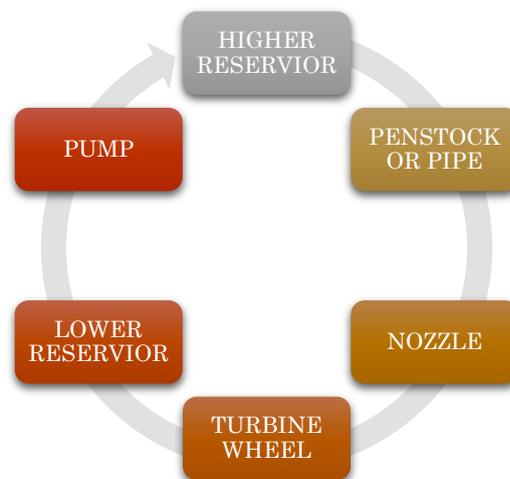

Figure 1: Water-recycling hydropower generation principle

This research project aims to design and build a recycled Pico hydroelectric system that generates electricity from a 100-liter water source. The focus is on using minimal water through a closed-loop approach, since most current pico-hydro studies prioritize natural streams or rivers. The system will use a dynamo AC/DC motor to convert the water's kinetic energy into electricity, which will power a pump and external devices such as LED bulbs. It will operate in a closed loop, with the pump returning water from the outlet back to the source.

2.0 Materials and Methods
2.1 Materials
The materials used in this research are tabulated in Table 1.

Table 1: Materials selection

S/N	Material/components	Purpose
1.	Stainless sheet (plate)	chosen for the turbine wheel
2.	PVC (Polyvinyl Chloride) Pipes	lightweight, cost-effective, and corrosion-resistant, used for water flow
3.	Elbow of 45°	used to change the direction of fluid flow
4.	Center Rod	to provide support, alignment, or balance.
5.	Bolt and nut	used to join two or more components together securely
6.	Angle iron	Used for constructing a water tower

2.2 Method
The research was achieved by considering the procedure as follows.
    i.   Determination of the storage capacity: Selection of a suitable storage tank and capacity that has a

sufficient head (vertical drop) to generate the desired power.
  ii.   Calculation of power requirements: the amount of power to be generated based on the available head, which helped to determine the size and specification of the turbine.
  iii. Selection of materials/components: Materials such as nozzles, pipes, valves, bearings, and other mechanical components.
  iv.   Connecting the electrical component: Connecting the turbine to an electrical generator or alternator.

2.2.1 Choice of Turbine

A Pelton turbine was chosen for this work because of the following reasons.
  i.   Small to medium flow rates: Pico hydropower Pelton turbine system typically involves smaller flow rates, and Pelton wheels are capable of operating effectively in this range.
  ii. High efficiency: Pelton turbines are known for their high efficiency in converting water energy into mechanical energy.
  iii. Durability and low maintenance: Pelton turbines are robust, which contributes to their durability and low maintenance requirements.
  iv. Control and stability: Pelton turbines offer good control and stability, especially in variable flow conditions.

2.2.2 Design procedure of the Pelton turbine

The design procedure of the Pico recycling hydropower system is presented in the following sections.

1. Head

The head is the vertical distance between the water source and the turbine, and it is the most important factor in determining the power output of the turbine. The higher the head, the greater the potential energy available to the turbine. Pelton turbines are designed to operate efficiently at high heads, typically between 300 and 1,800 meters. The Net head can be expressed by the following formula, shown in Equation (1).

$$H_n = H_g - H_{tl} \tag{1}$$

Where: H_n=Net head, H_g= Gross head and H_{tl}=Total head losses

2. Gross Head

The gross head (H_g) is the maximum available vertical fall in the water, from the upstream level to the downstream level. The actual head seen by a turbine will be slightly less than the gross head due to losses incurred when transferring the water into and away from the machine.

3. Total Head Losses

Total head losses (H_{tl}) is the head loss term, including hydraulic losses in the water conduits from head water to the turbine and from the turbine exit to the tail water. These are losses due to the open channel, trash rack, intake, penstock, and gate or valve. These losses are approximately equal to 6 % of gross head (i.e. $0.06H_g$) [5].

