

Small-scale river flow hydropower: Design, IoT monitoring, and field validation

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ABSTRACT

Hydroelectric energy represents a sustainable and reliable power source for off-grid and remote areas, particularly in environments where conventional electricity access is limited and solar energy performance is reduced by dense vegetation. This study addresses the need for a portable, small-scale hydroelectric solution by developing and validating a lightweight IoT-enabled micro-hydroelectric generator designed to operate in low-head, densely vegetated stream environments. The proposed system integrates a compact micro-hydro turbine with an ESP32 microcontroller and a multi-sensor suite, including water flow, voltage, and current sensors, enabling real-time performance monitoring via the Blynk mobile platform. The novelty of this work lies in the integration of a fully portable form factor with IoT-based real-time monitoring, allowing rapid field deployment and performance evaluation without permanent infrastructure, which distinguishes it from conventional fixed micro-hydro systems. Field evaluation conducted over a 30-minute period indicates that the voltage and current generally increase with operating time, reaching peak values of 10.03 V and 22.29 mA at the 25-minute mark, corresponding to a maximum power output of 224 mW. The observed trends suggest stable energy generation under natural river flow conditions, with minor variations attributed to environmental factors such as flow fluctuations. Overall, the results demonstrate the practical feasibility of the proposed system as a portable off-grid energy solution for rural, outdoor, and emergency applications.

1. INTRODUCTION

For a long time, hydroelectric systems have been acknowledged as one of the most sustainable and dependable methods of electricity generation. The kinetic energy of flowing water is converted into electrical power by these systems, which harness a natural resource abundant in many regions of the globe. Hydroelectricity is not only a renewable energy source but also has a minimal environmental impact compared to fossil fuel-based power generation¹. Traditionally, large-scale hydroelectric turbines have been a fundamental component of renewable energy for decades, supplying electricity to millions of individuals worldwide^{2,3}. Nevertheless, due to the increasing demand for sustainable energy solutions and

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technological advancements, smaller, more portable hydroelectric systems are becoming viable alternatives for specific user groups, particularly those in remote regions with restricted access to conventional power infrastructures.

The Internet of Things (IoT) and ESP32 microcontroller offer a simple yet powerful platform for developing small-scale projects that connect sensors and devices to monitor and control real-world environments^{4,5}. Significant advancements can be achieved in the monitoring and optimisation of environmental factors that are essential for the production of sustainable and efficient energy through the integration of IoT technology, including hydroelectric systems⁶. The increasing necessity to resolve energy challenges encountered by specific user groups, particularly those who reside in rural areas or participate in outdoor activities such as camping and trekking, has led to the development and optimisation of an IoT-based hydroelectric generator system⁷. The powering of essential devices is frequently a challenge for these groups due to their lack of access to traditional electrical sources. The inefficiency of conventional solar power systems is a significant obstacle in rural areas, particularly those with dense forest canopies. In these environments, solar energy is less reliable due to the limited exposure to sunlight, which results in the absence of a reliable power source for individuals who depend on portable electronics, such as phones or navigation devices. This concern is especially important for rural villagers, travellers, and campers who require a consistent and dependable electricity source to recharge their devices in rural areas.

Recent improvements in hydroelectric energy systems emphasise resource optimisation, economical designs, and energy conversion techniques. Sani et al. created an economical hydropower generator using locally procured materials for rural regions with restricted electrical availability⁸. Their methodology incorporates a straightforward turbine system that facilitates maintenance, with the objective of mitigating energy poverty through a sustainable, renewable energy source designed for distant areas. Hydroelectric power remains a sustainable energy source, particularly in off-grid rural areas. Several studies have explored different hydroelectric system designs, focusing on efficiency improvements, micro-hydro applications, and energy harvesting from small-scale water resources. Nonetheless, although current hydroelectric systems have achieved notable improvements in efficiency and design, numerous solutions remain unfeasible for portable, off-grid applications. There remains a demand for compact, deployable, and intelligent hydroelectric systems that can be effortlessly implemented in natural water bodies without necessitating permanent infrastructure. This study develops a fully portable and lightweight prototype for rapid field deployment in natural water bodies, enabling users to generate power without permanent infrastructure, unlike typical fixed micro-hydro systems.

1.1 Literature review

Renewable energy and hydroelectric power generation have gained increasing attention in recent years due to the global demand for sustainable and environmentally friendly solutions. Various studies have explored innovative approaches to harnessing hydropower, optimising energy management, and mitigating environmental impacts. This review critically examines recent research on pico-hydro systems, run-of-river (RoR) hydroelectric plants, real-time energy monitoring, and water quality monitoring, highlighting key findings and identifying existing research gaps.

