IC-003

Performance Improvement of pico-hydro power turbine using domestic technology

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ABSTRACT

Although pico hydropower technology's potential for low-cost renewable energy, importing such technology into Thailand can be costly, primarily due to the absence of domestic manufacturers. This project aimed to develop a domestically produced 3 kW hydropower turbine system by enhancing the KIRIWONG hydro turbine to meet international standards. The project succeeded in creating a prototype that achieves a head of 100 m and a flow rate of 5.05 l/s, generating AC electricity at 230 V and 50 Hz. The system features stainless-steel Pelton turbine blades, a 3 kW 6-phase synchronous motor, and an aluminum casting turbine support base, among other components, achieving a water-to-electricity conversion efficiency of 60.5%. Economic analysis showed the system's viability with a payback period of 1 year and 4 months and a cost of energy at 0.26 THB/kWh, proving its competitiveness against small diesel generators and conventional electricity sources. This development not only highlights the project's success in producing a cost-effective, efficient hydropower solution but also its impact on the local hydropower community, leading to increased orders and improved access to sustainable energy solutions.

Keywords: Pico hydro turbine, Performance, Nozzle, KIRIWONG hydro turbine.

1. Introduction

Energy is a critical factor in meeting the basic needs of populations across all sectors. However, current circumstances reveal an increasing trend in energy consumption across all sectors (Kanokkarn Srisurin, 2023), and energy prices in the country are subject to changes according to global market conditions. Prices cannot be controlled and are further trending upwards. This has implications for all sectors of society, including communities in remote areas. In response to the government's long-standing policy of ensuring equal access to electricity, especially in remote rural areas without power lines, there has been a significant push towards adopting renewable energy sources such as solar, hydro, wind, biogas, and biomass for electricity generation (Department of Alternative Energy Development and Efficiency, 2012). Over the past three decades, this initiative has led to numerous projects aimed at improving the quality of life for people in remote areas through the application of renewable energy technologies. However, the adoption of renewable energy, particularly solar and wind power, as well as small hydropower turbines, has been predominantly reliant on imported technology. Over the last thirty years, pico-hydropower systems, defined as having a capacity of under 5 kW, have become increasingly recognized as viable, sustainable, and cost-effective options for providing off-grid electrical and mechanical power, particularly in efforts to electrify rural areas (Cobb & Sharp, 2013). The Pelton turbine, a specific type of impulse water turbine, has been at the forefront of this development due to its relevance and effectiveness in such settings. This has sparked a growing interest among researchers in its potential and optimization. Consequently, a substantial body of research, including both numerical simulations and practical experiments, has been dedicated to improving the efficiency and design of the Pelton turbine, reflecting its critical role in enhancing the performance of hydropower stations (Chitrakar et al., 2020)(Liu et al., 2015).

Although the installation and use of pico hydropower turbines have been successful in several developing countries(Gallego et al., 2021), for Thailand, importing hydropower turbine technology from abroad for electricity production can cost up to 80 THB/W. This is because there are no domestic manufacturers of pico hydropower turbines, necessitating the sole importation of technology, thus preventing widespread installation and use. In 2009, researchers collaborated with the KIRIWONG community in Nakhon Si Thammarat province to design, build, and install the KIRIWONG hydro turbine prototypes for use in high-head locations. These Pelton wheel turbines, ranging from 0.3 to 1 kW, were developed alongside technology transfer to the KIRIWONG hydro turbine community enterprise. To date, over 160 systems have been installed, contributing more than 110 kW of power. Despite these achievements, the widespread adoption of the KIRIWONG turbines has been limited to the Nakhon Si Thammarat province and has not expanded significantly to other regions or received broad support from governmental and private sectors. For wider deployment, comprehensive development is necessary, including enhancing the entrepreneurial capabilities for efficient production processes, creating distinctive and market-accepted products, and diversifying product types to add value.

Recognizing the need for development, the KIRIWONG hydro turbine community enterprise has initiated the development of a 3-kW hydro turbine prototype, sufficient for rural household use, and aims to elevate the KIRIWONG hydro turbine products to international standards. This effort involves collaboration between the community enterprise and the Integrated Clean Energy System Development and Training Institute's research lab at King Mongkut's University of Technology Thonburi.

2. Purposes

1) To develop a prototype of a 3-kW hydroelectric turbine using domestic technology, relying on the upscaling of the existing KIRIWONG turbine set.
2) To study the performance and return on investment of the 3 kW KIRIWONG hydro turbine set.

