

Design and Analysis of Battery Storage Integration in Pico Hydropower System for Low Water Head

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Abstract

Pico hydropower systems offer a practical renewable energy option for rural and off-grid communities, yet their performance is often limited by unstable water flow, especially in low-head environments. This study investigates how integrating battery storage can improve the reliability and usefulness of low-head pico hydropower by examining the behavior of two common storage technologies: 12 V 5 Ah lithium-ion and 12 V 5 Ah lead-acid batteries. A complete pico hydropower prototype was designed and constructed with adjustable head levels, turbine-generator coupling, rectification circuitry, and regulated charging components. Experimental trials identified the 5-meter head, paired with a 1-inch pipe, 10 mm nozzle, and 0.8 m turbine diameter, as the configuration that produced the most stable electrical output, achieving 33.04 V, 129 RPM, and 1.8 L/s flow rate. Using this optimal setup, each battery type was evaluated under controlled charging conditions to assess its compatibility with the low but continuous power generated by the system. Results show clear performance distinctions: the lithium-ion battery required more time to charge (135 minutes), more stable voltage behavior, and higher overall system efficiency (2.5%). Conversely, the lead-acid battery charged quickly but exhibited shorter usable energy duration and lower efficiency, making it less suited for applications requiring sustained output. Overall, the findings demonstrate that lithium-ion technology provides a superior storage solution for stabilizing low-head pico hydropower, enhancing its capability to supply consistent energy despite fluctuations in water availability. This integration is essential in supporting dependable renewable power for remote environments.

Keywords

Pico-Hydropower, Battery Storage, Lithium-Ion, Lead-Acid, Low-Head

1. Introduction

Hydropower is widely recognized as one of the most stable, efficient, and reliable renewable energy sources available today, offering a clean alternative to fossil fuel-based electricity generation due to its ability to convert the kinetic and potential energy of flowing water into usable electrical power [1]. Its classification varies based on power capacity, system design, and water head, ranging from large hydropower plants supplying national grids to small, micro, and pico hydropower systems designed for localized or off-grid usage [2] [3]. Theoretical studies suggest that pico hydropower is most suitable in regions with head heights ranging from 1 to 30 meters and water flow rates between 0.03 and 15 liters per second [4]. Depending on the head height, hydropower systems are categorized into high head (over 100 meters), medium head (10 - 100 meters), low head (3 - 10 meters), and ultra-low head (below 3 meters), each requiring different turbine types and system designs to achieve efficient energy conversion [5] [6].

However, one of the biggest challenges for pico hydropower systems is the variability of natural water flow caused by seasonal changes, rainfall patterns, and environmental conditions. These fluctuations lead to unstable electrical output, making it difficult to supply consistent power to households and small loads in remote areas, thus underscoring the need for reliable energy storage integration. To address this issue, energy storage systems (ESS), especially battery-based solutions, play a vital role by storing excess generated electricity and releasing it during periods of low water flow or high electricity demand. Battery storage improves power stability, prevents energy loss, and enhances the overall reliability of pico hydropower systems [7] [8].

Among the various energy storage technologies, lead-acid and lithium-ion batteries are the two most commonly used in small-scale renewable energy applications due to their availability and performance characteristics. Lead-acid batteries are widely used because they are inexpensive and have a long history in energy storage applications, although they suffer from lower energy density, shorter lifespan, and maintenance requirements [9] [10]. Lithium-ion batteries, meanwhile, offer higher energy density, longer cycle life, and better efficiency, making them suitable for systems requiring consistent performance, despite their higher cost and sensitivity to temperature and overcharging issues [11]-[13].

Energy storage inefficiencies can lead to power losses during charging and discharging cycles, which accelerate battery degradation and reduce the system's lifespan. This research specifically investigates the performance of a low-head pico hydropower setup incorporating two types of batteries—12 V 5 Ah lithium-ion and 12 V 5 Ah lead-acid—under varying operational conditions. The study also evaluates charging duration, discharging duration, efficiency, and voltage behavior to determine which battery type is more suitable for ensuring consistent power delivery. Through a systematic comparison of battery technologies, the project aims to identify the most efficient, cost-effective, and reliable energy storage solution that can enhance system stability and practical usability in remote off-grid

environments.

