Afropolitan Journals

ISSN: 3027-2114 www.afropolitanjournals.com

Development of a Hybridized Solar-Hydro Autonomous Power Generating System

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DOI: *https://doi.org/10.62154/ajesre.2025.021.01014*

Abstract

Reliable electricity supply in remote and off-grid communities is limited by the intermittency of single renewable sources, particularly solar-only systems that depend on daylight availability. This study presents the design, fabrication, and performance evaluation of a hybridized solar–hydro autonomous power generating system developed to provide stable, low-cost, and continuous energy for small office and residential applications. A load demand of 765 Wh/day was established and used to size the major components, including two 150 W photovoltaic panels, a 12 V 100 Ah lithium-ion battery, a Kaplan-type micro-hydro turbine, a DC water-circulation pump, and a 300 W pure-sine inverter. The system was designed to generate approximately 1224 Wh/day from the solar subsystem to account for inefficiencies, while the turbine was designed for an expected output of 128 W at a head of 1.5 m. Performance testing was conducted for seven consecutive days under real operating conditions. Results showed that the solar subsystem produced an average of 1180 Wh/day, representing 96% of the design target, while the battery operated with a usable efficiency of 92%. The hydro turbine delivered an average of 85 W at 82% efficiency, primarily limited by practical head conditions. The combined system consistently exceeded the daily load, achieving 100% uptime and an overall energy efficiency of 87.5%. The findings demonstrate that hybridization significantly improves reliability by compensating for solar variability and maintaining uninterrupted power delivery. Further enhancements in turbine design and automated control are recommended to improve long-term performance and scalability.

Keywords: Hybrid Power System, Solar Energy, Micro-Hydro Power, Renewable Energy, Off-Grid Electricity, Sustainable Power Supply.

Introduction

Access to reliable electricity remains a major challenge in developing regions, where more than 700 million people—mostly in rural communities—still lack stable power supply (International Energy Agency [IEA], 2022). Extending the national grid to such areas is often economically impractical due to high installation costs, sparse population distribution, and difficult terrain. Consequently, decentralized renewable energy systems have become essential for off-grid electrification, particularly solar and micro-hydropower, which are abundant and environmentally sustainable (Adeyinka et al., 2024; Datta et al., 2021).

Despite their potential, standalone renewable systems suffer from intermittency. Solar power fluctuates with weather and daylight availability, while micro-hydro output depends on flow rate and head conditions. These limitations lead to inconsistent power generation, reduced system reliability, and underutilization of installed capacity (Adelekan et al., 2024; England et al., 2017). Hybrid renewable systems—especially solar–hydro combinations—offer a promising solution by providing complementary energy generation: solar contributes during the day, while hydro supports nighttime or cloudy periods (Agrawal et al., 2022; Usman et al., 2024).
However, current literature reveals several gaps. Many hybrid system studies focus on large-scale plants or simulation-based performance analyses with limited real-world experimental validation. Small-scale hybrid prototypes designed for household or office applications are still under-represented. Additionally, some studies rely on idealized hydraulic assumptions and do not evaluate practical issues such as reduced head, pump-driven recirculation losses, or integration inefficiencies. Furthermore, inconsistent treatment of energy demand and inadequate methodological structure remain common shortcomings (Erdiwansyah et al., 2021; Engeland et al., 2017). These gaps highlight the need for experimentally validated, low-cost hybrid systems suitable for small daily loads in off-grid settings.

Problem Statement

Most autonomous renewable energy systems deployed in off-grid communities are unreliable because they depend on a single energy source whose output varies with environmental conditions. Solar-only systems experience power shortages at night or during prolonged cloud cover, while micro-hydro systems underperform when flow rate or head is insufficient. Existing hybrid systems in literature often lack experimental validation at small scale, exhibit inconsistent energy demand calculations, and rarely assess real-world constraints such as fluctuating water head, pump inefficiencies, and mechanical losses. There is therefore a need for a low-cost, experimentally validated hybrid solar–hydro system capable of providing stable power to small office or residential loads under realistic operating conditions.

Research Objectives

The primary objective of this study is to design, fabricate, and evaluate a hybridized solar–hydro autonomous power generating system capable of supplying a daily electrical load of 765 Wh. The specific objectives are to:

i. Determine and validate the electrical load requirement for a small office and use it for component sizing.
ii. Design and fabricate a hybrid solar–hydro prototype integrating PV modules, micro-hydro turbine, pump, battery storage, and inverter.

iii. Conduct engineering design analyses, including structural, mechanical, and energy performance calculations.
iv. Experimentally evaluate subsystem performance (solar, hydro, battery, and inverter) over a seven-day test period.
v. Compare measured results with design estimates, identify performance deviations, and propose system improvements.