3. Research Methodology

3.1 Conceptual Framework

This research aims to enhance the efficiency of the existing 1 kW KIRIWONG water turbine, enabling it to produce up to 3 kW of power at a lower cost compared to importing similar technologies. The project focuses on three technological advancements: optimizing turbine blade design through mathematical algorithms to achieve the best shape and size for maximum energy transfer, developing precise nozzle technology to control the flow and direction of water for optimal turbine blade impact, and implementing control technology to ensure the turbine operates at peak electrical power output continuously. These enhancements are designed to improve the turbine's performance and the quality of the electricity generated, offering a cost-effective, sustainable energy solution.

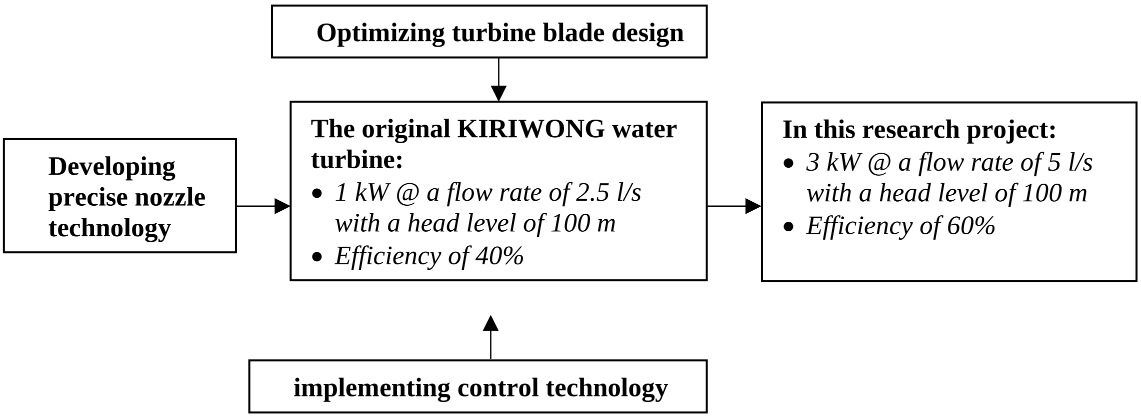

Figure 1 Conceptual Framework

3.2 Analysis of Performance

3.2.1 Data collection

Laboratory testing of water turbines adheres to key international standards to ensure accurate and reliable results. These standards include IEC TC 4, which outlines requirements for hydraulic turbines; IEC 61116, a guide for electromechanical equipment in small hydroelectric installations; IEC 620-06: 2011, specifying acceptance tests for small hydroelectric installations; and IEC 60041:1995, detailing field acceptance tests for assessing the hydraulic performance of turbines, storage pumps, and pump-turbines. A suite of precision instruments is employed to collect data on turbine electricity generation, including a SFC model 300 pressure gauge for head level measurement, a Portaflow ultrasonic flow meter for flow rate, Philips E27 electric bulbs to simulate electrical load, a Digicon DT235T tachometer for shaft speed, a Fluke 179 power meter for electrical data, and a GwINSTEK GDS-2102A oscilloscope for electrical signal analysis, as show in Figure 2.

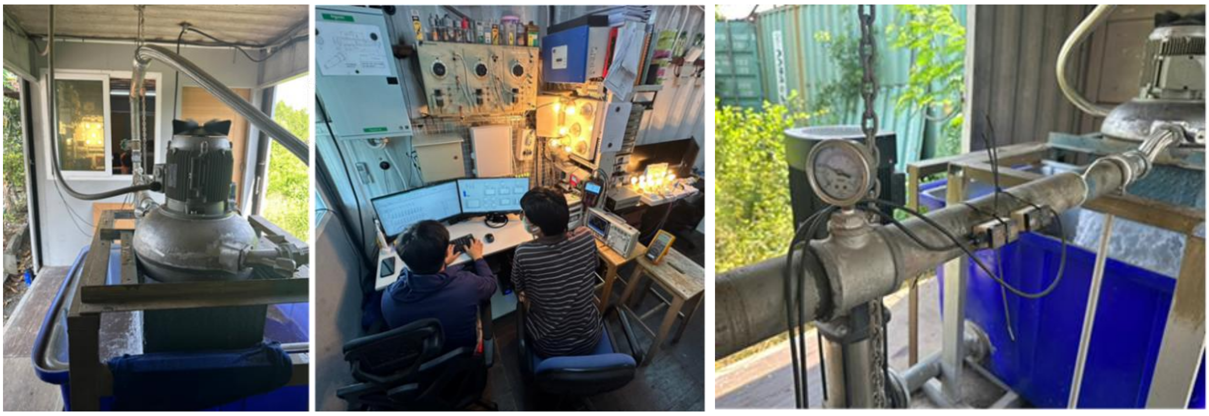

Figure 2 The hydro turbine test rig.