Pico-hydro power generation is a promising solution for small-scale renewable energy applications. Azuddin et al. proposed a pico-hydro generating system integrated with a Smart Energy Storage Battery Management System (SES- BMS) for household use⁹. The system efficiently converts domestic water flow into electricity, achieving an output of 68 mW at a flow rate of $0.075 \times 10^{-3} \text{ m}^3 \text{ s}^{-1}$. While the study demonstrates the feasibility of domestic pico-hydro energy, it does not address scalability challenges or explore alternative turbine designs that could enhance efficiency. Similarly, Delante et al. investigated the energy potential of an irrigation-based pico-hydro system utilising an under-shot waterwheel¹⁰. The research demonstrated a stable power output of 4.35 W, appropriate for low-energy applications like street lighting. Nevertheless, they exhibit deficiencies in portability and modularity, rendering them less appropriate for those in rural regions, campers, or hikers who require lightweight, easily installable systems. Moreover, seasonal and environmental fluctuations, including variable river flow and sediment deposition, have not been adequately considered, which is essential for systems intended for unpredictable outside environments.

The optimisation of hydroelectric power in large-scale and RoR systems has been a significant area of research. Gómez-Beas et al. utilised a stochastic Bayesian model to examine flow variability in run-of-river hydroelectric facilities, revealing that tiny water storage reservoirs (3–30 days) markedly improve operational reliability, particularly in arid months¹¹. Notwithstanding these findings, the study fails to evaluate the financial and environmental viability of

deploying such storage options. Özalp and Özay investigated the effects of successive RoR hydroelectric facilities on water quality in Türkiye's Kabaca Stream, noting a considerable rise in total dissolved solids (TDS) and a marked decrease in dissolved oxygen (DO)¹². The report emphasises the environmental repercussions of RoR projects but fails to suggest viable mitigation techniques to reduce ecological harm. Most studies resemble this one, as they concentrate on large-scale uses and fail to offer insights into the adaptation of these technologies for personal or home use. Environmental impact assessments in RoR studies identify concerns such as sediment disruption and water quality deterioration; yet, they fail to investigate methods for developing low-impact mini-hydro systems that can operate sustainably within natural river ecosystems without significant infrastructure alterations.

The optimisation of hydropower dispatch and the integration of IoT-based monitoring systems have both been thoroughly investigated. Filho et al. proposed a real-time dispatch approach for multi-unit hydroelectric facilities, utilising AC optimum power flow (ACPF) modelling to reduce transmission losses¹³. The method resulted in a 5% decrease in energy loss; nevertheless, the model's computational complexity restricts real-time application. Nuri et al. presented the Hydro Quality Monitoring System (HydroQS) to evaluate real-time water quality indicators, including pH, turbidity, and dissolved oxygen, in the Melaka River¹⁴. The technology offers a cost-efficient substitute for conventional water testing; however, it has not been validated for industrial pollution and severe weather conditions. In another study, Rozali et al. develop a miniature hydroelectric generator using a vortex turbine and microcontroller-based monitoring system, optimising basin materials and outlet radii to enhance voltage generation efficiency. The results indicate that aluminium and PVC provide the best stability, with a 100 mm outlet radius yielding the highest voltage of 5.8 V¹⁵. However, the study lacks real-world deployment, long-term durability testing, and a detailed performance comparison with existing small-scale hydro systems.

Current IoT-based monitoring and energy optimisation systems prioritise smart grid integration and backup energy supply; however, these solutions are often intended for fixed installations rather than portable or standalone units. The real-time water quality monitoring system demonstrates the capability for ongoing evaluation of river conditions; however, its implementation currently confined to fixed monitoring stations instead of being incorporated into mobile hydroelectric systems that could deliver both energy and water quality information to off-grid users¹⁶. Notwithstanding progress in hydroelectric technology, portable and small-scale hydroelectric devices for off-grid applications remain inadequately developed. The majority of current hydroelectric systems are intended for permanent installations and are not tailored for users who need portability, such as campers, hikers, and rural populations with restricted access to the power grid. Furthermore, solar energy is inconsistent in shaded areas, especially in deep forests or isolated regions, rendering hydroelectricity a feasible option¹⁷. Moreover, numerous systems lack the integration with intelligent technologies for real-time monitoring, which constrains their effectiveness in variable outdoor environments.

