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Potential of Small-Scale Hybrid Solar and Pumped Storage Hydropower Systems for Off-Grid Applications

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Abstract

The increasing demand for reliable electricity in off-grid regions, particularly in remote areas, calls for innovative solutions. This project focuses on the integration of Pumped Storage Hydropower (PSH) with solar photovoltaic (PV) systems, aiming to provide a clean, sustainable, and stable energy solution. The primary goal is to design and develop a small-scale hybrid system that utilizes solar energy to pump water into an elevated reservoir, which can then be released to generate electricity via a turbine when solar generation is low or unavailable. An Arduino-based monitoring system was developed to track the performance of both the solar panel and the hydro generator. The system was designed, simulated, and tested under real-world conditions. Results indicate that although the system demonstrates potential for off-grid applications, the small-scale PSH prototype is less efficient compared to direct battery-based solar storage in terms of consistency and output power. The findings suggest that improvements in system design, turbine efficiency, and storage capacity are required to enhance the performance and reliability of the hybrid system. The outcomes highlight the viability of hybrid renewable systems for sustainable off-grid electrification but also indicate areas for future research, particularly in optimizing system design and scaling for broader applications.

Keywords

Hybrid Solar System, Pumped Storage Hydropower, Energy Management, Arduino, Off-Grid Electrification

1. Introduction

Electricity access remains a major issue in remote, off-grid areas where expanding the traditional grid is expensive and often impractical. While solar power has been widely adopted as a solution, its intermittent nature makes it unreliable for continuous energy supply. To address this, this project proposes a hybrid system that combines solar photovoltaic (PV) technology with Pumped Storage Hydropower (PSH) to provide a stable and sustainable energy source for off-grid communities. Solar energy can be used to pump water into an elevated reservoir, storing potential energy, which can then be released through a turbine to generate electricity when solar generation is low. However, the intermittent nature of solar energy and limitations of battery storage, such as high costs and short lifespan, present significant challenges. PSH offers a practical and environmentally friendly energy storage alternative by utilizing excess solar energy to generate electricity during periods of low solar output. This project aims to design and develop a small-scale hybrid PSH and solar system, integrate an Arduino-based monitoring system to control and track performance, and evaluate the system's efficiency and reliability in off-grid applications.

2. Literature Review

2.1. Fundamentals of Hybrid Solar and Pumped Storage Hydropower Systems

Hybrid Renewable Energy Systems (HRES) combine multiple renewable energy sources to mitigate the intermittent issues associated with individual systems, like solar or wind, ensuring more stable and reliable energy output. HRES are crucial for electrifying remote areas not connected to the national grid. They provide energy independence and improve the quality of life for communities, as seen in the Solar Hybrid Station at RPS Kemar, Gerik, Perak [1]. Integrating solar photovoltaics with pumped-storage hydropower (PSH) is particularly effective.