3.3.2 The equation for calculating the performance of a pico hydro turbine.

The assessment of a water turbine's performance for generating electricity is primarily influenced by two factors: the flow rate of the water and the head level. The efficiency of a Pelton water turbine can be calculated using the ratio of the electrical power output to the input power, where the input power is a function of the water flow rate and head level. This relationship is expressed in Equation (1) as follows:

$$\eta_{turbine} = \frac{E_{power}}{\rho g Q H} \qquad (1)$$

Where $\eta_{turbine}$ is the efficiency of the water turbine system, E_{power} is the electrical power output (W), ρ is the density of water (kg/m3), g is the acceleration due to Earth's gravity (m/s^2), Q is the flow rate of water, and H is the head level.

3.3 Economic Analysis

This study evaluates the economic feasibility of implementing KRW-3000 hydro turbine systems by analyzing their cost-effectiveness, returns, and profitability in comparison to traditional electricity sources such as regional power utilities and generators. The evaluation is based on several assumptions: a project lifespan of 10 years, an interest rate of 6.244%, a turbine efficiency of 60%, and specific recurring costs like capacitor replacements every three years. Additionally, the study factors in a capacity utilization rate of 50% and compares the cost of electricity from grid connections (4.42 THB/kWh) and generator operations (30 THB/kWh, assuming fuel consumption of 0.8 liters per kWh), to thoroughly assess the financial advantages of hydro turbine installations over conventional energy options.

3.3.1 Investment Costs Analysis

To accurately estimate the investment required for the hydro turbine system, the study sourced cost data from inquiries made to the KIRIWONG hydro turbine community enterprises. This includes the costs of materials, equipment, and labor needed to construct the hydro turbine system. Detailed pricing information for the equipment utilized in the project is presented in Table 1, offering a transparent view of the initial financial outlay for the hydro turbine system implementation.

3.3.2 Return on Investment analysis

Investing in small-scale hydroelectric turbine systems presents a compelling benefit by offering rural communities an alternative method for generating electricity tailored to their specific needs. A key advantage derived from the deployment of these systems is the ability for villagers to access electricity around the clock. This continuous access is made possible through the operation of the hydroelectric turbine, which, with a capacity utilization rate of 50%, is capable of producing 13,140 kWh of electricity annually. This enhancement in electricity availability signifies a substantial improvement in quality of life and productivity for the community, marking a direct return on investment from the adoption of hydroelectric turbine technology.

Table 1 The installation costs for the RRW-3000 hydro turbine set.

Item	Price (THB)
KRW-3000 hydro turbine set	52,000
- Machine base	8,200
- 200 mm Pelton turbine blade	8,000
- 2 Adjustable jet nozzles	7,000
- 3 kW 3 HP 6 Pole motor	16,000
- Stainless steel flexible pipe, Y-junction, and nipples	2,500
- Generator control unit	2,500
- Automatic voltage control unit	3,000
- Miscellaneous (e.g., nuts, machining, handling fees)	4,800
Installation accessories:	15,000
- Civil work (e.g., foundations, buildings)	10,000
- Electrical work (e.g., electrical cables, poles)	5,000
Water conveyance work:	182,400
- Water pipes and fittings	182,400
Total	249,400

3.3.3 Equations for calculating economic indicators.

In evaluating the economy of pico hydro systems, three main economic indicators are considered:

1)Total Net Present Cost (NPC):

The NPC represents the present value of all costs incurred throughout the system's lifetime minus the present value of all revenues earned during the same period. Costs include capital, replacement, operation and maintenance, fuel, emissions penalties, and power purchase from the grid. Revenues comprise salvage value and revenue from selling power to the grid. The total net present cost is calculated using Equation (2):

$$C_{NPC}=\frac{TAC}{CRF(i,N)} \tag{2}$$

where TAC is the total annualized cost (USD/year) and CRF, the capital recovery factor is a function of the annual real interest rate (i), and the project lifetime (N) in years. CRF is given in equation (3) (Olatomiwa et al., 2015):

$$CRF(i, N)=\frac{i(1+i)^N}{(1+i)^N-1} \tag{3}$$

The NPC criteria are: If the NPC is positive, the investment is economical, a negative NPC is denotes the return are worth less than the initial investment, the financial viability of a project is uncertain with zero NPC. For independent projects, the higher the NPC value the better.