Existing studies on micro-hydro and IoT-based energy systems predominantly focus on fixed, site-specific installations, with limited emphasis on portability, rapid deployment, and operation in shaded or forested environments where solar energy is unreliable¹⁷. This gap is particularly significant for rural electrification, outdoor expeditions, and emergency response scenarios, where quick installation and stable off-grid power are essential¹⁸. The proposed portable IoT-enabled hydroelectric generator addresses this gap by combining lightweight design, ease of deployment, and real-time monitoring, enabling power generation in locations unsuitable for permanent infrastructure. The adaptability of this solution has the potential to impact industries by supporting disaster relief operations, temporary construction sites, and rural electrification projects, where conventional power sources are either impractical or cost-prohibitive. This research seeks to overcome these deficiencies by developing a small, portable IoT-enabled hydropower generator that may function as a dependable power source for off-grid and emergency situations. It also presents important advances, including the integration of an ESP32-based real-time monitoring system that offers Wi-Fi/Bluetooth connectivity and cloud-based tracking via the Blynk platform. The system also incorporates a lightweight, and deployable hydropower architecture, facilitating rapid installation in natural watercourses without requiring permanent infrastructure.

2. METHOD AND MATERIALS

This study focuses on the development and validation of a portable IoT-enabled hydroelectric generator, designed for off-grid applications in rural and outdoor settings. The system harnesses river water flow to generate electricity and integrates real-time monitoring capabilities for to track performance.

2.1 System development and hardware integration

Fig. 1 shows the block diagram of the system, emphasising the seamless integration of an ESP32 microcontroller with a micro turbine generator and a current sensor as input components, in conjunction with an LCD display and the Blynk mobile application as output interfaces. ESP32 was selected over conventional Arduino-based implementations due to its higher processing power, built-in Wi-Fi/Bluetooth connectivity, and lower power consumption, making it more efficient for continuous energy monitoring in remote settings. The water flow sensor is integrated to monitor hydrodynamic conditions, allowing for real-time tracking of turbine efficiency varying river flow rates. This feature is crucial for ensuring stable and uninterrupted energy generation, especially in outdoor environments where water velocity fluctuations can impact power output.

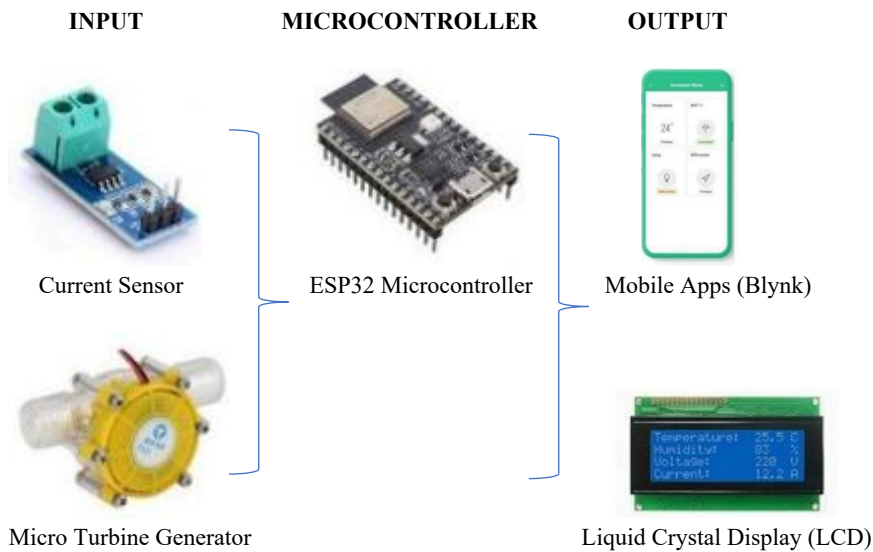


Fig. 1. Block diagram of IoT-based hydroelectric generator

Source: Author's own data

The micro hydro turbine generator used in this study has a rated output of 12 V DC at a nominal flow rate of 25 L min⁻¹, with a maximum rated power of 10 W under optimal conditions. The turbine's impeller diameter is 60 mm, housed in a compact PVC casing suitable for portable applications. During the field test at Alur Lempah, the estimated flow rate was approximately 22 L min⁻¹ with a measured hydraulic head of 0.35 m at the inlet point. These parameters were selected to match the portable and low-head operational design, ensuring compatibility with small natural streams and rivers.

Meanwhile, Fig. 2 illustrates the system's functionality. Upon activation, the ESP32 processes input data from the voltage and current sensors, computes power output, and transmits the results to both the LCD display and the Blynk application. The Blynk interface provides remote accessibility, allowing users to monitor power generation via mobile devices or web-based platforms. This IoT-enabled approach enhances usability and enables real-time decision-making, enabling users to efficiently track and optimise energy output. This combination of hardware and software exemplifies a remarkably efficient and user-centric methodology for real-time energy monitoring.

