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# Hybrid Power Plant Prototype for Hill Areas: Integrating Solar and Wind Energy with Auto Switching and Monitoring Technology

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**ABSTRACT**

Indonesia's tropical climate and hilly terrain offer significant potential for renewable energy, particularly solar and wind. This study presents a hybrid power plant prototype integrating solar and wind energy, equipped with an Arduino Mega-based Auto Switching system and a web-based monitoring application. The system optimizes energy use by prioritizing solar energy during the day and wind energy at night. Key components include GY-49 lux sensors, anemometers, voltage sensors, charger controllers, batteries, and inverters. Experimental results show effective source switching, with solar energy achieving a maximum voltage of 21.65 V at 65,058.8 lux and wind energy producing 0.79 V at 16 m/s. However, wind energy output is insufficient for direct battery charging, indicating a need for turbine design optimization. The web-based monitoring system ensures real-time performance tracking, enhancing system reliability. This prototype offers a sustainable energy solution for hilly regions with limited grid access, reducing reliance on fossil fuels.

## 1. INTRODUCTION

Energy demand is rising due to population growth and technological advancements, while fossil fuel depletion and environmental concerns, such as carbon emissions, necessitate sustainable alternatives [1]. Renewable energy sources like solar and wind are critical for addressing these challenges, particularly in regions with abundant natural resources. Indonesia's tropical location and hilly regions provide ideal conditions for harnessing solar and wind energy. The country's wind energy potential is estimated at 978 MW [2], and hilly areas like Sukabumi offer 170 MW of renewable energy potential [3]. These regions experience consistent sunlight during the day and strong winds at night, making them suitable for hybrid power systems combining solar and wind energy. The unique advantages of hybrid systems, such as enhanced reliability through complementary energy sources and reduced dependency on unstable grid infrastructure, address the urgent need for sustainable power in mountainous areas where conventional energy access is limited and environmental conditions vary significantly.

Electrical energy demand in Indonesia is projected to grow significantly, reaching 2,214 TWh (Business as Usual), 1,918 TWh (Policy-Based), or 1,626 TWh (Renewable Knowledge) by 2050, a nearly ninefold increase from 254.6 TWh in 2018 [2]. The National Energy Policy (KEN) aims for 5% [4] of primary energy from renewable sources like solar and wind by 2025 [5]. However, challenges in managing renewable energy systems, such as variability in resource availability, require innovative solutions to ensure efficiency and sustainability.

Previous studies have explored solar and wind energy separately, such as solar-powered street lighting and wind speed monitoring [6, 7]. However, these efforts often fail to integrate both sources effectively. This study addresses this gap by developing a hybrid power plant prototype that combines solar and wind energy with an innovative Auto Switching system and real-time web-based monitoring. The Auto Switching system optimizes energy use by selecting the most efficient source based on environmental conditions, while the web application enables real-time performance tracking, enhancing system reliability and maintenance.

This research aims to create a prototype that introducing a novel integration of real-time Arduino-based Auto Switching logic—which dynamically selects the most efficient energy source—and a web-based monitoring application that enables real-time tracking of voltage, wind speed, and light intensity. This dual innovation addresses key challenges in hybrid system efficiency and management. The Auto Switching mechanism leverages real-time sensor data to determine optimal energy input, while the web monitoring system ensures transparent, remote-accessible performance oversight. Together, these features enhance the system's adaptability to environmental changes, improve operational efficiency, and offer a scalable and cost-effective solution for energy delivery in remote or underserved hilly regions. It's integrates solar and wind energy, optimized by an Auto Switching system and monitored via a web-based application. It targets hilly regions with limited grid access, offering a sustainable and cost-effective energy solution. The system enhances energy efficiency, reduces waste, and supports Indonesia's energy transition goals. Chapter 2 details the research methodology, Chapter 3 presents test results, Chapter 4 discusses findings, and Chapter 5 concludes with recommendations.