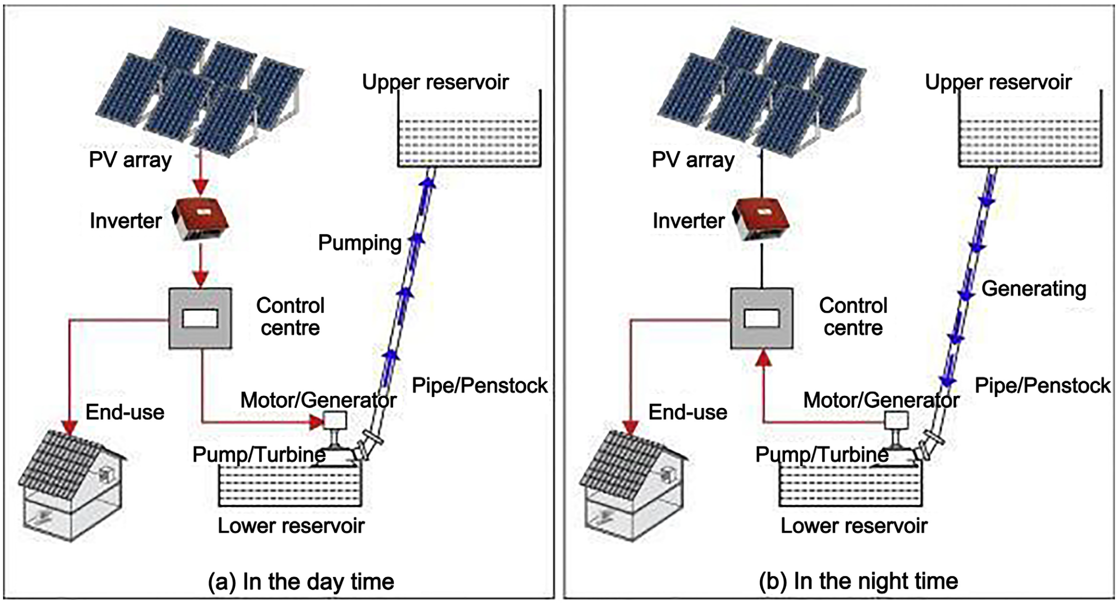


Figure 1. Diagram of PSH with stand-alone PV power generation unit [2].

Solar PV generates energy only when the sun shines, while PSH stores surplus solar energy as potential energy in water, which is released when solar power is unavailable. This integration, as seen in **Figure 1**, not only optimizes energy utilization but also enhances grid stability while reducing CO_2 emission [3]-[5].

2.2. Solar-Pumped Storage Hybrid Energy System

The core concept of a solar-Pumped Storage Hybrid Energy System is to use solar PV to directly power loads or charge a battery. Excess solar energy is used to pump water into an elevated reservoir, storing the energy as potential energy. When solar energy is unavailable (e.g., at night or during cloudy periods), the stored water is released through turbines to generate electricity, ensuring a continuous power supply [6] [7]. This integration, as can be seen in **Figure 2**, solves the intermittency of solar energy by providing backup power from the PSH system during low solar input, making it especially beneficial for off-grid areas [8].

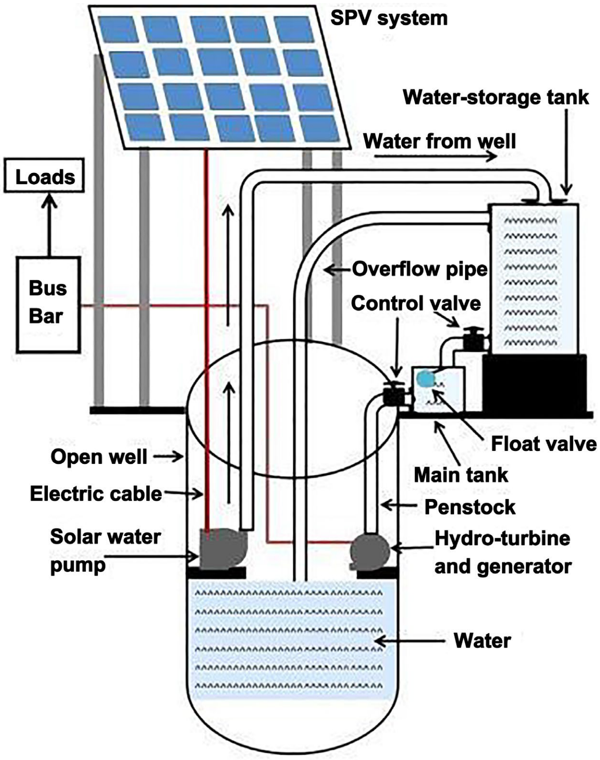


Figure 2. Photovoltaic power generating combined with pumped storage [8].

2.3. Arduino-Based Hardware Prototype Development

Arduino-based systems have become a popular choice for real-time monitoring and control in renewable energy applications, particularly in hybrid solar and pumped storage hydropower (PSH) systems. These systems automate essential processes such as water pumping and energy management, improving efficiency and reliability. For example, one study demonstrated the use of Arduino for automating solar-powered pumps, where it optimizes the pump's operation based on solar generation and water flow conditions, ensuring efficient energy usage [9]. Another example integrates Arduino with micro-hydro systems for frequency control, stabilizing power output by dynamically adjusting system parameters [10].

In hybrid systems, Arduino interfaces with various sensors such as current monitors and water level detectors, enabling real-time management of energy flow between components. The use of Wi-Fi modules like the ESP8266 allows for remote monitoring, making the system more adaptable for off-grid applications [9]. Furthermore, the integration of Arduino enables the use of Maximum Power Point Tracking (MPPT) algorithms to optimize solar energy conversion and manage the switching between solar and hydro power generation based on environmental conditions and load demands [10].