4. Discharge Q

The flow rate of this turbine, Q, was determined using the power equation [29] as shown in Equation (2).

$$Q = \frac{P}{\eta \rho g H} \tag{2}$$

Where P = Power, η = efficiency, ρ = density of water, g = acceleration due to gravity, and H = head

5. Specific Speed

The specific speed (Ns) is a dimensionless parameter used to classify turbines based on their shape, geometric dimensions, blade angles, and gate opening. It is the speed at which a turbine operates to develop a unit power when working under a unit head while maintaining geometric similarity and efficiency. The correlation between specific speed and the net head for the Pelton turbine c is given in Equation (3).

$$N_S = \frac{85.49 \times \sqrt{n_j}}{H_n^{0.235}} \tag{3}$$

Where: Ns specific speed (rpm)
  n_j = number of jets
  H_n= Net Head

The total hydraulic power available (P_{avail}) for the turbine is calculated from the net head H_n of the turbine was given by Equation (4).

$$P_{\text{avail}} = \rho g Q H_n \tag{4}$$

6. Power estimation

Fundamentally, power produced by a hydropower system is converted from one form to another; some is lost at each stage. For the proposed pico-hydro system, this refers to the friction loss in the pipelines [30]. Before the losses in the pipelines are taken into account, the drop is referred to as the gross head, and after losses have been subtracted, it is called the net head [30]. Thus, the electrical input power to the turbine is found using Equation (5).

$$P_t = \rho g C_n{}^2 H_n Q \tag{5}$$

where, Pt = turbine input power

g = gravity acceleration constant (9.81 m/s²)

C_n = nozzle (jet) discharge coefficient (0.98)

ρ = Density, Q = Discharge and H_n = Net head

The power output (Generator output) is determined by Equation (6).

$$P_{out} = \eta P_{in} \tag{6}$$

7. Turbine Rotational Speed

The rotational speed (N) of the runner can be calculated based on the design head and the power to be generated according to the relation in Equation (7) [30].

$$N = \frac{N_S H_n{}^{5/4}}{\sqrt{P_{ti}}} \tag{7}$$

The velocity of the jet at the inlet is given by Equation (8).

$$V_{\text{JET}} = K_N \sqrt{2gHn} \tag{8}$$

Where K_N is the nozzle velocity coefficient (normally around 0.95 to 0.99)

The velocity of the wheel (U) was calculated using Equation (9).

$$U = \emptyset \sqrt{2gH} \tag{9}$$

Where $\emptyset$ = speed ratio, its value lies between 0.43 to 0.48

The mean diameter or the pitch circle diameter (D) of the Pelton turbine was estimated from Equation (10).

$$U = 60 \,\pi DN \tag{10}$$

8. Penstock design

The parameters of the penstock were determined as follows:

a. Penstock Diameter: The required penstock diameter was calculated based on the flow rate and head pressure. Thus, $3/4$ inch and $1/2$ inch PVC (pipe) were selected.

b. Penstock Length: To minimize head losses, the penstock size was selected to be 1.2 m, matching the direct-path measurement from the water higher reservoir to the turbine inlet.

c. Valves and Control Mechanisms: A suitable valve of $3/4$ An inch was mounted along the penstock to control flow and isolate the turbine during maintenance or emergencies.

d. Thickness of penstock: The thickness of penstock (t_p) is calculated by the relation given in Equation (11).

$$t_p = \left[\left(\frac{D_{pt} + 508}{400} \right) + 1.2 \right] \times 10^{-3} (\text{m}) \tag{11}$$

Where D_{pt} represent the diameter of the penstock connected to the turbine was determined using Equation (12).

$$D_{pt} = 2.6 \left(n_{p2} \times Q_{t2} \times \frac{L_{pt}}{H_g} \right)^{0.1875} \tag{12}$$

Where, n_{p2} = Manning factor of penstock (0.009)

L_{pt} = Length of penstock (2 m assumption)

e. Penstock velocity: The penstock velocity was determined using Equation (13).

$$Q = A \times V_P \tag{13}$$

f. Penstock efficiency: The penstock efficiency η_{pt} was calculated using the relation in Equation (14).