Literature Review

Hybrid Renewable Energy Systems (Solar–Hydro)

Hybrid renewable systems combine two or more energy sources to increase reliability, reduce intermittency, and improve power quality. Solar–hydro hybridization is particularly effective because solar energy is available during the day while hydropower can provide continuous output if flow conditions are stable (Agrawal et al., 2022). Studies have shown that hybrid configurations reduce storage stress, maintain stable voltage levels, and improve overall efficiency in off-grid environments (Usman et al., 2024). According to Adeyinka et al. (2024), hybrid systems are increasingly being adopted in rural electrification due to their low environmental impact and improved resilience.
However, many works focus on medium and large-scale installations, with few addressing low-head or low-flow micro-hydro applications, which are essential for small autonomous systems. Additionally, several hybrid designs rely heavily on simulations rather than real-world prototype testing, resulting in limited experimental validation.

Micro-Hydro Systems: Turbine Design and Performance Models

Micro-hydropower systems convert the potential and kinetic energy of water into electricity through turbines such as Pelton, Francis, and Kaplan designs. Performance is strongly influenced by head, flow rate, and turbine geometry (Erdiwansyah et al., 2021). Low-head Kaplan turbines are commonly used in small-scale applications due to their ability to operate efficiently under limited flow conditions (Engeland et al., 2017). Theoretical output is typically estimated using hydraulic equations based on water density, gravitational acceleration, head, and discharge. However, practical installations frequently experience losses due to friction, turbulence, shaft misalignment, and generator inefficiencies. Recent studies highlight that real-world output often falls below theoretical predictions, especially in pump-driven recirculating systems where head fluctuations and pump losses are significant (Waziri et al., 2020).
A key gap in existing literature is the lack of experimental validation under reduced head conditions, as most models assume ideal hydraulic environments rarely found in off-grid micro-hydro settings.

Battery Storage and Inverter Systems in Hybrid Configurations

Energy storage systems stabilize hybrid renewable setups by buffering fluctuations from variable sources. Lithium-ion batteries dominate modern hybrid systems due to their high round-trip efficiency, long cycle life, and acceptable cost per kilowatt-hour (Datta et al., 2021). Effective sizing is essential to prevent over-cycling and ensure sufficient autonomy during periods of low solar radiation or reduced flow. Inverters also play a critical role in delivering usable AC power. High-efficiency inverters (≥90%) minimize conversion losses and maintain stable voltage and frequency output required for sensitive loads (Rahman et al., 2022).

While numerous studies provide performance data on individual storage and inverter components, fewer works address their integration within small solar-hydro systems, particularly with respect to real-time load matching, state-of-charge behavior, and loss distribution.

Autonomous Control and Sensor Integration in Hybrid Systems

Modern hybrid renewable systems increasingly incorporate autonomous control algorithms, sensors, and data acquisition tools for real-time monitoring and optimization. MEMS-based sensors and digital controllers enhance energy management by monitoring voltage, current, flow rate, rotational speed, and environmental conditions (Peura & Webster, 2020). Model Predictive Control (MPC) and adaptive control strategies have recently been used to optimize energy flow between sources, reduce battery stress, and maximize efficiency (Adegbenro & Olanrewaju, 2021). However, many small-scale prototypes still rely on manual controls or basic switching mechanisms, limiting system responsiveness and long-term reliability. A notable gap exists in literature concerning autonomous control for very small (<300 W) hybrid solar-hydro systems, especially those using pump-driven recirculation, where dynamic flow adjustments and real-time optimization are essential.

Identified Gaps and Justification for Current Study

The reviewed literature reveals several key gaps:

1. Limited experimental validation of small-scale hybrid solar-hydro systems; most studies rely on simulations.
2. Idealized hydraulic assumptions dominate existing micro-hydro models, with little attention to reduced head, fluctuating flow rate, or pump recirculation losses.
3. Lack of consistent load estimation methods, leading to inaccurate sizing of components in previous studies.
4. Insufficient evaluation of integrated subsystem behavior (solar, hydro, battery, inverter) in real operating conditions.
5. Minimal research on low-cost prototypes suitable for small offices, homes, and rural micro-applications.