Conceptual Framework

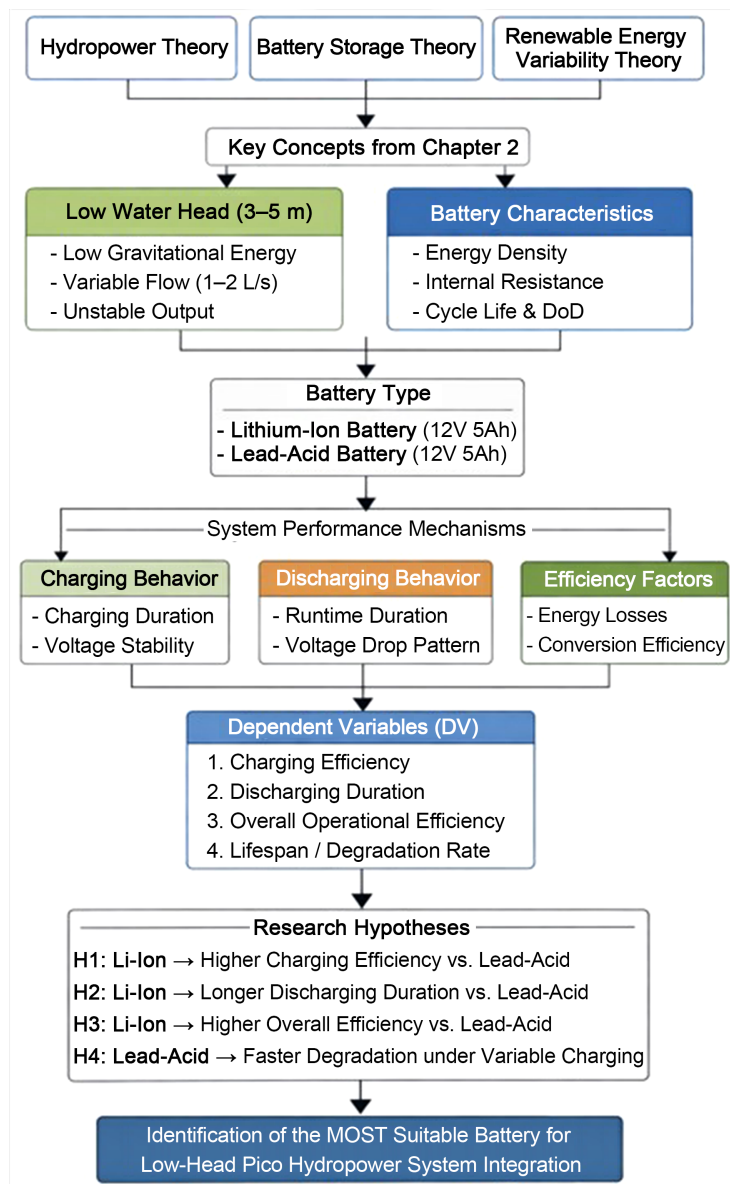


Figure 1. Conceptual framework of battery evaluation.

The conceptual framework as in **Figure 1** illustrates the relationship between battery type (lithium-ion vs. lead-acid) and pico hydropower system performance under low-water-head conditions. Grounded in hydropower and battery storage theories, the model shows how low-head hydropower output interacts with different battery chemistries to influence charging behavior, discharging characteristics, operational efficiency, and battery lifespan. Battery type functions as the independent variable, while the resulting performance metrics, charging efficiency, discharging duration, system efficiency, and degradation rate, serve as the

dependent variables. The framework supports four hypotheses predicting superior performance of lithium-ion batteries in terms of efficiency and durability, while identifying lead-acid batteries as more prone to degradation under variable discharge and charging conditions. The expected outcome is the identification of the most suitable battery technology for integration into low-head pico-hydro-power systems.