2) Levelized Cost of Energy (LCOE)

The LCOE equals the ratio of lifetime costs to lifetime electricity generation, discounted back to a base year. This metric reflects the average cost per kWh of electricity produced by the system and is given by:

$$LCOE=\frac{TAC}{E_{anloadserved}} \tag{4}$$

where: $E_{anloadserved}$ is the total annual load served by the system (kWh).

3) Simple Payback Period (SPB)

The SPB is a financial metric used to estimate how many years it will take to recoup the initial project costs. It is calculated without considering the time value of money, using a zero-discount rate, as shown in Equation (5):

$$\sum_m \Delta IIC_m \leq \sum_m \Delta S_m \qquad (5)$$

where ΔIIC_m is the incremental investment cost at zero discount rate in period m and ΔS_m is sum of the annual cash flows net annual costs at zero discount rate in period m.

Results

4.1 The 3 kW KIRIWONG water turbine

The project successfully developed a 3 kW KIRIWONG water turbine prototype, leveraging local materials and technologies, and introduced a new business strategy to enhance its market presence. This hydroelectric turbine, designed for optimal efficiency and durability, incorporates a Pelton turbine set (KRW-3000) tailored for a 100 m head and a 5 l/s flow rate. It produces single-phase AC electricity at 230 V and 50 Hz. Essential to its design are stainless steel Pelton blades, chosen for their high strength (750 – 850 N/mm^2) and cost-effectiveness, connected directly to a 3 kW, 3-phase, 6-pole induction motor that serves as an efficient generator. The structure is supported by an aluminum cast base, ensuring strength (90-250 N/mm^2) at a reduced cost, and features adjustable nozzles for precise water flow. The inclusion of a control unit for the induction generator, complete with capacitors and a voltage meter, alongside an automatic voltage control system that stabilizes power output through load division, highlights the prototype's advanced engineering. This system, capable of maintaining a consistent power level amid load changes, underscores the KIRIWONG turbine's potential as a forward-looking solution for hydroelectric power in appropriately selected locations, as shown in Figure 2.


(a) (b)

Figure 2 The original KIRIWONG turbine (a), The 3 kW KIRIWONG water turbine (b)

4.2 The system performance

4.2.1) Evaluating performance across various heads and flows.

The Pelton water turbine's performance was assessed at a 40 m head and multiple flow rates, as detailed in Figure 3. Observations revealed that, without an electrical load, the turbine's rotational speed correlates directly with the flow rate, influenced by the Spear Valve's adjustment. A single turn of the Spear Valve allowed the turbine to achieve its peak speed of 800 rpm at a 1.2 l/s flow rate. Introducing an electrical load, such as connecting the turbine to an electric bulb via a generator, resulted in a linear decrease in speed proportional to the electrical power generated. At full electrical load, the turbine system could produce a maximum of 230 W at 714 rpm. As the flow rate increased, a pattern emerged showing the maximum power output to have an exponential relationship with the turbine speed and a linear relationship with the flow rate. Specifically, at a flow rate of 5.1 l/s, the system reached a maximum power output of 1,385 W, translating to a 69% efficiency rate. This performance metric was consistent across various testing scenarios involving different head levels and flow rates, as illustrated in Figure 4.

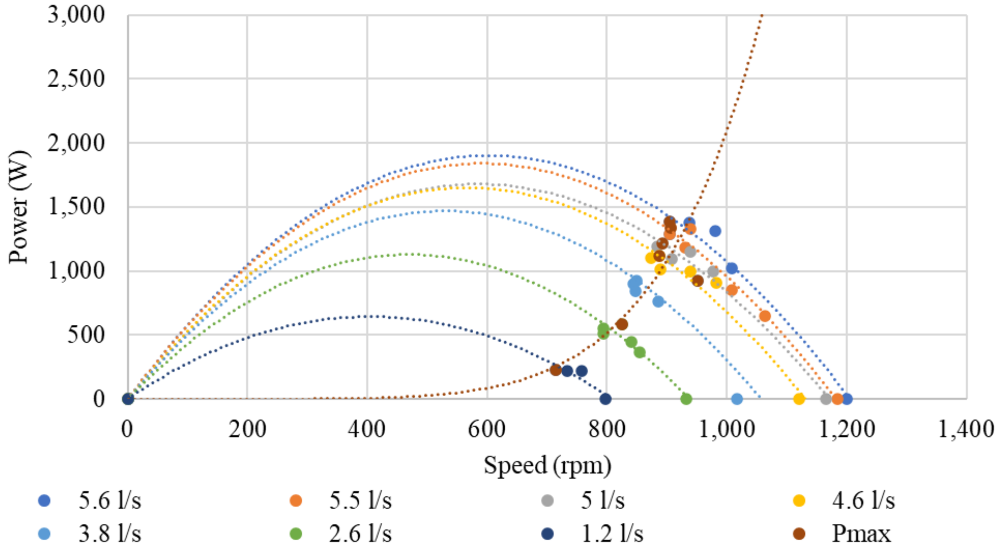

Figure 3 Results of the water turbine testing at a head of 40 m.