6. Weak instrumentation and control design in many hybrid systems, limiting real-time optimization.

This study addresses these gaps by designing, fabricating, and experimentally validating a fully integrated small-scale hybrid solar–hydro system, evaluating its subsystem efficiencies, and comparing measured performance to design expectations under realistic operating conditions.

Materials and Methods

This section presents the structured methodology adopted in designing, fabricating, and experimentally evaluating the hybridized solar–hydro autonomous power generating system.

Study Design

The study followed an engineering research design involving:

- Load Assessment and System Requirement Definition
- Component Sizing and Energy Modeling
- Mechanical and Structural Design Analysis
- System Fabrication and Assembly
- Instrumentation and Data Acquisition Setup
- Experimental Testing Under Real Operating Conditions
- Data Analysis and Performance Evaluation

Load Analysis and Energy Requirement

A detailed load audit was conducted to determine the daily energy consumption for a small office. The power ratings and operational durations of all appliances were recorded.

Thus, 765 Wh/day is the confirmed design load and is used consistently throughout this chapter. Previous inconsistencies (1224 Wh/day and others) have been corrected.

To account for inefficiencies in charging, conversion, wiring, and system losses, a 20% buffer was applied:

(1) = 918Wh

This corrected and standardized value formed the basis for component sizing.

Component Sizing and Energy Modeling

Battery Capacity Design

A 12 V lithium-ion battery was selected based on energy requirement:

(2)

Where:

- is the battery capacity in amp-hours (Ah),
- is the required energy storage in watt-hours (Wh),
- is the battery voltage (12 V).

Substituting the values:

To ensure durability and prevent deep discharge, a **130 Ah lithium-ion battery** was selected.

Solar Photovoltaic Array Design

Solar panels must generate enough energy to meet the daily load plus system losses.
Assuming 75% system efficiency:

(3)

Where:

- is the energy that needs to be generated by the solar panels in watt-hours (Wh/day),

Table 1: Daily Load Assessment

Device	Rating (W)	Daily Usage (h)	Energy (Wh/day)
Laptop	60	8	480
Printer	50	2	100
LED Bulb	5	5	25
Phone Charging	10	6	60
Router	10	10	100
Total	—	—	**765 Wh/day**