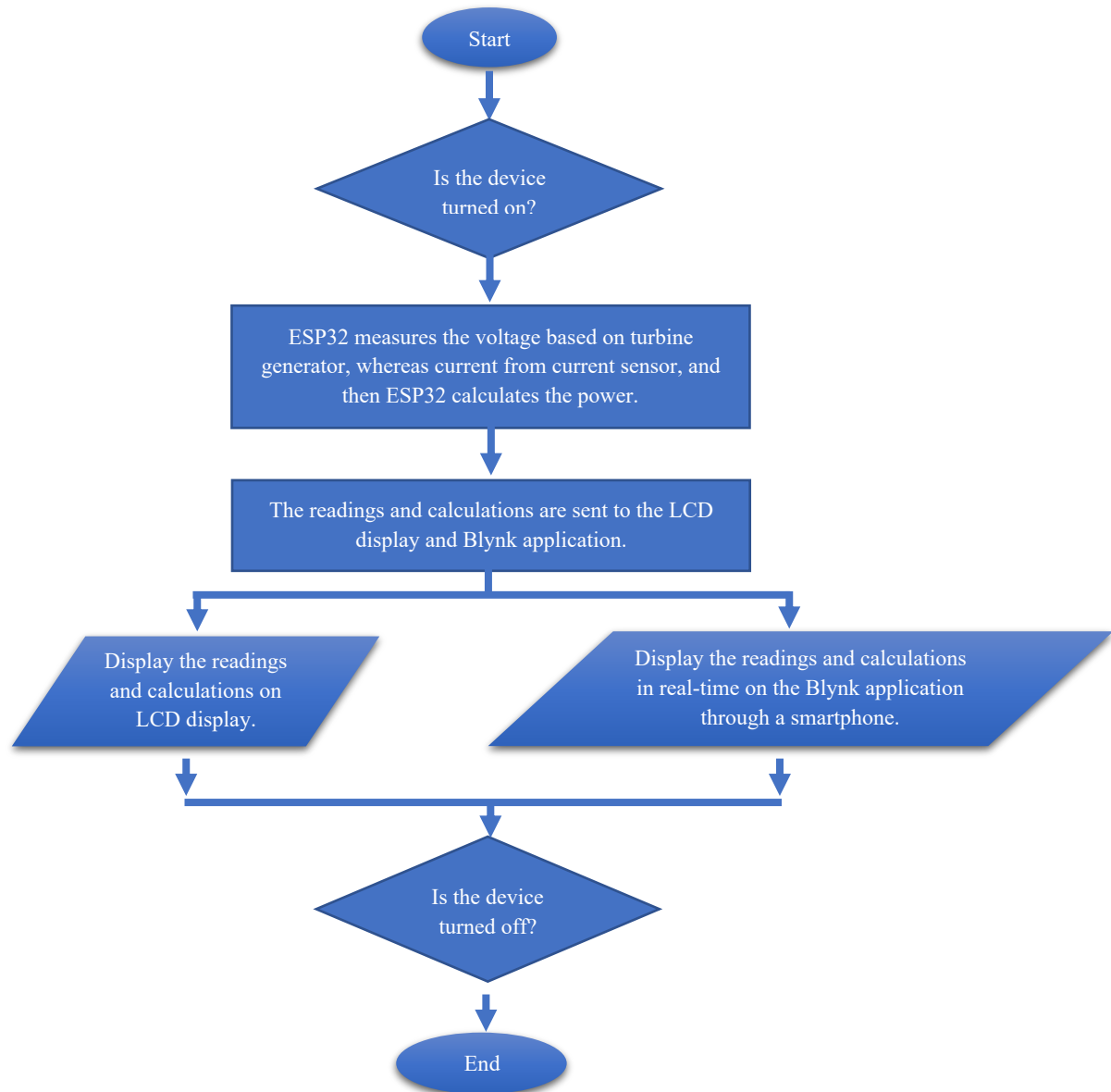


Fig. 2. Flowchart of the prototype system

Source: Author's own data

2.2 Software development and monitoring platform

The software development for this project includes programming the ESP32 microcontroller to gather real-time data from sensors, compute power output, and transmit the results to both the LCD display and the Blynk cloud platform. Fig. 3 shows the Blynk interface, available via a mobile application (left) and a web-based dashboard (right), providing a user-friendly monitoring platform. Both interfaces present essential performance parameters, including voltage, current, and power production, accompanied by relevant graphs, allowing users to effortlessly monitor and optimise system performance from their chosen device.

Unlike previous small-scale hydroelectric systems that only logged data locally, this study implements real-time cloud-based monitoring, enabling remote tracking of energy production trends. This enhances accessibility and usability, making it more practical for rural users, outdoor enthusiasts, and emergency situations where real-time energy tracking is necessary. Future work can explore data logging and predictive analytics, using historical trends to further optimise turbine performance dynamically.