$$\eta_{pt} = \frac{H_n}{H_g} \times 100 \tag{14}$$

g. Fluid velocity: The fluid velocity (V_1) was calculated using Equation (15).

$$V_1 = jet\ velocity - Bucket\ speed = V_j - \cup \tag{15}$$

Where $C_n = 0.98$ and $V_j = C_n \times \sqrt{2g \times H_n}$

h. Runner diameter: The runner diameter at maximum efficiency was calculated using Equation (16).

$$D_r = \frac{60U}{\pi \times N} \quad \text{or} \quad D_r = 38.6x\frac{\sqrt{H_n}}{N}$$ 16)

Where, Dr = runner diameter and x = maximum efficiency ratio (between 0.46 to 0.47)

9. Design formula for the bucket

The ratio of pitch circle diameter of the Pelton wheel to the jet diameter is known as the jet ratio, represented by m as in Equation (17), and it is a size parameter for the turbine [31].

$$m = \frac{D_r}{d_j}$$ **(**17)

The jet diameter is an important parameter in the design of a Pelton wheel. For maximum hydraulic efficiency, the jet ratio lies between 6 and 25.

Certain empirical formulae have been developed for determining the number of buckets. One such formula widely used is given by [30]. According to that, the number of buckets, Z, is approximately estimated by Equation (15).

$$Z = 0.5m + 15$$ (18)

10. Casing

The turbine housing was fabricated from 1.5 mm aluminum sheet, forming a rectangular enclosure with internal dimensions of 60 cm (L) × 50 cm (W) to accommodate the Pelton wheel assembly.

2.2.2.11 Selection of the generator/pump

The alternator and pump used for testing the designed hydropower system were selected based on availability. Figures 2 and 3 illustrate the alternator and pump used to generate electrical energy and return water from the lower reservoir to the higher reservoir, respectively. A DC alternator with a power output of approximately 30 W and 10 rpm was used to test the designed hydro plant due to availability constraints. On the other hand, two pumps with a combined capacity of $0.00015\text{m}^3/\text{sec}$ and power requirement of 10 W was used for the testing.

Figure 2: alternator/generator   Figure 3: pump

15. Conceptual drawing

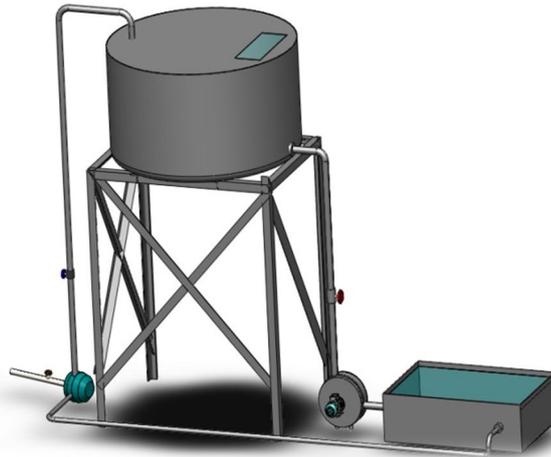Figure 4 depicts the conceptual drawing of the pico-hydropower system.

Figure 4: General setup of the system

15. Conceptual drawing

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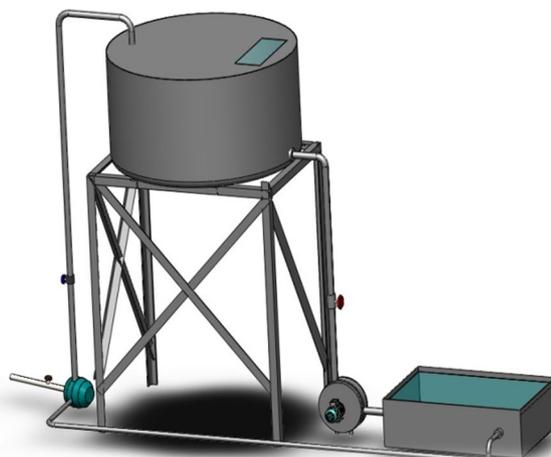

Figure 4: General setup of the system

3.0 Results and Discussion

The results of the design are summarized as shown in Table 2.