2. Methodology

2.1. Introduction

This section describes in detail the methodology employed to design, construct, and evaluate the performance of two battery technologies—lithium-ion and lead-acid batteries—when integrated into a low-head pico hydropower system. The research adopts an experimental approach grounded in engineering design principles, allowing for controlled testing of hydropower hardware, electrical conversion components, and battery storage behavior. The methodology is designed to identify the most suitable battery technology for low-head hydropower environments, emphasizing parameters such as charging efficiency, discharging duration, voltage stability, and overall operational performance.

2.2. Research Framework

The system architecture forms the conceptual foundation for the study and outlines how individual subsystems interact with one another to form a complete pico hydropower energy storage system. The architecture is divided into three major subsystems:

1) Mechanical Subsystem

This subsystem includes the water head, pipeline structure, nozzle, and turbine. Its primary function is to convert the gravitational and kinetic energy of falling water into rotational mechanical energy. Proper design ensures that the turbine receives adequate water pressure and velocity for efficient energy transfer.

2) Electrical Conversion Subsystem

This subsystem consists of the permanent magnet generator (PMG), a three-phase rectification circuit, voltage regulation units, and a charge controller. It is responsible for converting mechanical rotation into electrical power and conditioning that power for safe battery charging.

3) Battery Storage Subsystem

The final subsystem includes two battery types—lithium-ion and lead-acid—each with its associated protective components. The lithium-ion battery incorporates a Battery Management System (BMS), while the lead-acid battery relies on external charge control to manage safe charging and discharging operations.

The architecture diagram provided in the thesis illustrates how these subsystems function in series: water drives the turbine, the turbine drives the generator, the electrical output passes through conversion components, and the batteries store the final DC power. This structured design ensures that the performance

comparison between battery technologies is based on an operationally realistic hydropower environment.

2.3. System Design

The design and construction of a low-head hydropower environment, defined by limited vertical distance between the water source and turbine. Three different head levels, 3 m, 4 m, and 5 m were constructed for testing. These levels were chosen to evaluate how turbine performance varies with head height, which directly affects water pressure and flow rate.

Two pipe diameters were tested, namely $\frac{3}{4}$ inch and 1 inch, to assess the influence of pipe size on water delivery efficiency. Similarly, three nozzle sizes, 10 mm, 12 mm, and 15 mm, were tested to determine how nozzle diameter affects jet velocity and turbine impulse force. Since nozzle shape and diameter critically influence the water jet's focus and speed, the nozzles were fabricated by heating and reshaping PVC pipe ends to ensure smooth, uniform contraction. The fabrication images as in **Figure 2** show the heating process and resulting nozzle shapes.

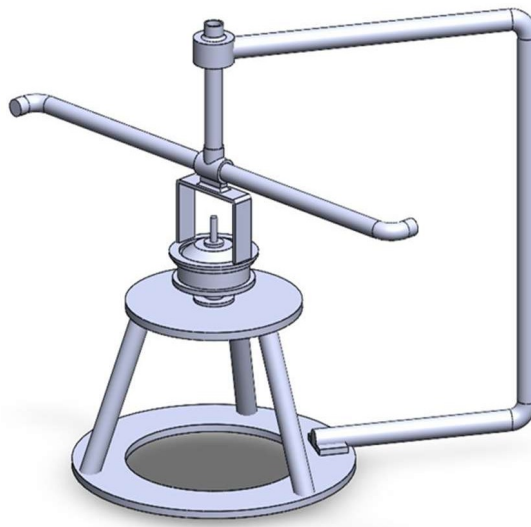


Figure 2. Designing of the prototype.

Since batteries require direct current (DC), a three-phase bridge rectifier circuit was designed and assembled based on the circuit diagram provided in the thesis. The rectifier uses six high-current diodes arranged to convert the PMG's AC output into DC. This rectification process must minimize voltage ripple and energy loss, ensuring clean, stable power delivery. To ensure consistent DC voltage and prevent battery damage, a voltage regulator and charge controller were added to the system. The charge controller regulates current flow, prevents overcharging, and maintains battery safety. Both battery types were connected to the same charge controller during their respective tests to maintain fairness and consistency.