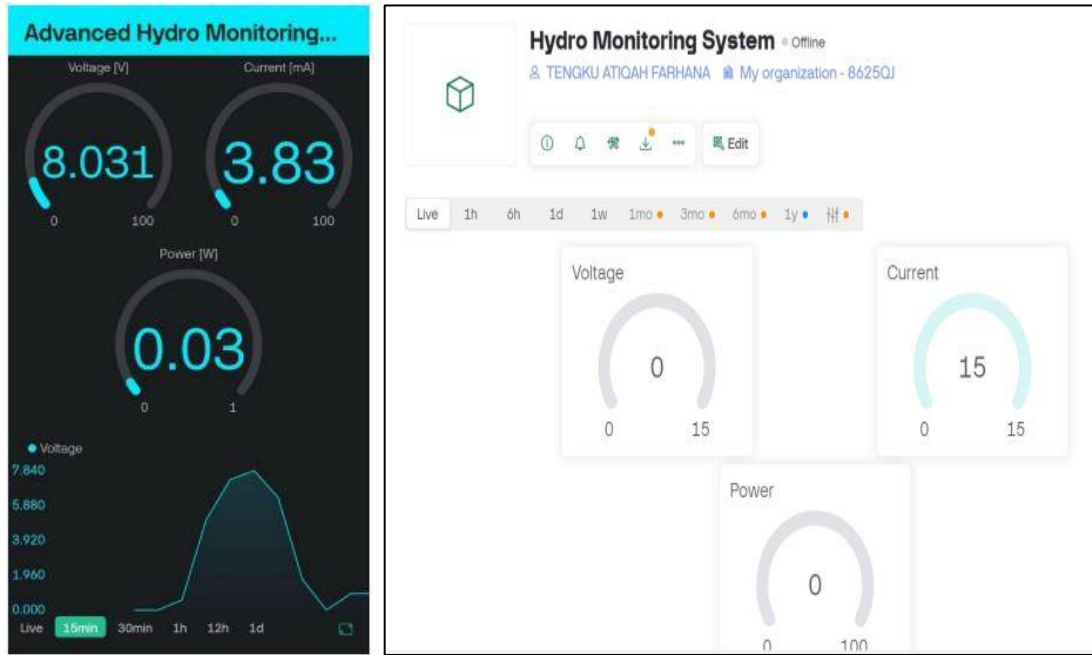


Fig. 3. (left) Blynk interface at mobile application; (right) web-based application

Source: Author's own data

2.3 Field deployment and testing configuration

The IoT-enabled hydropower generator features a cohesive design that highlights its internal and external attributes. The internal configuration depicted in Fig. 4 (left) illustrates the inside compact arrangement of key components, with the ESP32 microcontroller as the primary processing unit and a current sensor for measuring electrical current. This effective configuration guarantees portability and versatility for field use. The outside system features an LCD display for real-time monitoring of essential parameters and a light bulb to demonstrate realistic electricity generation, as illustrated in Fig. 4 (right). The external design prioritises usability and functionality, seamlessly integrating renewable energy utilisation with user-friendly operation.

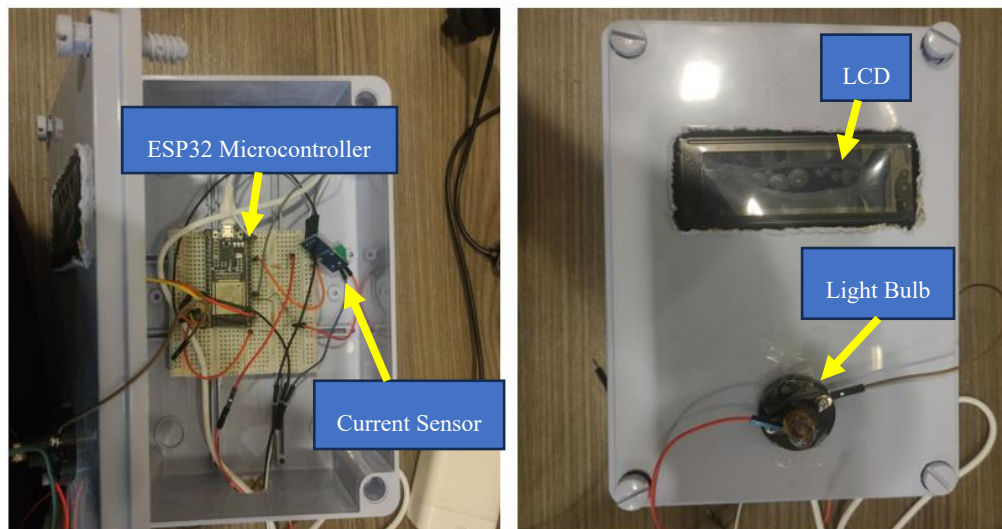


Fig. 4. (left) IoT hydroelectric generator configuration from inside; (right) view from outside of the IoT box