Arduino's ability to interface with multiple sensors and actuators, along with its low cost and ease of use, makes it an ideal choice for developing scalable, efficient hybrid renewable energy systems [11]-[14]. These systems can be deployed in off-grid areas to enhance energy access and sustainability, offering real-time control, data logging, and improved system performance by integration of an Arduino Uno.

In conclusion, combining solar PV with pumped-storage hydropower (PSH) in Hybrid Renewable Energy Systems (HRES) offers a reliable solution for off-grid energy generation, addressing solar intermittency [15]-[17]. Arduino-based systems enhance efficiency by automating control, real-time monitoring, and data logging. The flexibility and low cost of Arduino make it ideal for developing scalable, sustainable systems in remote areas, ensuring continuous energy supply [18]-[20]. Future improvements in system optimization and energy management will further strengthen the potential of these hybrid systems.

3. Methodology

3.1. Introduction

This project focuses on developing a small-scale hybrid system that integrates solar photovoltaic (PV) technology with pumped-storage hydropower (PSH). The primary goal is to design and implement a system that can autonomously switch between solar power and hydro generation, ensuring a continuous energy supply for off-grid applications. The methodology involves system design, hardware implementation, and performance testing to evaluate the feasibility and efficiency of the hybrid system.

3.2. System Design

The hybrid system design integrates solar panels, a hydro generator, a battery, and an Arduino Uno microcontroller for controlling and monitoring system operations. Key components of the system include:

- Solar Panels: These are the primary energy generation source, providing electricity to charge the battery during daylight hours. The specification can be seen in **Table 1**.

- Hydro Generator: The hydro generator uses stored water to produce electricity when solar energy is insufficient. It is connected to an elevated water reservoir that stores energy in the form of potential energy.
- Battery: The battery stores excess energy generated by solar panels for later use, ensuring continuous power when solar energy is not available.
- Arduino Uno: The Arduino Uno is the heart of the control system. It continuously monitors system parameters (such as voltage, current, and water level) and switches between solar and hydro power generation based on the energy demand. Arduino is responsible for automating the energy storage process, logging data, and managing the transition between energy sources. The Arduino Uno uses various sensors (e.g., voltage sensors, current sensors, and water level sensors) to monitor the system's performance and make decisions in real time, optimizing energy usage and ensuring efficiency. Data is logged onto an SD card for further analysis and troubleshooting.

This system design ensures that the transition between solar and hydro generation is smooth, minimizing system downtime and maintaining a reliable energy supply.

Table 1. Solar panel specifications.

Specification	Detail
Maximum output power (P_{max})	100 W
Voltage at max power (Vmp)	17.7 V
Current at max power (Imp)	5.7 A
Open circuit voltage (Voc)	22.1 V
Short circuit current (Isc)	6 A
Dimensions	77 × 67 × 3 cm
Weight	6 kg
Cell type	Monocrystalline silicon
Connector type	MC4
Efficiency grade	Class-A
Quantity	3 unit × Solar panel

3.3. Project Architecture

The system architecture is divided into four main phases as can be seen in **Figure 3**.

The phases were explained as follows.

- Solar Charging: During the day, the solar panels generate electricity, which charges the battery. The system is designed to monitor the battery's charge level, ensuring that it is adequately charged before switching to hydro generation.