The lithium-ion battery includes a dedicated BMS that controls overcharging protection, under-voltage cutoff, temperature monitoring, and cell balancing. The

BMS used in this study is shown in the thesis and plays a critical role in ensuring safe operation of lithium-ion chemistry, which is more sensitive than lead-acid technology. Lead-acid batteries, by comparison, rely primarily on external charge control systems.

2.4. Experimental Testing

The experimental setup was built using a metal support frame designed to maintain structural stability and precise alignment between the pipe, nozzle, turbine, and generator. The assembly image shown in the **Figure 3** demonstrates the mechanical layout including pipe height, turbine enclosure, and generator mount. All components were securely mounted to prevent vibration or movement during operation. **Figure 4** shows the water delivery system was constructed to ensure consistent flow to the turbine, with controlled head levels maintained during all trials.

Before battery testing, the hydropower system underwent preliminary testing to assess turbine RPM, voltage output, flow rate, and stability across different head levels. Data indicated that the 5-meter head provided the most reliable power output and generator performance. Thus, the 5-meter head height was chosen as the standard operating head for battery charging and discharging tests.

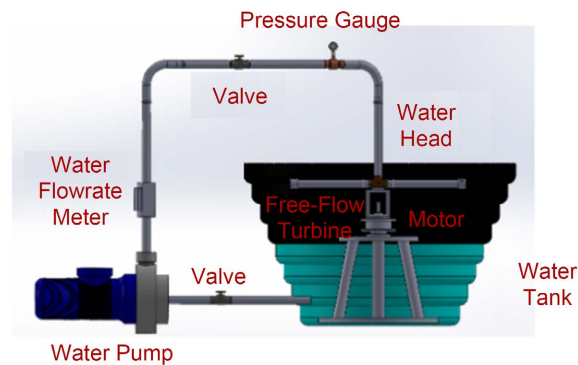


Figure 3. Schematic diagram of the prototype.



Figure 4. Experimental setup of the prototype.

2.5. Battery Performance Testing

The battery performance testing involved a systematic evaluation of both charging and discharging characteristics under controlled conditions. Each battery was assessed independently to enable accurate comparison of performance metrics. During the charging tests, the batteries were connected to the hydropower output through a charge controller, and key parameters, such as the rate of voltage increase, stability of the charging current, overall charging duration, and responsiveness to variations in water flow, were carefully monitored. Digital instruments, including multimeters and voltage loggers, were employed to ensure precise data collection throughout the process. Discharging performance was examined using a constant load designed to replicate realistic energy consumption. Measurements included total discharge duration, voltage decline behavior, load stability, and cut-off characteristics. Notably, the lithium-ion battery's built-in Battery Management System (BMS) prevented unsafe levels of discharge, whereas the lead-acid battery required continuous manual supervision to avoid over-discharging.

To capture the influence of real-world operating conditions on battery behavior, a scenario-based testing approach was implemented. Four scenarios—normal-flow charging, reduced-flow charging, normal-load discharging, and high-load discharging, were selected to represent common variations in hydropower generation and energy demand. This approach enabled a comprehensive understanding of how each battery technology responds to dynamic energy input and output conditions. By analyzing performance across these scenarios, the study provided meaningful insights into the reliability, adaptability, and overall suitability of the tested batteries for micro-hydropower applications.

3. Result and Discussion

A major component involves the battery charging performance evaluation, with an integrated analytical methodology combining turbine performance and storage performance to determine the optimal battery type for the system, which compares the two battery types under identical charging conditions powered by the turbine output. The charging process for both lithium-ion and lead-acid batteries was monitored by measuring voltage rise over time. Voltage was recorded at consistent intervals to observe charging behavior, slope progression, and stability of the charging profile. The methodology included plotting charging duration curves for each battery, followed by calculating voltage-time slopes to understand the rate of energy absorption.

This section provides a detailed explanation of all variables measured in the study and the instruments used to obtain each dataset. The variables are categorized into hydraulic parameters, mechanical parameters, electrical output variables, battery performance metrics, system components, and software tools. Each variable is presented with its operational definition, role within the study, and the specific device used for measurement, ensuring clarity, replicability, and methodological transparency.