Source: Author's own data

The IoT-enabled hydroelectric generator was deployed at Alur Lempah, a tributary of the Selangor River, Malaysia, for real-world performance testing. Unlike laboratory setups, this field evaluation exposed the system to natural water flow conditions, allowing an accurate assessment of system stability, environmental adaptability, and energy conversion efficiency. The micro hydro turbine generator was positioned within a controlled water flow path using PVC pipes and hoses, as shown in Fig. 5. This setup enabled better flow direction management, optimising power output while ensuring stable operation even under fluctuating river conditions. The ESP32 continuously processed real-time sensor data, computing power output variations over a 30-minute period. Testing also evaluated the system's resilience to environmental challenges, such as changes in water velocity and minor debris accumulation, ensuring practical feasibility for real-world deployment.

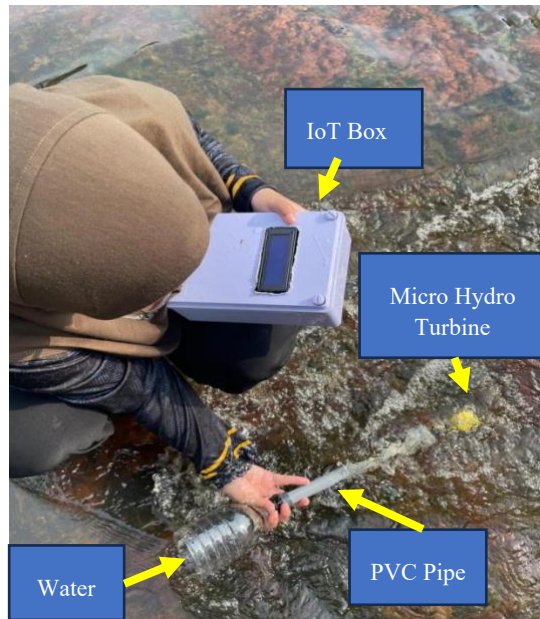


Fig. 5. Setup of IoT-enabled micro hydro turbine generator at Selangor River

Source: Author's own data

3. RESULTS AND DISCUSSION

The performance of the IoT-enabled hydroelectric generator was evaluated by measuring voltage, current, and power output over a 30-minute test period. The results provide insights into the stability and reliability of the system under natural river conditions, highlighting its potential for off-grid energy solutions

3.1. Voltage and current trends

Fig. 6 (left) illustrates the temporal voltage trend, commencing at 5.11 V and progressively ascending to 10.03 V at 25 minutes, then a slight decline to 9.18 V at the 30-minute interval. This trend indicates that the generator effectively converts water flow into electrical energy, achieving stability as the turbine attains ideal speed. The tiny voltage drop at the end may be ascribed to slight fluctuations in river flow or augmented electrical resistance over time. Fig. 6 (right) similarly depicts the prevailing tendencies, exhibiting a proportionate pattern that ascends from 7.05 mA to 22.29 mA at minutes then declines to 17.13 mA. The stable voltage-current connection illustrates system efficiency, with energy conversion according to Ohm's Law, which asserts that voltage is precisely proportional to current when resistance is constant. The marginal decrease in voltage and current at the conclusion of the test suggests that external factors, such as water turbulence or modest debris accumulation, may have temporarily impacted turbine performance. Optimising turbine blade design or implementing self-cleaning technologies could improve operational consistency during prolonged outdoor deployments.

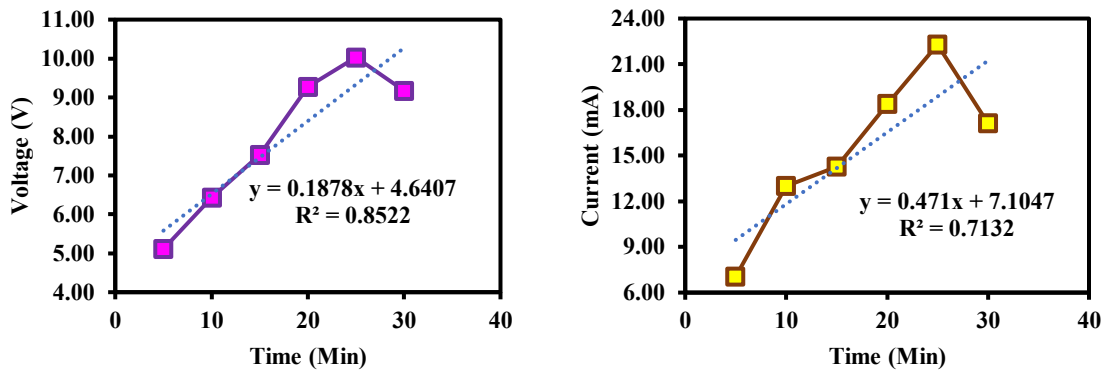


Fig. 6. (left) Voltage measurement over 30 minutes; (right) current measurement over 30 minutes