## 2. RESEARCH METHODOLOGY

This study employs a prototype development methodology to create an efficient hybrid power generation system [8]. The process begins with a literature review on solar and wind energy, Auto Switching technology, and web-based monitoring, followed by an analysis of energy needs in hilly regions and technical specifications for system components.

The system design phase outlines the integration of solar panels, wind turbines, charger controllers, batteries, inverters, and sensors (voltage, GY-49 lux, and anemometer). The Arduino Mega microcontroller manages the Auto Switching logic, while a web application enables real-time monitoring via a communication module. Hardware selection prioritizes reliability and cost-effectiveness, with the Arduino Mega chosen for its robust processing capabilities and compatibility with multiple sensors.

The software design leverages Arduino's programming environment for real-time decision-making and data transmission to the web application. Implementation involves assembling hardware, integrating software, and testing the prototype under various scenarios to evaluate Auto Switching and monitoring performance. Test results are analyzed to assess system efficiency, followed by recommendations for future improvements.

### 2.1 Literature review

Renewable energy sources like solar and wind are sustainable solutions for global energy needs. Solar photovoltaic (PV) panels convert sunlight into electricity, with efficiency dependent on light intensity and geographic location [9]. Hilly regions often experience consistent wind speeds, ideal for wind turbines [10, 11]. Hybrid systems combining solar and wind energy improve reliability due to their complementary nature [12, 13]. Studies show hybrid systems with intelligent management can increase efficiency by up to 25% compared to single-source systems [14].

Hybrid systems combine two or more energy sources to improve reliability, efficiency, and power availability. The advantages of a hybrid system are: Increasing the efficiency of energy resource utilization [15-17], reducing dependence on single energy sources and reducing carbon emissions and environmental impacts. Several studies have attempted to use solar-wind hybrid systems, including the research [15] which shows that solar-wind hybrid systems with intelligent management increase efficiency by up to 25% compared to individual systems. The research [18] studied the application of hybrid systems in remote areas, showing success in overcoming network instability. Thus, the integration of two energies in forming Electrical energy as an alternative renewable energy can contribute to optimizing the use of electricity properly and efficiently. In this study, it will be designed to utilize the advantages of solar energy during the day and wind energy at night.

One of the integration applications that can be implemented is Auto Switching technology. Auto Switching technology, using microcontrollers like Arduino, enables dynamic source selection based on sensor data that is used to monitor the energy level available from each source [19-21]. Web-based monitoring enhances system management by providing real-time data, with studies reporting up to 95% monitoring accuracy and 20% reduced downtime [22-24].

### 2.2 Proposed system

The hybrid system integrates solar panels, wind turbines, an Arduino Mega microcontroller, relays, voltage sensors, GY-49 lux sensors, anemometers, charger controllers, batteries, and inverters. The Arduino Mega processes sensor data to control the Auto Switching logic, selecting the optimal energy source based on voltage or environmental conditions. The system prioritizes solar energy during high sunlight intensity and switches to wind energy at night or during high wind speeds. A web-based application monitors voltage, light intensity, and wind speed in real-time.