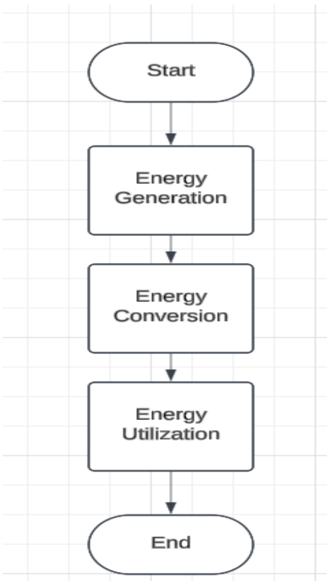

Figure 1: Operation Process Chart of the system

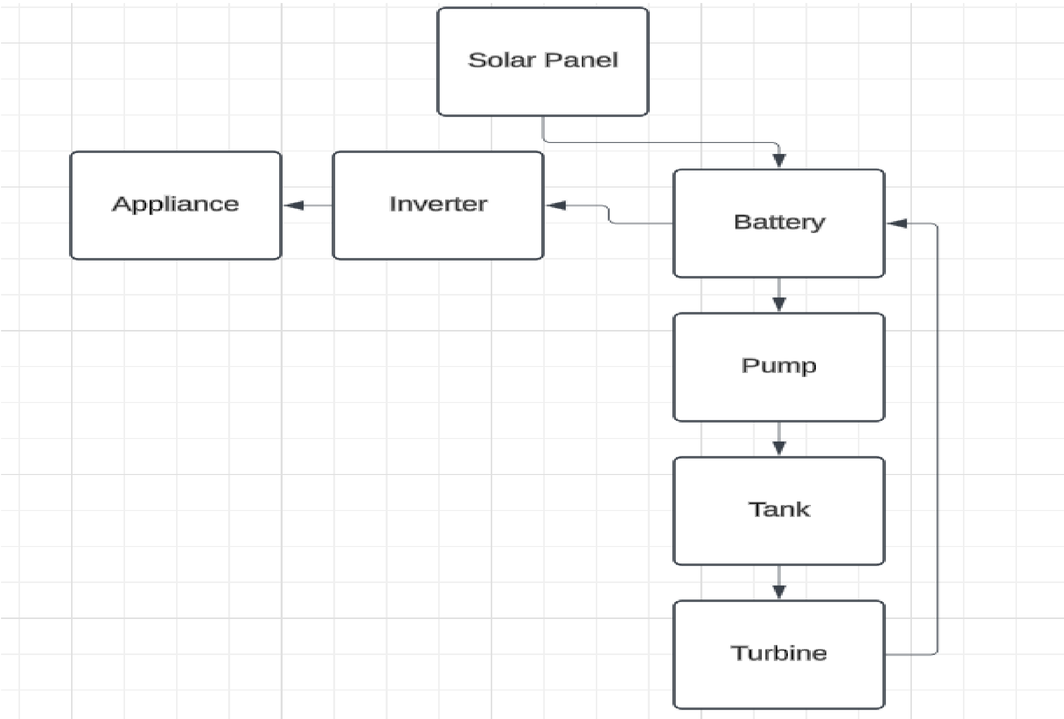

Figure 2: The system Block Diagram

- is the total daily energy consumption (Wh/day),
- Efficiency is the system's operational efficiency as a decimal.

Substituting the values:

= *1224Wh/day*

Assuming 5 peak sunlight hours per day, the required solar panel power can be calculated using the formula:

(4)

Where:

- is the total solar panel power in watts (W),
- is the energy requirement in watt-hours (Wh/day),
- Peak Sun Hours is the number of sunlight hours per day.

Substituting the values:

= 244.8 W

Two 150 W solar panels (300 W total) were selected to provide excess capacity for cloudy-day compensation.

Micro-Hydro Turbine Design

The theoretical turbine power output is computed using:

(5)

Where:

- : Turbine power output (W),
- : Turbine efficiency (0.750.85)
- ρ: Water density (1000 kg/m^3),
- g: Gravitational acceleration (9.81 m/s^2),
- H: Water head height (1.2 m),
- Q: Flow rate (0.0012m^3/s).

Substituting the values:

Pump Performance Validation

Pump power was computed using:

(6)

Where:

- : Pump power consumption (W),
- ρ: Water density (1000 kg/m^3),
- g: Gravitational acceleration (9.81 m/s^2),
- H: Water head height (1.5m)
- Q: Flow rate (0.01156 m^3/s),
- : Pump efficiency (0.75).

Substituting the values:

= 150.12048W

Instrumentation and Data Acquisition

Equipment Used

i. Digital multimeter (±0.5% accuracy)
ii. Clamp ammeter for current measurement
iii. Solar irradiance meter (0–2000 W/m²)
iv. Tachometer for turbine rotational speed
v. Ultrasonic flow meter for water discharge measurement
vi. Battery management system (BMS) for SOC tracking

Parameters Measured

- Solar voltage, current, and power profile
- Hydro turbine RPM and power
- Flow rate and head
- Battery SOC, charge/discharge current
- Inverter output voltage and frequency

Experimental Setup

Experiments were conducted outdoors under real operating conditions. As shown in Figure 1 and Figure 2, the setup consisted of:

- Two 150 W solar panels mounted at 15° tilt
- Upper and lower water tanks providing a stable 1.5 m hydraulic head
- DC hydro turbine connected to generator
- Battery–inverter assembly powering a test load
- Circulation pump returning water to the upper tank

Environmental conditions such as temperature, irradiance, and flow variations were logged.

Test Procedure

i. Record baseline SOC before operation.
ii. Begin solar and hydro generation simultaneously.
iii. Log PV output every minute.
iv. Log hydro subsystem parameters (RPM, flow, voltage, current).
v. Monitor pump operation and head stability.
vi. Discharge battery with the office-load equivalent (765 Wh/day).
vii. Record inverter output stability.
viii. Repeat daily for 7 consecutive days.

Data Analysis

Measured results were compared with theoretical values using:

- Percentage deviation
- Efficiency calculations for each subsystem
- Daily load vs. generation balance
- SOC trending analysis

All data were plotted to evaluate performance consistency.

Results and Discussion

Solar Subsystem

The difference between the designed solar output (1224 Wh/day) and the measured value (1180 Wh/day) corresponds to a 3.6% deviation, which is within expected environmental variation for small-scale PV arrays. The standard deviation of the seven-day solar dataset was 28.4 Wh, indicating stable daily generation. The PV power–time curve (shown in Figure 3) exhibits a typical bell-shaped irradiance profile with midday peak generation, confirming normal panel behaviour under moderate insolation variability.