Source: Author's own data

3.2 Power output and system performance

According to Fig. 7, power generation trends show that the system's power output increases steadily, peaking at 224 mW at 25 minutes and then declining slightly to 157 mW at 30 minutes. This variance may result from dynamic water flow changes or slight inefficiencies in energy conversion as the turbine adjusts to actual flow conditions. Moreover, Fig. 8 also illustrates the system's performance, with an R^2 value of 0.7492 signifying that roughly 74.92% of the variance in power production is attributable to the time factor. The results suggest a positive relationship between time and power generation, demonstrating that the system's power output often rises as testing advances. Nonetheless, the remaining 25% indicates that additional factors, such as variations in water flow or system resistance, may have affected the results and overall performance. This pattern illustrates the system's potential to provide escalating power as the water flow stabilises. The noted decline in power at the 30-minute interval indicates possible external influences on performance, underscoring the need for further tuning to achieve more consistent and stable output. Although the system operates effectively throughout most of the testing phase, rectifying the noted irregularities could enhance its performance, thereby increasing reliability in practical applications. These insights are crucial for optimising the system's architecture and improving its overall efficacy as a renewable energy option.

The proportionality between voltage and current is a critical indicator of the system's efficiency, confirming the linear relationship between these two variables. The system's performance demonstrates that as water flow stabilises, both current and voltage rise simultaneously, which is crucial for maintaining consistent energy generation in hydroelectric systems. Both trends adhere to Ohm's Law, which asserts that voltage is directly proportional to current when resistance is constant¹⁹. When the water flow reaches equilibrium, the system operates optimally, converting available energy into voltage output with minimal losses. The clear linearity observed in both figures highlights the system's stability, since voltage and current increase appropriately with time.

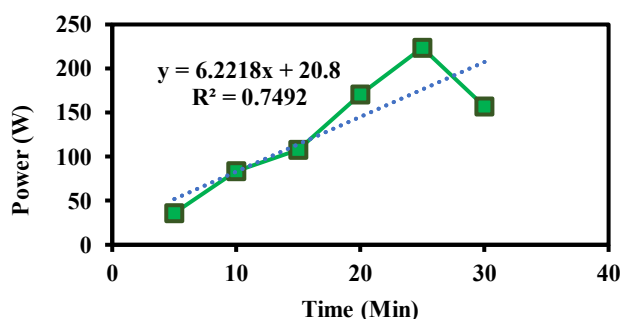


Fig. 7. Power generated from the prototype. Temperature influence on energy generation

Source: Author's own data

Fig. 8 depicts the relationship between power output (W) and water temperature (°C) over a 30-minute duration during the functioning of the IoT-based hydroelectric generator. The temperature was measured using a commercial test pen capable of recording five different parameters, including temperature. The blue line shows power output, while the orange line shows river water temperature. Power production rises steadily, reaching a peak of roughly 224 mW at the 25-minute mark, then declines slightly towards the end. The water temperature varies slightly between 28.9 °C and 29.7 °C, with a maximum recorded around the 25-minute mark. The alignment of peaks suggests a possible association between temperature and power production; however, the effect appears indirect and constrained by the narrow range of temperature variation.

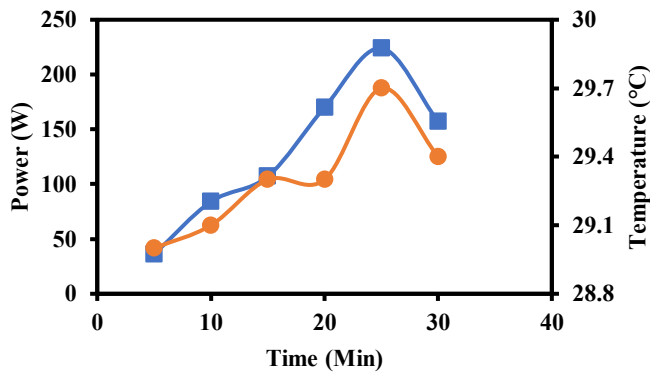


Fig. 8. Correlation between power output and water temperature over time

Source: Author's own data

The observed alignment between the peaks in water temperature and power output suggests a possible association; however, this relationship is more likely indirect given the narrow temperature range recorded (28.9 °C – 29.7 °C). From a physical standpoint, water temperature can influence flow dynamics by altering viscosity and density. Slightly higher temperatures reduce viscosity, allowing water to flow more freely and potentially improving turbine rotation efficiency²⁰. Conversely, elevated temperatures may marginally lower water density, thereby reducing the energy available for conversion. In the context of this prototype test, the limited temperature variation likely had minimal direct impact on energy generation. The observed timing of maximum power coinciding with peak temperature is more plausibly linked to stabilised water flow conditions rather than a direct causal effect of temperature. This interpretation aligns with the short-term nature of the test and the stable environmental conditions during deployment.