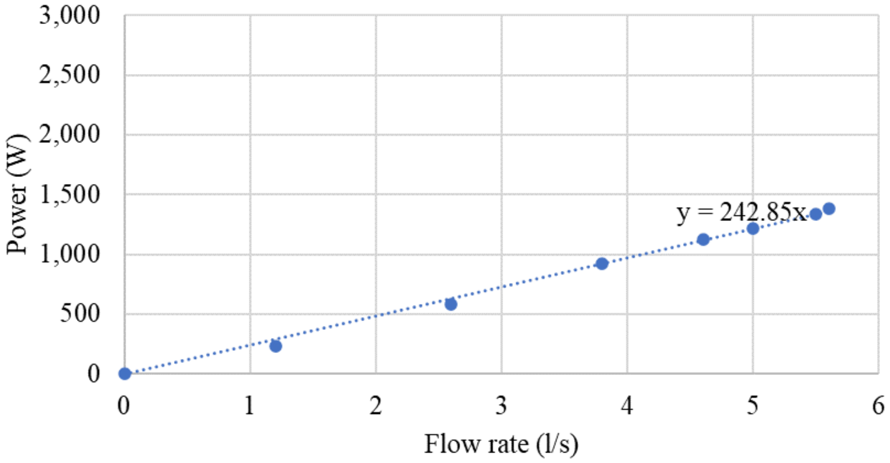

Figure 4 Relationship between maximum power and flow rate at a head of 40 m.

4.2.2) Performance of the water turbine set at designed head levels and flow rates.

Due to the constraints imposed by the motor/pump setup employed to emulate head levels within a laboratory setting, testing the water turbine set at its intended design parameters—specifically a head level of 100 meters and a flow rate of 5 liters per second—was not feasible. The achievable testing conditions were limited to a maximum head level of 60 meters at a flow rate of 5 liters per second. Consequently, the evaluation of the water turbine set's performance at its designed specifications had to be inferred from the established relationship between electrical power output and flow rate across varying head levels, as depicted in Figure 5. This approach allowed for an indirect assessment of the turbine's performance potential under the designed operating conditions, based on the extrapolation of data from observable trends and relationships presented in the figure 5.

$$P\ (W)\ \text{at}\ 90\ m = 450.95 \times Q\ (l/s) \tag{6}$$

$$P\ (W)\ \text{at}\ 80\ m = 408.77 \times Q\ (l/s) \tag{7}$$

$$P\ (W)\ \text{at}\ 70\ m = 375.99 \times Q\ (l/s) \tag{8}$$

P (W) at 60 m = 345.42 x Q (l/s) (9)

P (W) at 50 m = 289.30 x Q (l/s) (10)

P (W) at 40 m = 242.37 x Q (l/s) (11)

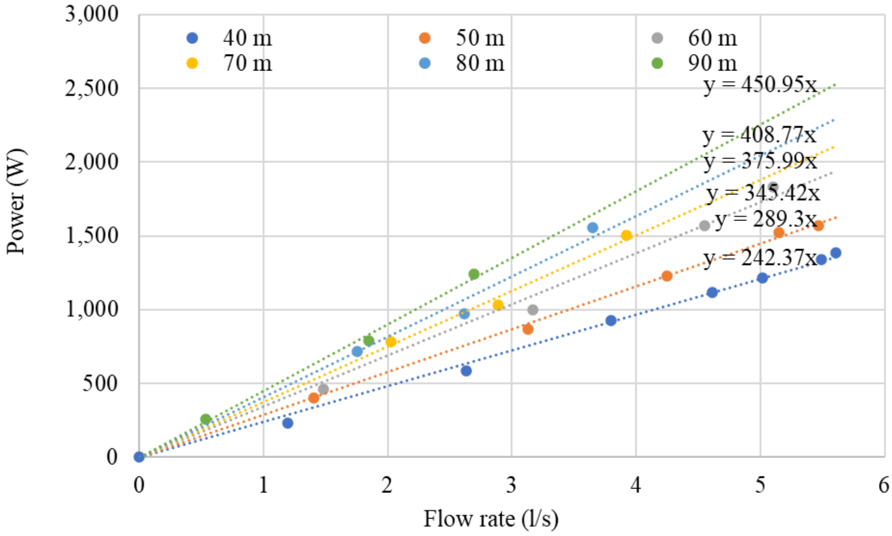

Figure 5 Relationship between electrical power and flow rate at different head.