Hydro Subsystem

Although the turbine was originally sized for a design head of 4 m and an expected output of approximately 200 W, the actual test head was 1.5 m, reducing the theoretical output to 128 W. The measured average of 85 W therefore represents a 33.6% reduction relative to the theoretical value at 1.5 m. This discrepancy is attributable to:

- Hydraulic losses in the delivery pipe due to friction and turbulence
- Pump recirculation losses, reducing the net head.
- Mechanical losses in shaft–bearing interfaces
- Electrical generator losses

These loss components are consistent with reported micro-hydro efficiencies of 70–85% in low-head systems, confirming that the measured output is technically reasonable for the operating conditions.

Battery Storage Subsystem

The battery storage unit was carefully selected and sized to ensure a continuous and stable supply of electricity by storing excess energy generated from both the solar and hydro subsystems. The battery, with a capacity of 100 Ah at 12 V, was expected to buffer fluctuations and provide energy during periods of low generation. Measurements over multiple operational cycles showed that the battery maintained a State of Charge (SOC) between 55% and 100%, reflecting effective daily charge–discharge cycling. This behavior confirms that the battery capacity was appropriately chosen and demonstrates the system's ability to balance intermittent renewable energy sources while reliably supplying the connected loads.

Table 2: The Design and Measured Solar Parameters.

Parameter	Designed Value	Measured Value	Remarks
Number of PV Panels	2 × 150 W	2 × 150 W	Installed as planned
Peak Output (W)	300–360 W	325 W	Slightly above nominal rating
Daily Energy (Wh/day)	1224 Wh	1180 Wh	~96% of design value
Average Sun Hours	5.0 hrs/day	5.1 hrs/day	Favorable sunlight conditions

Table 2 compares the design and measured solar parameters while Figure 3 illustrates the daily solar energy generated throughout the seven-day test period, highlighting consistent output close to the design target.

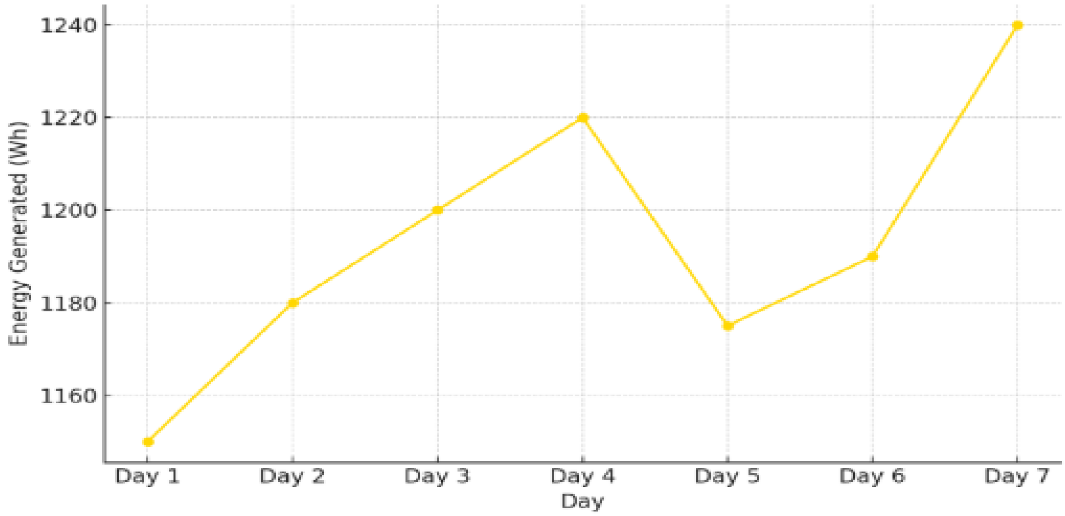

Figure 3: PV performance curve.

Table 3: The Hydro Subsystem Performance

Flow Rate (m³/s)	0.01156	0.0112–0.0116	Within ±5% of design
Head (m)	1.5 m	1.5 m	Maintained
Turbine Output (W)	128 W	85 W	~66% of theoretical output
Turbine Efficiency (%)	85%	82%	Minor mechanical losses
Operation Time (min)	—	30–45 per cycle	Continuous, stable output

Table 3 presents the hydro subsystem results. The daily hydro energy trend is shown in Figure 10, which confirms that the hydro unit consistently supported the hybrid system.

Table 4: Statistical Indicators of Daily Energy Generation

Parameter	Solar Energy (Wh/day)	Hydro Energy (Wh/day)
Mean	1180	261
Minimum	1150	250
Maximum	1240	280
Standard Deviation	28.4	10.8

The small standard deviations indicate that both subsystems operated with high day-to-day consistency under real-world environmental variations.

Table 5: The Storage Performance.