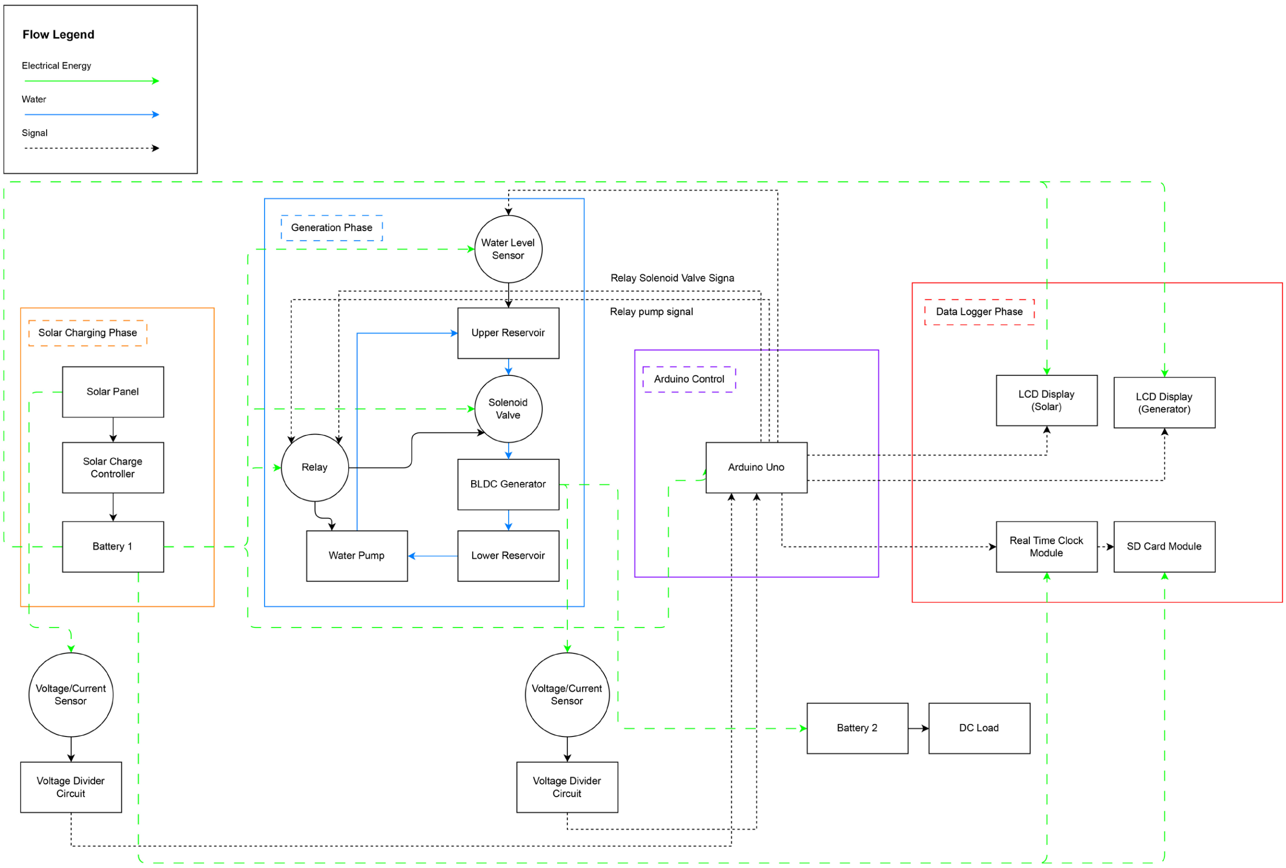


Figure 3. Photovoltaic power generating combined with pumped storage.

- Hydro Generation: When solar energy is insufficient (e.g., at night or on cloudy days), the Arduino triggers the hydro generator to release stored water from the elevated reservoir. The hydro generator converts the potential energy of the stored water into electricity, providing power to the system. The Arduino controls this phase by monitoring water levels and adjusting the release of water to generate the required electricity.
- Arduino Control: The Arduino Uno microcontroller is responsible for managing the entire system. It reads sensor data (voltage, current, and water level) and makes decisions regarding energy generation. The Arduino automates the switching process between solar power and hydro power, ensuring that the system always remains operational.
- Data Logging: An SD card module and LCD display connected to Arduino allow for real-time data logging and system monitoring. The system logs essential data, such as energy production from the solar panels and hydro generator, battery charge level, and water levels, for analysis and optimization.

This architecture enables seamless operation of the hybrid system, with automated switching between solar and hydro generation based on the availability of solar power and the energy demand. The system is designed to be scalable and adaptable to various off-grid applications.

4. Results and Discussion

4.1. Performance Testing

The hybrid system was tested through simulation using Proteus to evaluate the system's performance and the capability of data logging under different conditions as illustrated in **Figure 4**. The simulation was designed to replicate real-world conditions, including varying sunlight and load scenarios.