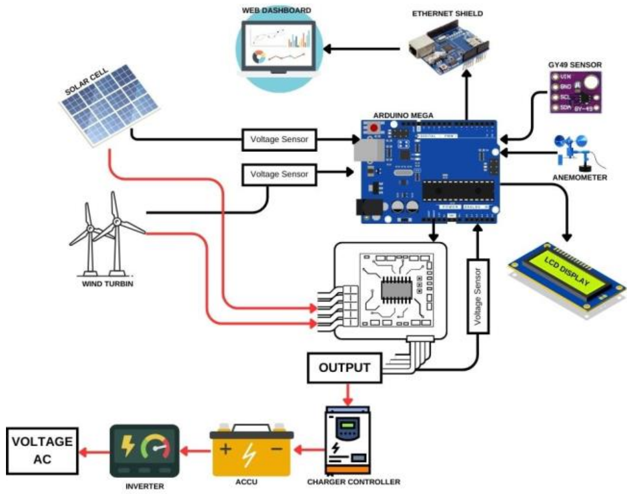


**Figure 1.** Block diagram of the hybrid power plant

Figure 1 presents the block diagram illustrates the system's architecture, depicting solar panels and wind turbines as primary energy sources. Arrows indicate the flow of electrical energy from these sources to voltage sensors, which connect to the Arduino Mega microcontroller. The Arduino Mega integrates data from GY-49 lux sensors and anemometers, controlling a relay for Auto Switching between energy sources. The system includes a charger controller linked to a battery for energy storage, an inverter for DC-to-AC conversion, and an LCD display for local data output. A communication module connects the Arduino Mega to a web-based monitoring application, enabling real-time performance tracking. This prototype optimizes renewable energy utilization, delivering a stable and sustainable energy solution for remote hilly areas with abundant solar and wind resources.

### 2.3 Flowchart of the proposed system

Figure 2 presents the flowchart for the hybrid power plant, addressing logical errors in the original design to ensure operational functionality. The system initializes sensors, measures voltage and environmental parameters (light intensity, wind speed), and selects the energy source with the highest power output based on voltage and current. If no source meets the threshold, the system defaults to battery power. Data is displayed on an LCD and transmitted to the web application for monitoring.

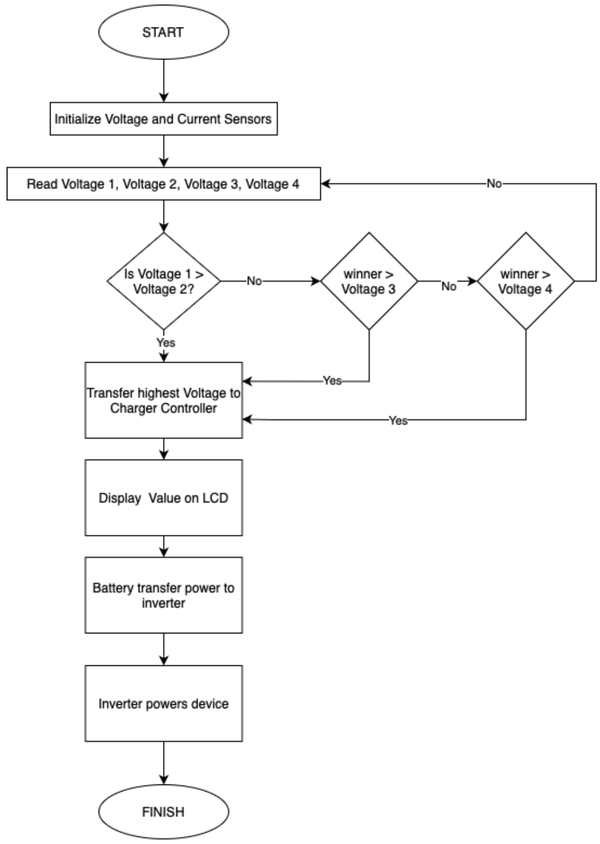


**Figure 2.** Flowchart of the hybrid power plant

This system integrates solar and wind power sources to efficiently manage energy production and storage. The flowchart delineates the step-by-step process by which the system automatically reads voltage data from different energy sources and assesses these sources according to preset voltage thresholds. The operation begins with the initialization of voltage and current sensors, which are tasked with measuring data from the power sources, including solar panels and wind turbines. The voltage from each energy source is then assessed to determine if it meets the necessary criteria for charging the battery. If the voltage exceeds the predefined threshold for solar energy, it is directed to the charger controller; otherwise, the system proceeds to evaluate the next energy source. Once a suitable voltage is supplied, the system displays the voltage reading on the LCD screen, providing a status update on the operational state of the system and the resources being utilized. The voltage directed to the charger controller is used for charging the battery. After the energy is stored, the inverter converts the direct current (DC) from the battery into alternating current (AC) suitable for household appliances. The entire process is continuously monitored to ensure the system operates optimally, adjusting the energy source selection dynamically to maximize efficiency. The switching mechanism, outlined in this study, is designed to automatically select the energy source providing the highest voltage among multiple energy inputs. This selection is governed by Eq. (1):