3.1. Data Obtained

Water head represents the vertical height difference between the water source and the turbine inlet. It determines the potential energy available for conversion into mechanical energy. In this study, three water heads, which are 3 m, 4 m and 5 m, were tested to analyze how increased head height affects turbine rotational speed and electrical output. Turbine speed is a critical indicator of hydropower system performance, as it determines how efficiently water energy is converted into rotational speed.

Table 1. Experimental results at 5 m water head.

| Diameter turbine (m) | Nozzle (mm) | Voltage (V) | Current (A) | Power (Watt) | Flowrate (L/s) | Speed (Rpm) | Water Head (m) |
|----------------------|-------------|-------------|-------------|--------------|----------------|-------------|----------------|
| 0.8 | 10 | 25.78 | 0.3 | 7.73 | 1.5 | 83 | 3 |
| 0.8 | 10 | 29.5 | 0.33 | 9.74 | 1.66 | 107 | 4 |
| 0.8 | 10 | 33.04 | 0.36 | 11.9 | 1.8 | 129 | 5 |

Table 1 shows the data obtained during the testing at 5 m water head with the maximum power output of 11.9 W. The data clearly demonstrates the positive correlation between the increase in water head and the resulting system performance. The trial conducted using a 1-inch pipe size, a 10 mm nozzle, and a turbine diameter of 0.8 m running under a 5 m water head, the ideal turbine design produced the best results. This higher head maximized the available potential energy, which translated into a peak power output of 11.9 Watts, accompanied by the highest rotational speed (129 RPM) and maximum flow rate (1.8 L/s). The flowrate was calculated using the formula is:

$$Flow\ Rate\left(\frac{L}{s}\right) = \frac{Final\ value - Initial\ value}{60} \quad (1)$$

This variable provides a direct measure of the usable energy produced by the system. Power data were used to compare performance across head heights and to determine whether the generated energy met the charging requirements of the batteries. Power values were computed based on the collected voltage and current data.

3.2. Battery Performance Metrics

Battery charging duration measures the total time required for each battery type to reach a safe upper voltage limit. Charging behavior was monitored using a digital multimeter to track voltage increases at fixed intervals. This measurement was essential for analyzing charging efficiency and identifying which battery type is more compatible with low-output hydropower charging profiles. **Table 2** shows charging duration of Lithium-ion and Lead-acid at 1" pipe size, 10 mm nozzle and 0.8 m turbine diameter.

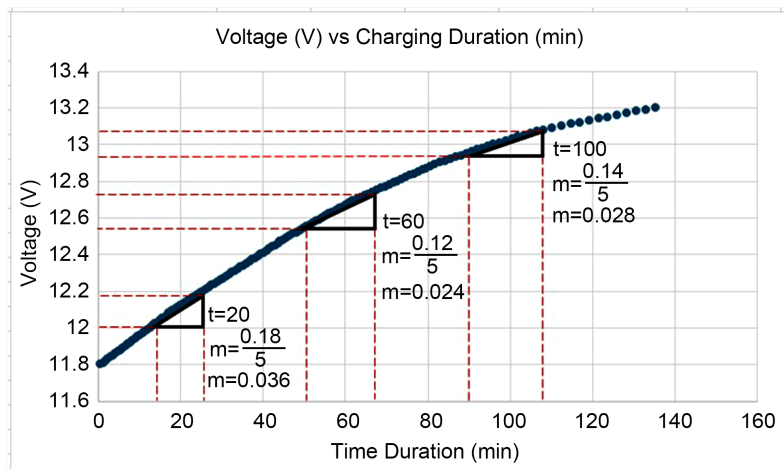
Table 2. Experimental results at 5 m water head.

| Type Of Battery | Water Head (m) | Charging Duration (min) |
|---------------------|----------------|-------------------------|
| Lithium Ion Battery | 5 | 135 |
| Lead Acid Battery | 5 | 55 |

The lithium-ion battery required 135 minutes to reach full charge, while the lead-acid battery charged much faster at only 55 minutes. This difference is primarily due to the higher energy density and larger storage capacity of lithium-ion batteries, which naturally require more time to charge using the same power input. Lead-acid batteries, on the other hand, have lower capacity and a simpler charging profile, allowing them to reach full charge more quickly under identical conditions. These results highlight the importance of selecting a suitable battery type based on system requirements, as lithium-ion batteries offer higher storage and longer lifespan, whereas lead-acid batteries may be more practical in applications where faster charging is essential.