Based on the equations derived from the study, a graph illustrating the correlation between head level and flow rate for various electrical power outputs has been compiled. This relationship is visually represented in Figure 6, with the associated mathematical expressions detailed in equations (6) – (11). This graphical representation and its corresponding formulas provide a comprehensive view of how the turbine's electrical power generation varies with changes in head level and flow rate, offering valuable insights for optimizing turbine performance across a range of operating conditions.

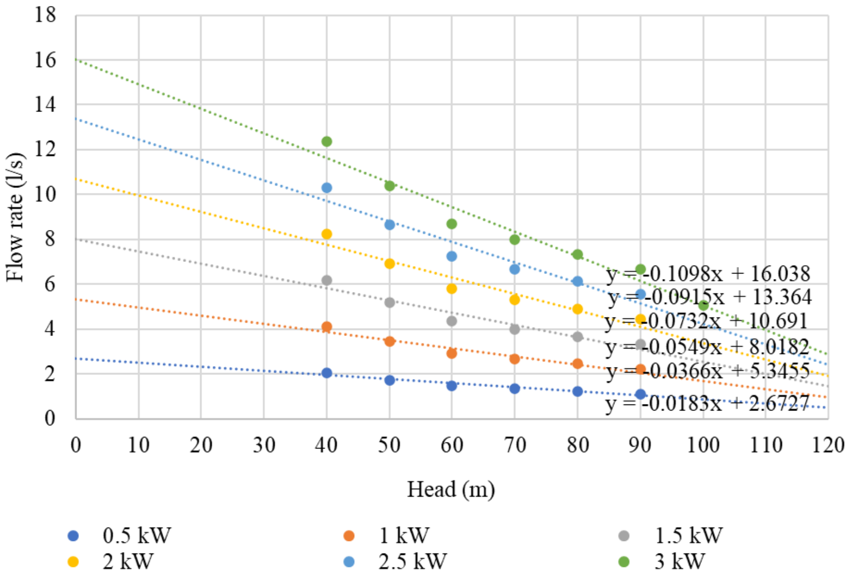

Figure 6 Relationship between head level and flow rate at different electrical powers

$$Q\ (l/s)\ \text{at}\ P\ 3.0\ kW = (-0.109 \times H\ (m)) + 16.03 \tag{12}$$

$$Q\ (l/s)\ \text{at}\ P\ 2.5\ kW = (-0.091 \times H\ (m)) + 13.36 \tag{13}$$

$$Q\ (l/s)\ \text{at}\ P\ 2.0\ kW = (-0.073 \times H\ (m)) + 10.69 \tag{14}$$

$$Q\ (l/s)\ \text{at}\ P\ 1.5\ kW = (-0.054 \times H\ (m)) + 80.18 \tag{15}$$

$$Q\ (l/s)\ \text{at}\ P\ 1.0\ kW = (-0.036 \times H\ (m)) + 5.34 \tag{16}$$

$$Q\ (l/s)\ \text{at}\ P\ 0.5\ kW = (-0.018 \times H\ (m)) + 2.67 \tag{17}$$

Equation (12) indicates that the water turbine set is capable of producing 3 kW of electricity at a head level of 100 meters, provided it operates at a flow rate of 5.05 liters per second. This operation results in a conversion efficiency of 60.5% from water energy to electrical energy, aligning closely with the design specifications.

4.3 The return on investment

The cost analysis for implementing a hydroelectric turbine system totaled 249,400 THB, incorporating the periodic replacement of the Capacitor, which incurs a cost of 600 THB every three years, across its anticipated 10-year operational life. The analysis also accounts for the financial savings from diminished reliance on oil for electricity generation, estimated at 30 THB/kWh, and compares the annual maintenance expenses of a generator, roughly 3,000 THB, with the operational costs of the turbine system. Moreover, it evaluates the cost-effectiveness of the turbine installation against purchasing electricity directly from the Provincial Electricity Authority, highlighting a cost reduction to 4.42 THB/kWh. These comparative financial benefits are detailed in Table 2.

Table 2 The results of economic analysis.