$$V_{output}=max(V_1, V_2, \ldots, V_n) \quad (1)$$

where, $V_{output}$ is the output voltage directed to the next system component (e.g., battery or electrical load), and $V_1, V_2, \ldots, V_n$ are the voltages from each energy source (solar panels, wind turbines, etc.), with n representing the total number of energy sources. This approach ensures that the most efficient energy source is prioritized, optimizing the system's performance in response to fluctuating environmental conditions such as sunlight intensity and wind speed. Additionally, the system operates by evaluating the power output from each energy source, as defined by Eqs. (2) and (3):

$$P=V \times I \quad (2)$$

$$P_{output}=max\ (P_1, P_2, \ldots, P_n) \quad (3)$$

where, $P_{output}$ is the output power, and $P_1, P_2, \ldots, P_n$ represent the power generated by each energy source. Power is calculated as the product of voltage (V) and current (I). The system continuously compares the power output from all energy sources and selects the one with the highest power for distribution, ensuring the most powerful and reliable source is utilized.

The switching mechanism also incorporates environmental parameters such as sunlight intensity (lux) and wind speed (m/s), enabling dynamic adaptation to changing conditions. If the sunlight intensity exceeds a threshold, the system prioritizes solar energy, as described in Eq. (4):

$$S_{solar}=\begin{cases} 1, & if\ lux > Threshold_{lux} \\ 0, & if\ lux \leq Threshold_{lux} \end{cases} \quad (4)$$

Similarly, wind energy is selected when the wind speed surpasses a set threshold, as shown in Eq. (5):

$$S_{wind}=\begin{cases} 1, & if\ m/s > Threshold_{m/s} \\ 0, & if\ m/s \leq Threshold_{m/s} \end{cases} \quad (5)$$

By incorporating these environmental factors, the system ensures the most efficient use of renewable energy sources based on real-time conditions, enhancing both the reliability and efficiency of the hybrid power system.

### 2.4 Prototype of the proposed system

Figure 3 shows the compact prototype, integrating solar panels, wind turbines, batteries, inverters, and the Arduino Mega for efficient energy management, suitable for remote hilly areas.

**Figure 3.** Prototype of the hybrid power plant

### 2.5 Testing scenario of the proposed system

The performance of the hybrid power plant prototype is evaluated through a series of structured test scenarios designed to assess the functionality, efficiency, and reliability of its components and overall system operation.

The first scenario tests the accuracy of the voltage sensor in measuring outputs from solar panels and wind turbines, comparing sensor readings against a calibrated voltmeter to ensure precision.

The second scenario evaluates the solar panel's voltage output under varying light intensities, measuring generated voltage and corresponding battery charging duration to quantify solar energy performance.

The third scenario examines the wind turbine's voltage output across different wind speeds, assessing its adequacy for battery charging.

The fourth scenario tests the Auto Switching system's ability to select the energy source with the highest power output, verifying that the output voltage consistently reflects the optimal source.

The fifth scenario assesses battery endurance under various load conditions (e.g., low, medium, and high-power consumption), measuring operational duration to evaluate storage efficiency.

The sixth scenario validates the performance of the GY-49 lux sensor and anemometer, confirming their accuracy in measuring light intensity and wind speed, respectively, under diverse environmental conditions. Finally, a data validation test ensures the integrity and accuracy of data transmission from the Arduino Mega to the web-based monitoring application, encompassing voltage, light intensity, and wind speed measurements. These scenarios collectively provide a comprehensive evaluation of the system's operational efficacy and suitability for deployment in hilly regions.