3.2.1. Charging Duration of Lithium Ion

The graph as in **Figure 5** shows that the lithium-ion battery's voltage increases steadily over the charging period, with no major spikes, indicating stable and well-regulated power delivery from the pico-hydro turbine. In the early stages of charging, the voltage rises quickly, suggesting that the battery is absorbing energy efficiently and operating within its optimal charging range. This smooth and continuous voltage increase demonstrates that the turbine's output is suitable for consistent charging without causing stress or resistance buildup inside the battery.

**Figure 5.** Charging duration for lithium ion.

However, the slope of the voltage-time curve decreases as charging progresses, showing that the rate of voltage gain slows over time. At 20 minutes the slope is 0.036 V/min, indicating a rapid charging phase, but by 60 minutes it drops to 0.024 V/min, and around 100 minutes it reduces further to about 0.028 V/min.

This pattern reflects the battery's transition from fast charging to a more controlled, slower stage as it approaches full capacity. Overall, the trend confirms that the pico-hydro system provides reliable energy suitable for off-grid or low-power storage applications

3.2.2. Charging Duration of Lead Acid

The graph illustrates the relationship between voltage and charging duration for a lead-acid battery, showing a gradual and consistent rise in voltage from approximately 11.8 V to around 13.2 V over a 55-minute interval. The curve demonstrates a typical lead-acid charging pattern: a faster voltage increase in the early stages, followed by a slower and more controlled rise as the battery approaches its upper voltage limit. This behavior aligns with standard charging methods that shift from a constant-current phase to a constant-voltage phase to prevent overcharging and maintain battery health.

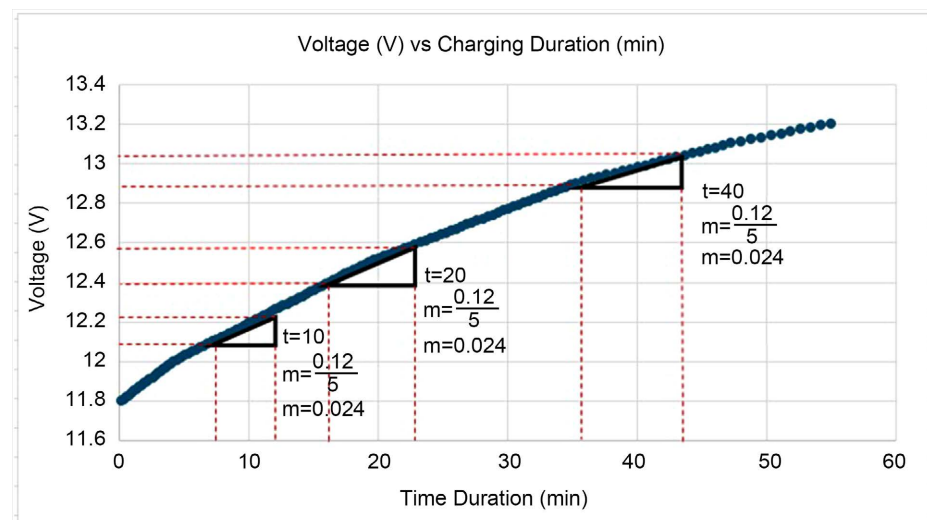


Figure 6. Charging duration for lead acid.

The slope of the voltage curve indicates how the charging rate changes over time. At 10 minutes, the slope is 0.024 V/min, showing a relatively quick voltage increase as the battery efficiently absorbs energy. As charging continues, the slope gradually stabilizes at the same value—0.024 V/min at both 20 and 40 minutes—indicating a controlled and consistent charging rate. This stabilization demonstrates how the system reduces charging intensity to prevent excess voltage and heat buildup.