Indicator	Compared to Generator	Compared to PEA
Net Present Value (THB)	1,683,592	171,981
Internal Rate of Return (%)	106%	19%
Benefit/Cost Ratio (B/C Ratio)	7.72	1.7
Payback Period (Years)	1 Year	4 Years 4 Months
Electricity Rate (THB/kWh)	0.26	0.26

The economic analysis, through a net present value comparison to a conventional generator, demonstrated the developed prototype Pelton hydro turbine set as a significantly beneficial investment over its lifespan. The project culminated with benefits surpassing the initial costs by 1,683,592 THB, featuring a rapid payback period of just one year and achieving an impressively low electricity production cost of 0.26 THB/kWh. This cost efficiency starkly contrasts with the 30 THB/kWh associated with generator-produced electricity. When juxtaposed with the costs of acquiring electricity from the Provincial Electricity Authority, the prototype's economic advantage remains clear. The analysis revealed that the Pelton hydro turbine set similarly presents a cost-effective choice, with net benefits of 171,981 THB upon project completion. The payback timeframe for the turbine installation extends to 4 years and 4 months, maintaining the same reduced electricity cost of 0.26 THB/kWh. This rate is considerably more economical, nearly 17 times less, than the 4.42 THB/kWh charged by the Provincial Electricity Authority for residential consumption exceeding 150 kWh/month.

Discussion

In the realm of small-scale hydroelectric turbines, a dichotomy exists between simplistic and complex designs, primarily differentiated by the intricacy of their manufacturing processes and the resultant performance metrics. Complex designs necessitate advanced expertise, particularly in the precise engineering of blade geometry and twist angles. This meticulous attention to detail typically culminates in enhanced performance capabilities but incurs a higher production cost. On the contrary, turbines with simpler designs are marked by their affordability and are predominantly manufactured in China and other Asian countries, although they may offer compromised performance in comparison.

Performance evaluations of these turbine sets reveal a distinct relationship between operational parameters and output. Specifically, our findings indicate an exponential correlation between the rotational speed of the turbine and both the maximum electrical power and efficiency. Conversely, a linear relationship is observed between the flow rate and these performance metrics. In practical terms, the prototype turbine under this study demonstrated the capability to generate 3 kW of electricity at a head of 100 m and a flow rate of 5.05 l/s, with an impressive efficiency of 60.5% in the conversion of hydraulic energy to electrical energy.

This efficiency surpasses findings from notable studies, such as those conducted by Bryan R. Cobb and Kendra V. Sharp (Cobb & Sharp, 2013), who reported an efficiency greater than 80% for the Turgo turbine under specific conditions, and Ibadullah Safdar et al. (Safdar et al., 2020), who identified the maximum efficiency of impulse turbines in pico hydro systems as 20.75% under their experimental setup. Furthermore, when juxtaposed with the efficiency metrics of commercially available Pelton turbines, like those offered by Rainbow Power Company Ltd (REUK – Renewable Energy UK, 2023)and Lingenhöle Technologie (*Pico Hydroelectric Plants*, 2023), our prototype not only demonstrates comparable efficiency but also showcases the potential for superior performance in certain respects.

From an economic perspective, the installation of the prototype Pelton turbine, inclusive of the necessary water conveyance infrastructure, represents a capital investment of 249,400 THB. The financial viability of this investment is underscored by a net present value analysis over the project's lifespan, revealing a promising payback period of merely one year, with the cost of electricity pegged at 0.26 THB/kWh. This cost efficiency significantly undercuts that of conventional generators and is substantively lower than the regional utility rates, offering a cost-effective alternative to traditional electricity sources (Basar et al., 2014). The analysis further confirms the economic soundness of the turbine installation, with a calculated payback period of four years and four months, positioning the prototype as a financially viable and environmentally sustainable solution for small-scale electricity generation.

Conclusions

This research aimed to advance the KIRIWONG water turbine technology, focusing on enhancing its quality and market viability through collaboration with the KIRIWONG water turbine community enterprise. The methodology involved rigorous testing and analysis of the current turbine models against relevant standards to identify areas for improvement. The goal was to design, construct, and test a new 3 kW hydroelectric turbine set both in the lab and through field installations in the KIRIWONG community, Nakhon Si Thammarat Province. Moreover, the project endeavored to uplift the community enterprise by broadening their expertise in market analysis, product design, development, and packaging, thereby adding value to the products and facilitating their entry into the market.