Table 2: Design result

Parameters	Calculated values
Net head, H_n	2.0 m
Flow rate, Q	0.0041 m³/sec
Turbine power input, P_{ti}	77W
Specific speed, N_s	72 rpm
rotational speed of a turbine, N	20 rpm
Velocity of the jet at inlet, V_{ji}	6.9 m/s
The velocity of the wheel, U	3.0 m/s
Fluid velocity, V_1	6.1 m/s
The thickness of the penstock, t_p	2.55 mm
penstock velocity, V_p	1.08 m/s
The runner diameter at maximum efficiency, D_r	27 cm
Diameter of penstock, D_{pt}	23.7 mm
Thickness of penstock, t_p	2.5 mm
penstock efficiency, η_{pt}	80%
Number of buckets, Z	10

3.1 Result of the Bucket Design

While designing Pelton buckets, two parameters are important.

(i) The ratio of the bucket width to the jet diameter

(ii) The ratio of the wheel diameter to the jet diameter.

The dimensions of the Pelton wheel bucket are determined as follows:

Bucket length, L   2 inch (by 45°)

Bucket width, B   50 mm

Notch width, M   1 inch

Bucket height, A   2 inch

Due to limited access to precision manufacturing equipment, the turbine assembly was constructed using improvised fabrication techniques. Figure 5 shows the completed Pelton wheel with attached buckets, demonstrating the functional design achieved through adaptive construction methods.

Plate 5: Bucket

Figure 6 depicts the complete assembly of the fabricated prototype of the Pico-hydropower system.

Figure 6a: Higher reservoir assembly   Figure 6b: Lower reservoir and turbine assembly

3.2 Performance analysis

The prototype system demonstrated satisfactory operational performance, with an efficiency of approximately 80% relative to its design scale and component specifications. Testing yielded a net electrical output of 24W, which aligns with power generation expectations for pico-hydropower systems using similarly sized alternators [5] (Paish, 2002). Although the power output level may seem low due to alternator size constraints, it is still significant and suitable for basic rural electrification needs, such as powering LED lighting, mobile charging, and small appliances in off-grid communities [19]. The system maintained a return flow rate of 0.000124 m³/s, demonstrating effective water recirculation - a critical feature for sustainable operation in water-constrained environments. This water recycling system will enhance water conservation, thereby helping to achieve sustainable development goals. The measured penstock efficiency of 79% indicates successful minimization of head losses, comparable to efficiencies reported in other small-scale hydropower installations [32].

When compared to similar pico-hydropower systems documented in literature, the prototype's performance

metrics show favorable characteristics. The 24W output falls within the typical 20-100W range for pico-hydro installations powering basic household needs in off-grid communities **[27]**. The water recycling efficiency surpasses that of conventional run-of-river Pico systems by approximately 15-20%, as reported in comparable closed-loop designs [7]. These results substantiate the technical viability of the design approach while highlighting areas for potential efficiency improvements through turbine optimization and reduced mechanical losses.

Figures 7, 8, and 9 show the images of the testing carried out at different stages.

Figure 7a: Water turning the turbine wheel   Figure 7b: Water entering the lower reservoir

Figure 8: Performance testing of generated electricity

Figure 9: Water return flow to the higher reservoir

The successful operation confirms the technical feasibility of the recycling hydropower concept at a small scale, with particular effectiveness in low-flow conditions. These findings suggest good potential for rural electrification applications where conventional power infrastructure is unavailable.

4.0 Conclusion

The experimental results demonstrate that the Pico water-recycling hydropower system, utilizing an optimized Pelton turbine (10 buckets, 2 m head, 80% efficiency), successfully generates 24W of clean power—sufficient for basic household needs in remote areas. While the system's 0.000124 m³/s return flow rate highlights its water-efficient design, further refinement could enhance hydraulic performance and energy recovery. The 0.0041 m³/s inlet flow rate and 79% efficiency confirm its viability under high-head, low-flow conditions, offering a cost-effective, eco-friendly alternative to fossil fuel generators. For broader adoption, future work should focus on improving the return flow mechanism to maximize resource utilization while maintaining the system's affordability and simplicity. This design represents a practical step toward sustainable off-grid electrification; even though, optimizations in water recycling could unlock greater potential.

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