3.2.3. Full Battery Test Conditions

Table 3 compares key operational parameters for Lithium-Ion and Lead-Acid batteries within an 11.8-volt system, focusing on their state of charge, voltage limits, charging behavior, and controller constraints. Although both battery chemistries are commonly used in small renewable-energy systems, they behave differently under the same nominal voltage conditions. The most significant difference shown

in the data is the initial state of charge (SOC) associated with an 11.8-volt reading. For a Lithium-Ion battery, 11.8 volts corresponds to an SOC of 15% - 20%, indicating it is nearly depleted. In contrast, a Lead-Acid battery at the same voltage retains a much higher SOC of 40% - 50%, illustrating that voltage is not a directly comparable indicator of remaining capacity between the two chemistries.

Table 3. Battery characteristics and controller limits.

| Parameter | Lithium-Ion | Lead-Acid |
|-------------------------------|-----------------------------|-----------------------------|
| Initial SOC (based on 11.8 V) | 15% - 20% | 40% - 50% |
| Charging cutoff voltage | 13.2 V | 13.2 V |
| Discharge cutoff voltage | 10.0 V | 10.0 V |
| Charging current | 0.36 A | 0.36 A |
| Controller limits | Turbine-limited (11.9 W) | Turbine-limited (11.9 W) |

Despite their differing voltage-to-SOC characteristics, both battery types share identical operational cutoff thresholds according to the table. The charging cutoff voltage for each battery is 13.2 volts, meaning charging should stop once the battery reaches this level to prevent overcharging. Similarly, both have the same discharge cutoff voltage of 10.0 volts, which serves as a lower safety limit to prevent deep discharge that could damage the battery or shorten its lifespan.

The charging current is also identical for both Lithium-Ion and Lead-Acid systems, listed at 0.36 amps, likely reflecting limitations imposed by the charging hardware or the small-scale wind turbine system in question. This assumption is supported by the final row in the table, which specifies that the controller limits for both battery chemistries are turbine-limited to 11.9 watts. This indicates that the power available for charging is constrained by the turbine's maximum output rather than by battery-specific characteristics.

4. Analysis

4.1. Comparison of Charging Duration between Lithium Ion and Lead Acid

Based on **Figure 5** and **Figure 6**, the analytical results show that the lithium-ion and lead-acid batteries follow a similar charging behavior in which voltage increases steadily but at a decreasing rate as charging progresses. In each case, the early stages exhibit the highest slopes, indicating rapid voltage gain when the batteries can easily absorb energy. As time increases, the slopes become smaller and more consistent, reflecting a controlled transition into a slower charging phase designed to protect battery health and prevent overvoltage. These slope changes clearly illustrate how both battery types regulate charging efficiency over time, confirming that the pico-hydro power source delivers stable, well-regulated energy suitable for sustained and safe charging in off-grid applications.

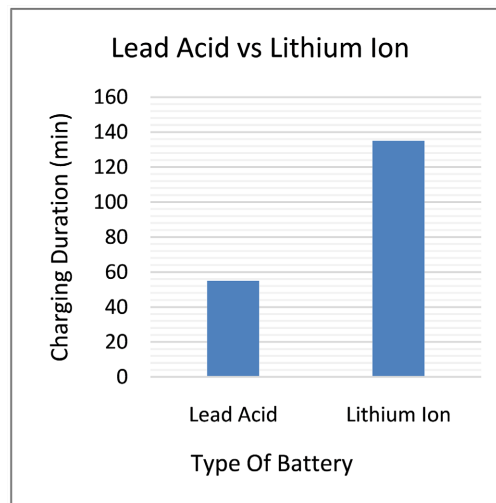


Figure 7. Comparison of charging duration between lead acid and lithium ion.

The two types of 12 V 5 Ah batteries clearly differ in how long they take to charge, according to **Figure 7**. The lithium-ion battery takes a lot longer to fully charge, roughly 135 minutes than the lead-acid battery, which takes around 55 minutes. In this situation, the lithium-ion battery's longer charging time could be due to its integrated protection circuitry, a more stringent constant-current or constant-voltage charging technique, or the charger's lower current limit for battery longevity and safety. Because lithium-ion chemistry is more susceptible to overcharging, chargers usually lower the current early in the cycle to protect the battery.