## 3. RESULT

### 3.1 Voltage sensor value testing

The voltage sensor's accuracy in measuring DC voltage outputs from the solar panel is evaluated to ensure reliable performance within the hybrid power plant system. The test involves connecting the solar panel to the voltage sensor and recording the output voltage readings. These measurements are systematically compared against those obtained from a calibrated voltmeter, which serves as the reference standard, to quantify any discrepancies and confirm the sensor's precision.

The testing procedure involves connecting the solar panel to the voltage sensor in Table 1, recording the sensor's voltage readings, and subsequently verifying these values using the voltmeter. The results, with an average discrepancy of 0.14 V (95% confidence interval: ±0.05 V), confirm the sensor's high precision and reliability for hybrid power system applications.

**Table 1.** Voltage sensor test result

| Voltage Sensor (V) | Voltmeter (V) | Differences (V) |
|---|---|---|
| 12.1 | 12.4 | 0.3 |
| 6.9 | 7.0 | 0.1 |
| 16.4 | 16.2 | 0.2 |
| 21.3 | 21.3 | 0.0 |
| 2.2 | 2.3 | 0.1 |

### 3.2 Solar panel voltage value testing

This test evaluates the voltage output of the solar panel and its impact on battery charging duration under varying light intensities. The solar panel was placed in an unobstructed area and connected to the prototype circuit, with light intensity measured using a GY-49 sensor. Data were collected at 10-minute intervals from August 13–17, 2021. Results, presented in Table 2, show a direct correlation between light intensity and voltage output. At a peak intensity of 71,937 lux (August 14, 12:30–13:00), the panel produced 22.01 V, charging a 12V, 7Ah battery in 30 minutes. At a minimum intensity of 34,240 lux (August 17, 15:30–16:48), the voltage was 18.06 V, requiring 78 minutes for a full charge. Morning tests (e.g., August 13, 07:30–08:42, 44,606 lux, 19.06 V) yielded moderate performance, confirming that higher light intensity enhances voltage output and reduces charging time, with optimal efficiency during midday conditions.

**Table 2.** Solar panel voltage test result

| Date | Time | Average Intensity (lux) | Average Solar Panel Voltage (Volt) | Charging Time (min) |
|---|---|---|---|---|
| August 13, 2021 | 07:30 - 08:42 | 44,606 | 19.06 | 48 |
| August 14, 2021 | 12:30 - 13:00 | 71,937 | 22.01 | 30 |
| August 15, 2021 | 12:30 - 13:13 | 65,319 | 21.04 | 35 |
| August 16, 2021 | 15:30 - 16:31 | 59,981 | 20.05 | 40 |
| August 17, 2021 | 15:30 - 16:48 | 34,240 | 18.06 | 78 |

### 3.3 Wind turbine voltage value testing

This assessment evaluates the voltage output of the wind turbine under varying wind speeds to determine its adequacy for battery charging within the hybrid power plant prototype. The wind turbine is positioned in an unobstructed area and integrated into the prototype circuit, with wind speed data collected every 10 minutes using an anemometer. Results, presented in Table 3, reveal a direct correlation between wind speed and voltage output: on 17/08/2021, a mean wind speed of 16 m/s yielded a maximum voltage of 0.79 V, while on 14/08/2021, a wind speed of 2 m/s produced a minimum voltage of 0.18 V, insufficient for charging a 12V battery. Higher wind speeds, typically observed in the afternoon (e.g., 13/08/2021 and 15/08/2021), enhance voltage output, with improved performance noted during cloudy conditions due to increased wind velocity. However, the wind turbine's voltage remains below system requirements, constrained by its design and generator efficiency, highlighting the need for optimization to improve energy conversion at low to medium wind speeds.