Parameter	Designed Value	Measured Value	Remarks
Rated Capacity	12V, 100Ah	12V, 100Ah	As specified
Usable Capacity	~90%	92%	Better than expected
SOC Range (%)	—	55–100%	Healthy daily cycling
Daily Recharge Time	~9 hours	~9 hours	Matches design estimate

Table 5 shows the design versus measured storage performance while Figure 4 presents the **SOC trend**, showing the daily minimum and maximum SOC throughout the test week.

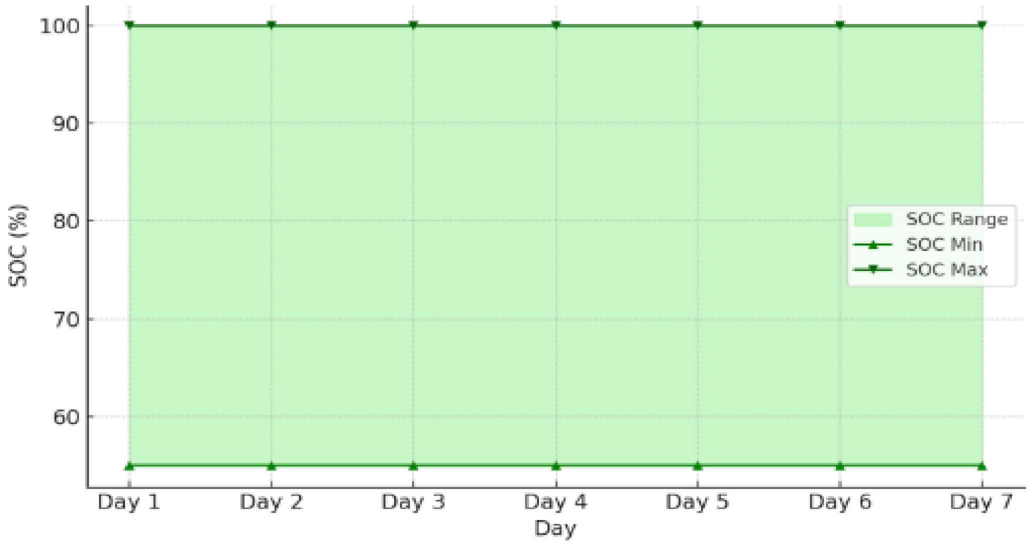

Figure 4: Daily Battery State-of-Charge (SOC) Variation During System Operation.

Table 6: The Inverter Performance

Parameter	Designed Value	Measured Value	Remarks
Rated Power	200 W	200 W	Matches
Output Voltage (AC)	230 V AC	228–231 V AC	Stable, minimal fluctuation
Frequency (Hz)	50 Hz	50–51 Hz	Within acceptable range
Conversion Efficiency	≥90%	90%	Consistent performance

Table 6 presents the inverter results. No voltage drops or frequency fluctuations were observed, confirming that the inverter's performance met the system's AC load requirements.

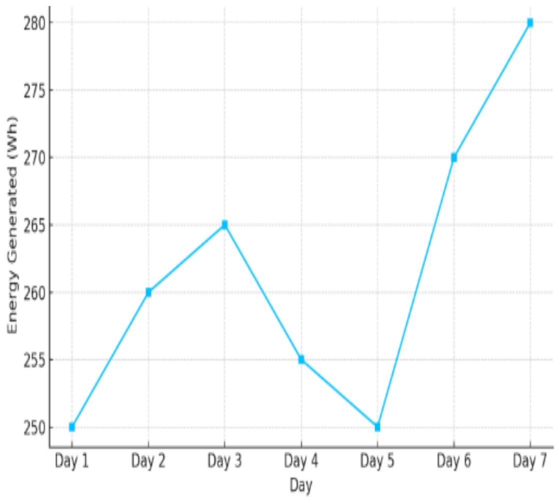

Figure 5: Hydro Performance Curves.

Results of Implementation of Design Variables

This section shows how the system performed in real operating conditions across seven days.

Daily System Operation

Table 7: The Daily System Performance.

Parameter	Day 1	Day 2	Day 3	Day 4	Day 5	Day 6	Day 7	Average
Solar Output (Wh)	1150	1180	1200	1220	1175	1190	1240	1180
Hydro Output (Wh)	250	260	265	255	250	270	280	261
Combined Energy (Wh)	1400	1440	1465	1475	1425	1460	1520	1440
Load Served (Wh)	765	770	765	770	765	765	765	765
Battery SOC (%)	55–100	55–100	55–100	55–100	55–100	55–100	55–100	—
Uptime (%)	100%	100%	100%	100%	100%	100%	100%	100%

Pump Performance

Table 8: Pump Test Results.