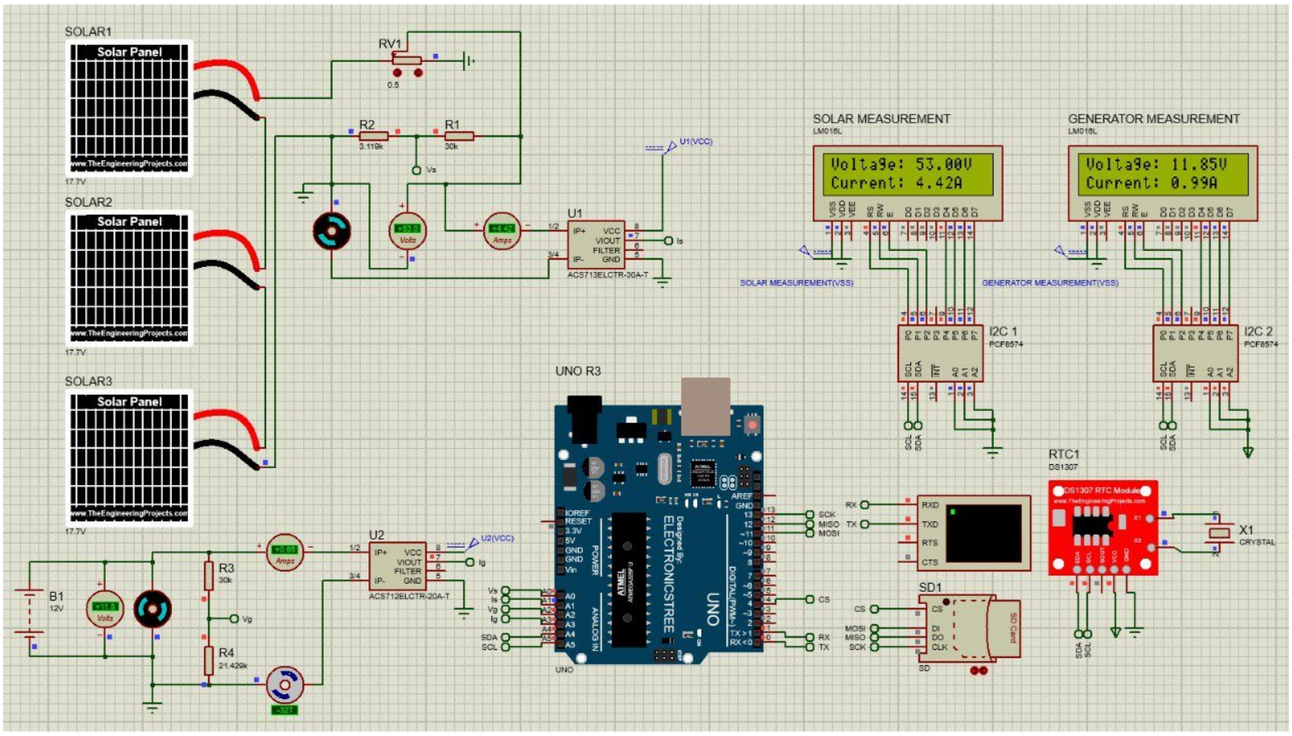
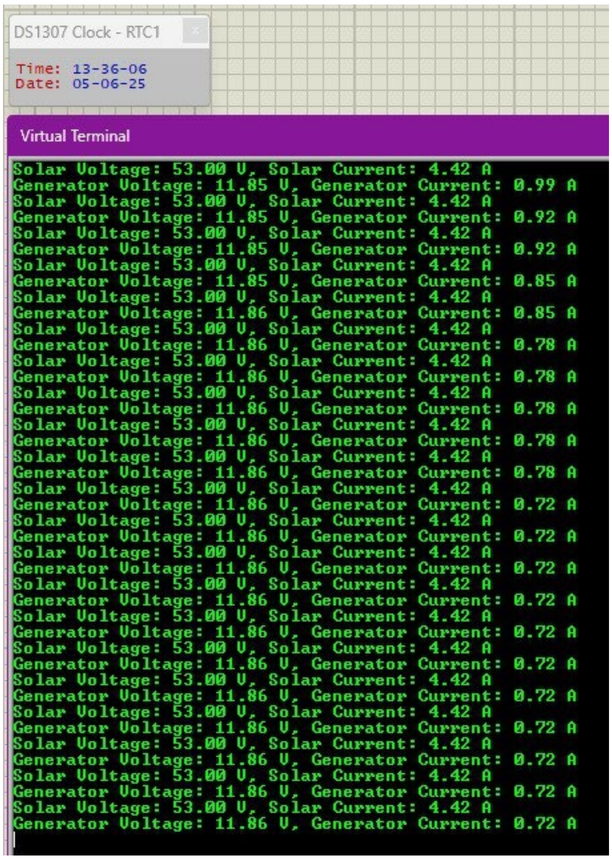