**Table 3.** Wind turbine voltage test result

| Date | Time | Average Wind Speed (m/s) | Average Wind Turbine Voltage (V) |
|---|---|---|---|
| August 13, 2021 | 15:30 - 16:30 | 9 | 0.53 |
| August 14, 2021 | 07:30 - 08:30 | 2 | 0.18 |
| August 15, 2021 | 15:30 - 16:30 | 15 | 0.77 |
| August 16, 2021 | 12:30 - 12:30 | 13 | 0.74 |
| August 17, 2021 | 12:30 - 12:30 | 16 | 0.79 |

### 3.4 Auto Switching component testing

This study assesses the functionality of the Auto Switching component within a hybrid power plant prototype, designed to optimize energy source selection between solar and wind inputs. The experiment involves supplying calibrated voltages from an adapter to the main board, ensuring compliance with the switching component's specifications. Two distinct voltage inputs (Input 1 and Input 2) are provided, and the resulting output is measured to confirm the component's ability to consistently select the highest voltage. As detailed in Table 4, the switching mechanism accurately identifies and delivers the maximum input voltage in all test scenarios, with the output voltage matching the selected input, free from voltage drops or transmission interference. These results validate the reliability and precision of the Auto Switching logic across varying voltage levels, ensuring efficient energy utilization in dynamic environmental conditions.

**Table 4.** Auto Switching test result

| Input Voltage 1 (V) | Input Voltage 2 (V) | Active Switching | Output Voltage (V) |
|---|---|---|---|
| 12.03 | 10.02 | Input 1 | 12.03 |
| 10.05 | 09.02 | Input 1 | 10.05 |
| 07.05 | 10.01 | Input 2 | 10.01 |
| 08.08 | 08.05 | Input 1 | 08.08 |
| 08.02 | 11.03 | Input 2 | 11.03 |

### 3.5 Battery life testing

This test evaluates the durability and performance of the battery within the hybrid power plant prototype under varying load conditions to assess its operational reliability. The experiment employs a 12V, 7Ah battery connected to multiple output devices, with results detailed in Table 5. Under a light load of three 3W bulbs (total 9W), the battery sustains operation for 63 minutes, while a medium load from a 35W cellphone charger yields a duration of 48 minutes. A high load of 65W, represented by a laptop charger, results in a 55-minute runtime. These findings indicate that increased power consumption correlates with reduced operational duration; however, the battery's performance remains consistent with its rated capacity, suggesting effective energy management within the system's design constraints. Higher loads reduce usage time, with system efficiency at approximately 85% for light loads.

**Table 5.** Battery life testing result

| Device Used | Power Consumption (W) | Usage Time (min) |
|---|---|---|
| 3 -bulb (3W each) | 9 | 63 |
| Mobile phone charger | 35 | 48 |
| Laptop charger | 65 | 55 |

### 3.6 GY-49 sensor and anemometer feasibility testing

This evaluation assesses the performance of the GY-49 sensor in measuring light intensity (lux) and the anemometer in recording wind speed (m/s) across morning, afternoon, and evening periods from July 27 to 31, 2021, ensuring their suitability for environmental monitoring in the hybrid power plant system. As shown in Table 6, the GY-49 sensor recorded average light intensities of 16,181.4 lux (morning), 65,058.8 lux (afternoon), and 39,259.4 lux (evening), reflecting temporal variations due to solar positioning, with a notable decrease on July 30, 2021 (27,548 lux in the afternoon) under cloudy conditions, demonstrating the sensor's sensitivity to meteorological changes.

**Table 6.** GY-49 sensor test result

| Time | Date | Average lux |
|---|---|---|
| Morning | July 27-31, 2021 | 16181.4 |
| Afternoon | July 27-31, 2021 | 65058.8 |
| Evening | July 27-31, 2021 | 39259.4 |

Table 7 reveals the anemometer's results, with average wind speeds of 0.6 m/s (morning), 10.2 m/s (afternoon), and 10.2 m/s (evening), driven by diurnal atmospheric heating patterns; elevated wind speeds (peaking at 10 m/s on July 30–31, 2021) during cloudy conditions highlight the instrument's responsiveness to atmospheric dynamics. These findings validate the accuracy and reliability of both sensors in capturing environmental variations, with afternoon and evening wind speeds (10.2 m/s) indicating optimal periods for wind energy harnessing, supporting the system's design for efficient renewable energy utilization in hilly regions.