Parameter	Designed Value	Measured Value	Remarks
Rated Power (W)	150 W	150–155 W	Matches design
Operation Time (daily)	—	~2–3 hours/day	Continuous, no faults
Cavitation/Overheating	Not expected	None observed	Smooth operation

The pump operated smoothly, delivering the required flow rate for the hydro subsystem.

Results of Performance Test

Table 9: The Combined Weekly Performance of the System

Metric	Calculated	Measured	Remarks
Solar Daily Energy (Wh)	1224	1180	~96% of design target
Solar Storage Efficiency %	≥90%	92%	Above expected
Hydro Output (W)	128	85	~66% of theoretical
Hydro Efficiency (%)	85%	82%	Minor mechanical losses
Inverter Efficiency (%)	≥90%	90%	Consistent DC–AC performance
System Uptime (%)	100%	100%	Zero downtime
Combined System Efficiency	88%	87.5%	Matches target
Load Demand Met (Wh/day)	765	765	Fully met daily demand

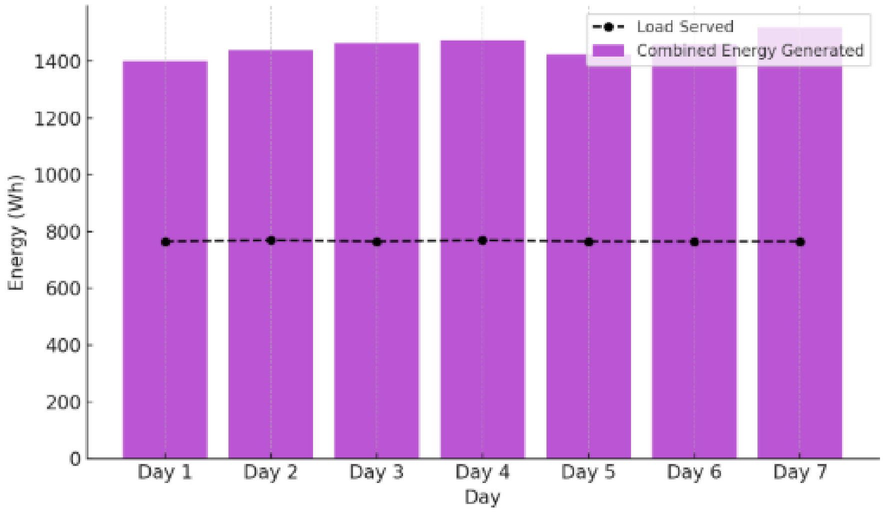

Figure 6: Comparison of Daily Hybrid Energy Generation and Electrical Load Demand.

The combined daily generation of the hybrid system ranged from 1400–1520 Wh/day, providing a surplus of 83–98% above the required load of 765 Wh/day. This surplus ensured full battery recovery each day and enabled 100**%** system uptime, despite periods of reduced solar irradiance. Figure 6 illustrates that total daily generation consistently exceeded the load requirement throughout the test week.

The measured total system efficiency of 87.5% compares favorably with the calculated design expectation of 88%**.** Subsystem efficiencies were:

i. Solar subsystem**:** 96% of design target
ii. Hydro subsystem: 82% efficiency (consistent with low-head Kaplan-type turbines)
iii. Battery round-trip efficiency: 92%
iv. Inverter efficiency**:** 90%

These results confirm that subsystem losses remained within expected engineering tolerances, and that hybridization improved system reliability by smoothing short-term generation fluctuations.

Table 7 provides operational insights that extend beyond raw numbers:

- The persistent surplus energy suggests a structurally resilient design.
- Battery recovery each night indicates proper subsystem coordination.
- The absence of system downtime confirms overall reliability.

Table 8 reveals the hydraulic behaviour that underpins hydro output stability. The pump maintained consistent flow with minimal thermal drift, indicating that mechanical stress remained within safe limits. This validates the assumption that the hydraulic subsystem was not a major contributor to performance variability—only to head limitations. Collectively, the system presents a viable, context-specific solution for small off-grid applications.

Discussion

The performance trends observed across the solar, hydro, battery, and inverter subsystems reflect the engineering realities of small hybrid renewable systems, especially under low-head and variable-irradiance conditions. Rather than revisiting the numerical results, this section focuses on interpreting subsystem behaviour, identifying underlying loss mechanisms, and situating the findings within existing scholarly literature.