The creation of a prototype Pelton turbine set was a key outcome, capable of generating 3 kW of electricity at a 100 m head and a flow rate of 5 l/s, achieving an impressive 60.5% energy conversion efficiency. This prototype includes innovative features such as stainless-steel Pelton blades with a 200 mm diameter, connected to a 3 kW 6-pole induction motor, and equipped with an adjustable nozzle system for optimized water flow. These technical advancements, coupled with a comprehensive control system for maintaining constant voltage, underscore the prototype's potential for practical application and its alignment with the design specifications aimed at enhancing performance and efficiency.

Economically, the project demonstrated significant promise. The total investment for the turbine's installation and operational setup was analyzed to be 249,400 THB, with a calculated return that justifies the initial expenditure. The prototype not only promises a rapid payback period of one year compared to conventional power generation but also positions itself as a competitive alternative with a cost of electricity at 0.26 THB/kWh. This rate substantially undercuts that of electricity purchased from the PEA, making the KIRIWONG water turbine a financially viable and environmentally sustainable option for rural electrification, especially in areas conducive to harnessing hydroelectric power.

Recommendations

While the hydroelectric turbine set analyzed in this study generates electricity at a cost lower than conventional power generators and regional electricity tariffs, its cost-effectiveness approaches that of the regional tariffs when the estimated electricity utilization dips below 90% of the actual power output, even with a projected lifespan of under five years. This highlights a significant potential for installations, especially across the diverse mountainous terrains of the country. Nevertheless, to fully leverage the advantages offered by these prototype hydroelectric turbines, careful consideration of the geographical and environmental conditions at potential installation sites is crucial. The research underscores that these prototypes are particularly well-suited for locations with water head heights exceeding 40 meters, suggesting a targeted approach to identifying and developing sites could optimize the turbines' performance and economic benefits. This strategic focus on site selection emphasizes the need to align technological capabilities with the natural characteristics of each location to ensure the most efficient and effective use of renewable energy resources.

Acknowledgment

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References

Basar, M. F., Sapiee, R., Rahman, S., Hamdan, Z., Borhan, S. & Sopian, K. (2014). Cost analysis of pico hydro turbine for power production. *Advances in Environmental Biology*, *8*(14), 147–151.

Chitrakar, S., Solemslie, B. W., Neopane, H. P. & Dahlhaug, O. G. (2020). Review on numerical techniques applied in impulse hydro turbines. *Renewable Energy*, *159*, 843–859. https://doi.org/10.1016/j.renene.2020.06.058

Cobb, B. R. & Sharp, K. V. (2013). Impulse (Turgo and Pelton) turbine performance characteristics and their impact on pico-hydro installations. *Renewable Energy*, *50*, 959–964. https://doi.org/10.1016/j.renene.2012.08.010

Department of Alternative Energy Development and Efficiency. (2012). Alternative Energy Development Plan (2012-2021). In *Alternative Energy Development Plan: AEDP2015* (Vol. 7, Issue 1, pp. 1–10).

Gallego, E., Rubio-Clemente, A., Pineda, J., Velásquez, L. & Chica, E. (2021). Experimental analysis on the performance of a pico-hydro Turgo turbine. *Journal of King Saud University - Engineering Sciences*, *33*(4), 266–275. https://doi.org/10.1016/j.jksues.2020.04.011

Kanokkarn Srisurin, S. T. and C. S. (2023). Forecasting of Peak Demand in Thailand. *The 10th National and the 8th International Conference on Research and Innovation : Research and Innovation Development for Developing Sustainable Communities*, 591–606.

Liu, X., Luo, Y., Karney, B. W. & Wang, W. (2015). A selected literature review of efficiency improvements in hydraulic turbines. *Renewable and Sustainable Energy Reviews*, *51*, 18–28. https://doi.org/10.1016/j.rser.2015.06.023

Olatomiwa, L., Mekhilef, S., Huda, A. S. N. & Ohunakin, O. S. (2015). Economic evaluation of hybrid energy systems for rural electrification in six geo-political zones of Nigeria. *Renewable Energy*, *83*, 435–446. https://doi.org/10.1016/j.renene.2015.04.057

Pico Hydroelectric Plants. (2023). https://www.lingenhoele.at/en/turbine-construction/pico-hydroelectric-plants/

REUK – Renewable Energy UK. (2023). *Rainbow Power 300W Hydro Generator*. Http://Www.Reuk.Co.Uk/Wordpress/Hydro/Rainbow-Power-300w-Hydro-Generator/.

Safdar, I., Sultan, S., Raza, H. A., Umer, M. & Ali, M. (2020). Empirical analysis of turbine and generator efficiency of a pico hydro system. *Sustainable Energy Technologies and Assessments*, *37*(August 2019), 100605. https://doi.org/10.1016/j.seta.2019.100605