Figure 4. Hardware design in Proteus.

The Proteus simulation demonstrated the system's ability to seamlessly switch between solar power and hydro generation. During periods of high sunlight, the solar panels charged the battery and powered the system, while the water pump was activated to store excess energy in the elevated reservoir. When solar generation decreased (e.g., during cloudy conditions or at night), the simulation showed that the hydro generator automatically took over, providing continuous power by releasing stored water to generate electricity.

Furthermore, the data logging functionality was successfully simulated in Proteus as can be seen in **Figure 5**. Data from various sensors, such as voltage, current, water levels, and battery charge status, were continuously logged and displayed in real time. The system recorded all parameters onto an SD card, which was simulated to track the energy production from both the solar and hydro sources, and the system's overall performance. The simulation confirmed that the hybrid system could reliably maintain energy supply, with the Arduino controlling the switching process and managing data logging without interruptions.



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Generator Voltage: 11.86 V, Generator Current: 0.72 A
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Figure 5. Simulation of data logger in Proteus.

The simulation results showed that the hybrid system provided a stable and continuous power supply, effectively managing energy from both the solar and hydro sources. This confirms the viability of the system for real-world applications and demonstrates the importance of simulation in testing the system's behavior and performance before physical implementation.

4.2. Data Collection and Analysis

Data was systematically collected over multiple days and tabulated in Table 2, Table 3 and Table 4 to assess the performance of the solar panels, water pump, and hydro generator within the hybrid energy system. This process included monitoring voltage, current, temperature, and power generation under various environmental conditions and can be divided into several performances as follows.

Table 2. Solar panel data collection day 1.

Time (Hour)	Voltage (V)	Current (A)	Power (W)	Temperature (˚C)
9 AM	57.5	6.06	348.45	51
10 AM	56.4	6.22	350.81	56
11 AM	56.7	6.68	378.76	53
12 PM	56.3	6.64	373.83	55

Continued

1 PM	56.2	6.00	337.20	56
2 PM	53.5	1.62	86.67	40
3 PM	55.4	2.31	127.97	38
4 PM	57.1	6.55	374.01	46
5 PM	48.6	0.44	21.38	37
6 PM	41.4	0.14	5.80	34

Table 3. Solar panel data collection day 2.

Time (Hour)	Voltage (V)	Current (A)	Power (W)	Temperature (˚C)
9 AM	56.1	1.98	111.09	33
10 AM	57.6	5.54	319.10	52
11 AM	56.7	5.75	326.03	53
12 PM	52.8	4.82	254.50	55
1 PM	56.3	4.28	240.96	53
2 PM	52.5	3.76	197.40	54
3 PM	56.6	2.68	151.69	48
4 PM	56.4	5.26	296.66	48
5 PM	55.9	1.38	77.14	45
6 PM	53.8	1.95	104.91	41

Table 4. Solar panel data collection day 3.

Time (Hour)	Voltage (V)	Current (A)	Power (W)	Temperature (˚C)
9 AM	56.2	2.98	167.48	56
10 AM	54.6	1.16	63.34	39
11 AM	57.5	5.99	344.43	56
12 PM	57.2	5.91	338.05	60
1 PM	57.1	5.87	335.18	52
2 PM	55.3	3.62	200.19	53
3 PM	55.4	3.51	194.45	52
4 PM	54.8	1.68	92.06	47
5 PM	51.2	2.46	125.95	39
6 PM	49.6	2.24	111.10	36

- Solar Panel Performance: Over three days of data collection, solar panel performance was evaluated in response to varying weather conditions, primarily cloud cover. Clear sky conditions allowed for nearly optimal power output, with maximum power generation exceeding 350 W. In contrast, cloudy conditions significantly reduced performance, dropping power output to less than

100 W. A clear correlation between solar output and temperature was observed, with higher temperatures often reducing the current output.