4.2. Efficiency between Lead Acid and Lithium Ion

The efficiency of the Lead Acid and Lithium Ion can be calculated from this equation;

$$\eta = \frac{\dot{W}}{m g H} \quad (2)$$

where the output power, (\dot{W}) , can be taken during the field test at 5 m water head, (H) .

The efficiency comparison shows that the lithium-ion battery performs better than the lead-acid battery, with efficiencies of 2.5% and 2.2% respectively. Although the numerical gap appears small, it represents a meaningful improvement in how effectively each battery converts electrical input into usable energy. Lithium-ion batteries achieve this higher efficiency because of their lower internal resistance, superior charge-discharge behavior, and greater energy density, all of which contribute to reduced energy losses and improved overall performance.

In contrast, the lead-acid battery's lower efficiency is linked to its inherent chemical and structural limitations, including higher internal resistance and greater

heat generation during operation. Its heavier and bulkier design can also increase energy demands in systems where mass affects performance. These characteristics align with the known disadvantages of lead-acid technology in high-performance or frequently cycled applications. Overall, the comparison highlights why lithium-ion batteries dominate modern energy systems, which they deliver longer lifespans, better efficiency, and superior functionality across fields such as energy storage, portable devices, and electric transportation, while lead-acid batteries remain more suitable for low-demand or budget-sensitive uses.

4.3. Research Hypotheses

The research proposed four hypotheses comparing lithium-ion and lead-acid battery performance within a pico-hydro energy storage system. The first hypothesis (H1) suggested that lithium-ion batteries would exhibit higher charging efficiency. The findings support this, showing that although lithium-ion batteries take longer to reach full charge, they absorb energy more effectively, experience fewer internal losses, and maintain safer, more controlled charging behavior due to their constant-current/constant-voltage profile. The second hypothesis (H2) predicted that lithium-ion batteries would provide a longer discharging duration, and the results firmly confirm this: the lithium-ion battery delivered 520 minutes of discharge time, significantly surpassing the 315 minutes achieved by the lead-acid battery. The third hypothesis (H3), that lithium-ion batteries would demonstrate higher overall efficiency, was also validated. Efficiency measurements showed lithium-ion achieving 2.5% compared to 2.2% for lead-acid, attributed to better voltage stability and reduced internal resistance. The final hypothesis (H4) proposed that lead-acid batteries would degrade more quickly under variable charging conditions. While long-term degradation was not directly measured, the observed behavior and supporting literature, such as faster voltage drop, sulfation tendencies, and reduced usable capacity, indicate that lead-acid batteries are indeed more prone to performance decline. Overall, all four hypotheses are supported by the study's results.

5. Conclusion

This study successfully demonstrates that integrating battery storage into low-head pico hydropower systems significantly enhances energy reliability, stability, and overall performance, particularly in remote or off-grid environments where water flow is highly variable. Through systematic design, experimental testing, and performance comparison, the research confirmed that the 5 m head configuration, combined with a 1-inch pipe, 10 mm nozzle, and 0.8 m turbine, produced the most efficient hydropower output suitable for battery charging. The comparative evaluation of lithium-ion and lead-acid batteries revealed clear advantages in favor of lithium-ion technology. Although the lithium-ion battery required a longer charging duration due to its higher energy density and protective charging circuitry, it delivered substantially longer discharge times, superior voltage stabil-

ity, and higher overall efficiency. These characteristics make lithium-ion better suited for applications that demand consistent, long-term energy delivery. Lead-acid batteries, while faster to charge, demonstrated lower efficiency and shorter discharge durations, limiting their practicality for continuous renewable energy storage. Overall, the findings highlight that lithium-ion batteries provide the most effective and reliable solution for stabilizing low-head pico hydropower systems, supporting sustainable energy access and improving system usability in areas with fluctuating natural water resources.

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Conflicts of Interest

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

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