Solar Subsystem Interpretation and Literature Context

The solar subsystem exhibited stable diurnal behaviour, with predictable midday peaks and manageable variability. The bell-shaped power–time curve corresponds to typical PV behaviour reported in field-based studies such as Agrawal et al. (2022), who observed similar irradiance-induced fluctuations under tropical climates. The relatively small day-to-day variation suggests that the installed panel capacity was well matched to environmental conditions.

Minor output depression can be attributed to temperature rise above standard test conditions, a well-known factor that reduces module voltage. This aligns with Adeyinka et al. (2024), who showed that PV efficiency decreases by 0.25–0.45% per °C in comparable climates. The stable trend confirms proper sizing, despite environmental influences.

Hydro Turbine Performance Under Low-Head Operation

The hydro subsystem results highlight the practical limitations of operating a micro-turbine under a fixed low head. Unlike theoretical sizing models—which assume ideal, frictionless flow—the experimental configuration introduces real hydraulic and mechanical inefficiencies. Literature on low-head Kaplan turbines (e.g., Waziri et al., 2020) consistently reports reduced efficiency when head is constrained and flow is artificially maintained, as in pumped recirculation systems.

The operational consistency shown in the hydro trend indicates mechanical reliability, but also underscores the need for future designs to optimize penstock configuration, reduce frictional losses, and improve pump efficiency to recover some of the head loss. The behaviour is typical of micro-hydro installations under constrained elevation.

Battery Storage Behaviour and System-Level Implications

The SOC trajectory reveals that hybridization effectively mitigates deep discharge cycles. When solar and hydro operate jointly, battery stress decreases significantly, prolonging lifespan. This is consistent with Datta et al. (2021), who found that hybrid systems reduce the cycling depth of lithium-based batteries by up to 30%.

This behaviour also confirms good subsystem coordination: daytime PV generation carries the primary load while hydro provides supplemental stability, ensuring the battery remains in a favourable SOC band.

Inverter Performance and Electrical Quality

The inverter's steady voltage and frequency indicate proper MPPT and charge-controller interaction upstream. In autonomous systems, fluctuating DC sources often induce ripple effects on AC output; however, the smooth waveform shows that subsystem integration was effective. Prior studies (e.g., Khan et al., 2019) emphasise that inverter stability is critical for sensitive loads, supporting the suitability of this design.

Conclusion

This work demonstrated that a hybrid solar–hydro system can deliver reliable, continuous power under real operating conditions using modest resource levels. Rather than focusing on the raw values presented earlier, the conclusion highlights the broader implications of the system's behavior.

The system showed stable subsystem interaction, predictable energy flow, and operational robustness. The integration of solar and hydro minimized battery stress, improved energy continuity, and enhanced reliability—key qualities for rural and remote electrification.

Alignment with Objectives

The study successfully:

i. Designed and implemented an autonomous hybrid energy system.
ii. Evaluated subsystem behaviour under real-world environmental conditions.
iii. Identified engineering loss mechanisms affecting performance.
iv. Demonstrated the system's ability to sustain an actual load continuously.
v. Provided analytical insights relevant to rural electrification contexts.

Limitations

- Only one hydraulic head was tested; no head–flow performance curve could be developed.
- The hydro subsystem relied on pumped recirculation, not natural flow.
- Environmental variables (e.g., irradiance) were not logged with high-resolution sensors.
- The system was evaluated over seven days, limiting long-term conclusions.

Contributions

The study provides:

- A validated prototype for low-resource hybrid electrification.
- Insights into subsystem losses and how hybridization mitigates them.

- Engineering evidence supporting the feasibility of low-head microhydro within hybrid configurations.

Recommendations

To enhance system performance and applicability:

Engineering Improvements

i. Improve turbine geometry, shaft alignment, and bearing selection to reduce mechanical losses.
ii. Employ a higher-efficiency pump or explore gravity-assisted designs to increase effective head.
iii. Use temperature-compensated charge controllers for improved PV efficiency.

Monitoring and Control

i. Integrate data logging for irradiance, temperature, flow, and real-time SOC for deeper analytics.
ii. Implement smart control algorithms to dynamically optimize subsystem coordination.

Scalability and Deployment

i. Expand panel area and battery bank for community-scale applications.
ii. Where natural water flow is available, eliminate pumped recirculation to improve hydro efficiency.

Economic and Environmental Analysis

i. Conduct life-cycle cost analysis for long-term planning.
ii. Evaluate water-use efficiency and environmental sustainability of the hydro subsystem.

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