During testing, the estimated flow rate was approximately 22 L min⁻¹ with a measured hydraulic head of 0.35 m at the turbine inlet, under stable weather conditions and moderate river flow. These conditions represent small rivers and streams in rural Malaysia, ensuring relevance to real-world deployment scenarios. While the prototype demonstrated stable performance in this setting, the system's modular architecture offers potential scalability. For example, larger turbine units or multiple generators in parallel could be deployed to increase total power output while maintaining portability. Such configurations could broaden the application scope from powering small electronics to supporting higher-demand loads, such as portable lighting systems or small community water pumps, without compromising the ease of transport and installation.

Power generation can be indirectly influenced by temperature through the dynamic changes in water flow. Elevated water temperatures decrease viscosity and density, potentially enhancing flow efficiency in some instances. Nevertheless, elevated water temperature may enhance evaporation, hence diminishing total flow volume over prolonged durations. The tiny temperature fluctuations in this experiment likely had an insignificant effect on the flow rate, as demonstrated by the steady power generation trend until the minor decline at the conclusion. This reduction may be ascribed to alterations in flow stability or resistance within the system, rather than the noted temperature fluctuations. The graph highlights the significance of sustaining stable water temperature and flow for reliable energy production. The narrow temperature range in this test produced little obvious impact; nevertheless, substantial temperature variations in natural settings may influence flow characteristics and energy conversion efficiency. Additional research

encompassing a broader range of temperature fluctuations and their direct effects on flow and turbine efficiency may yield better understanding on temperature influence in hydroelectric energy systems

4. CONCLUSION

This research effectively developed and assessed a portable IoT-enabled hydropower generator, intended to supply renewable energy for off-grid applications in rural and outdoor environments. The system utilised river water flow to produce consistent power output, incorporating real-time monitoring via an ESP32 microcontroller and the Blynk platform. The field test confirmed that the system achieved a maximum power output of 224 mW at 25 minutes, substantiating its viability for small-scale energy applications, including charging low-power devices at distant locations.

Nonetheless, the system has several limitations that offer opportunities for future enhancements. The system initially encountered swings in power output, potentially due to changes in river flow rate. This indicates a necessity for adaptive turbine control systems to improve stability and ensure constant energy production under variable conditions. Furthermore, the existing design lacks an energy storage mechanism, such as a battery, capable of retaining surplus energy for subsequent utilisation during periods of diminished water flow or nocturnal hours. The system's usefulness is limited to real-time power utilisation in the absence of energy storage.

Moreover, although the system demonstrated reliability in short-term evaluations, its long-term endurance in actual environmental settings has yet to be investigated. Subsequent research should focus on enhancing the system's robustness to environmental factors, including debris accumulation, sediment deposition, and severe weather events. Integrating self-cleaning turbine blades and durable housing materials may enhance its operational longevity and dependability. Rectifying these restrictions will enhance the system's viability as a sustainable, portable, and versatile renewable energy source for many off-grid applications

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6. CONFLICT OF INTEREST STATEMENT

The authors agree that this research was conducted in the absence of any self-benefits, commercial or financial conflicts and declare the absence of conflicting interests with the funders.

7. AUTHORS' CONTRIBUTIONS

Conceptualisation: A.M Markom

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Methodology: T.A.F. Tengku Azlan Shah, A.M Markom

Formal analysis: T.A.F. Tengku Azlan Shah

Visualisation: T.A.F. Tengku Azlan Shah & A.M Markom

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Supervision: A.M Markom

Funding acquisition: Not applicable

Project administration: Y. Yusof

8. DECLARATION OF GENERATIVE AI IN THE WRITING PROCESS

During the preparation of this work, the author(s) used ChatGPT to improve the clarity and language of the manuscript. After using this tool, the author(s) reviewed and edited the content as needed and take full responsibility for the content of the publication.

9. DATA AVAILABILITY/SUPPLEMENTARY MATERIALS

All data generated or analysed during this study are included in this published article.

10. ETHICS STATEMENT

The authors declare that this research did not involve human or animal subjects. All experimental procedures were performed following the institutional Safety, Health, and Environmental (HSE) protocols of Universiti Teknologi MARA (UiTM).

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