- Water Pump Analysis: The performance of the 12V DC water pump was assessed under three different head heights: 1.5 meters, 3 meters, and 4 meters as can be seen in **Table 5**. The pump showed optimal efficiency at 1.5 meters, with higher flow rates and lower power consumption. As the head height increased, performance declined due to increased resistance. At 4 meters, the efficiency dropped to 28.36%, demonstrating the limitations of the pump under high head conditions.

Table 5. DC water pump with different meter height test.

Different in height(m)	Time to fill upper tank	Voltage (V)	Max current (A)	Power (W)	Flow rate (ℓ/min)	Temperature (˚C)	Pump efficiency (%)
1.5	14m27s	12.81	1.412	18.09	11.21	160	84.1
3	34m27s	12.63	1.493	18.96	4.67	160	35.03
4	42m30s	12.62	1.562	19.71	3.78	160	28.36

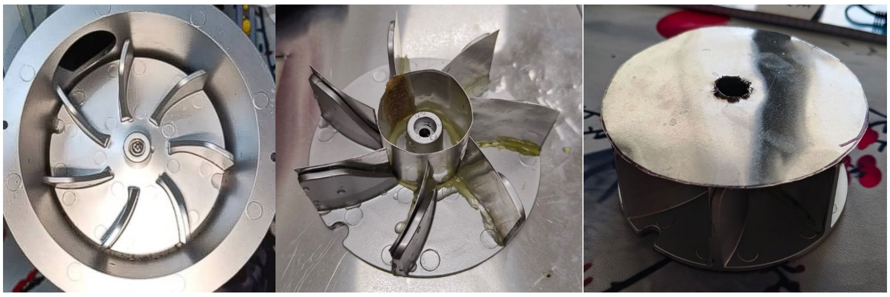
(a) (b) (c)

Figure 6. Hydro turbine for (a) Case 1, (b) Case 2, and (c) Case 3.

Table 6. Data collection from Hydro Turbine.

Type of cases	Inlet flow rate (ℓ/min)	Max voltage (V)	Max current (A)	Power (W)	Generator efficiency (%)
Case 1	32.76	6.212	1.416	8.8	24.22
Case 2	32.76	7.821	0.626	7.82	21.72
Case 3	32.76	11.398	0.177	2.02	5.61

- Hydro Generator Efficiency: Three different turbine designs labeled cases were tested as illustrated in **Figure 6** to evaluate the hydro generator's performance under controlled water flow while **Table 6** shows the results for the hydro turbine performance. The tests revealed that turbine efficiency was heavily influenced by the design modifications. While increasing the surface area for water interaction improved efficiency, however modifications that increased the turbine's weight resulted in slower rotations and reduced efficiency. This effect was observed in the transition from Case 1 to Case 2, and subsequently to Case 3. The highest efficiency observed was 24.22%, highlighting the importance of optimizing turbine design for small-scale hydro generation. These analyses are integral in understanding the hybrid system's reliability and efficiency in generating consistent energy, especially during periods of low solar input, which is mitigated by the hydro generation system.

5. Conclusions

In conclusion, the development of a small-scale standalone hybrid solar and pumped storage hydropower system offers a promising solution to the growing energy demands in off-grid, remote areas. The integration of solar photovoltaic systems with pumped storage hydropower provides a sustainable, clean, and reliable energy source capable of overcoming the intermittency of solar energy. Although the prototype demonstrated significant potential, further improvements in system efficiency, turbine design, and energy storage capacity are necessary to enhance overall performance and reliability.

Additionally, optimizing the system for scalability and long-term sustainability will be critical for its broader application in remote electrification projects. The findings suggest that hybrid renewable energy systems like the one proposed in this study can contribute to global energy sustainability goals and provide energy independence to underserved communities. Future work should focus on refining system design, enhancing turbine efficiency, and incorporating advanced energy management strategies to increase the feasibility and effectiveness of hybrid solar-PSH systems for off-grid applications.

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Conflicts of Interest

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

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