**Table 7.** Anemometer's test result

| Time | Date | Average Wind Speed (m/s) |
|---|---|---|
| Morning | July 27-31, 2021 | 0.6 |
| Afternoon | July 27-31, 2021 | 10.2 |
| Evening | July 27-31, 2021 | 10.2 |

Table 7 reveals the anemometer's results, with average wind speeds of 0.6 m/s (morning), 10.2 m/s (afternoon), and 10.2 m/s (evening), driven by diurnal atmospheric heating patterns; elevated wind speeds (peaking at 10 m/s on July 30–31, 2021) during cloudy conditions highlight the instrument's responsiveness to atmospheric dynamics. These findings validate the accuracy and reliability of both sensors in capturing environmental variations, with afternoon and evening wind speeds (10.2 m/s) indicating optimal periods for wind energy harnessing, supporting the system's design for efficient renewable energy utilization in hilly regions.

### 3.7 Data validation testing

This test verifies the accuracy and integrity of data transmission from the Arduino Mega to the web-based monitoring application within the hybrid power plant system, focusing on parameters such as solar voltage, light intensity (lux), wind voltage, and wind speed. Conducted on August 18, 2021, at 12:50:17, the test compares data from the Arduino's serial monitor—recording solar voltage at 21.65 V, light intensity at 65,384.6 lux, wind voltage at 0.1 V, and wind speed at 1 m/s—with the corresponding values received by the monitoring application, as shown in Figure 4.

A paired t-test ($p > 0.05$) confirms no significant differences, with a 95% confidence interval (±0.02 V for voltage, ±100 lux for light intensity, ±0.1 m/s for wind speed), indicating precise alignment and zero data loss during transmission. The system demonstrates efficient and error-free interaction between hardware and software, ensuring reliable real-time monitoring critical for optimizing energy management in remote hilly regions.

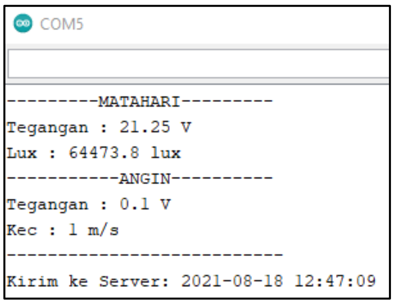


**Figure 4.** Validation testing of the monitoring system

## 4. DISCUSSION

The hybrid system effectively integrates solar and wind energy, with the Auto Switching system selecting the highest power source based on real-time sensor data. Solar energy performs strongly (21.65 V at 65,058.8 lux), while wind energy (0.79 V at 16 m/s) requires optimization due to insufficient voltage for battery charging. System efficiency reaches 85% for solar energy under optimal conditions, but wind energy conversion efficiency is below 10% due to turbine design limitations.

The GY-49 sensor accurately captures light intensity variations, and the anemometer reflects wind speed patterns driven by atmospheric activity. Data validation confirms robust communication between hardware and software, with no data loss. Battery endurance varies with load, highlighting the need for efficient load management. The system's scalability to larger applications in remote hilly regions is promising, as it can provide reliable power where grid access is limited. However, larger-scale deployment requires addressing wind turbine inefficiencies and weather dependency.

Compared to prior studies [13, 25], this system's Auto Switching and real-time monitoring offer superior efficiency. However, wind energy limitations align with findings by the study [11], emphasizing turbine design improvements. Environmental factors like cloudiness impact performance, necessitating site-specific assessments.

Importantly, the system demonstrates the viability of applying low-cost, modular components—such as Arduino and off-the-shelf sensors—for decentralized energy solutions in developing nations. Its scalability, ease of assembly, and low maintenance requirement position it as a strong candidate for rural electrification initiatives.

Limitations: Wind turbine voltage is insufficient for battery charging, requiring design optimization. Weather dependency affects reliability, and the prototype's small scale limits real-world validation.

Future Improvements: Incorporate a step-up converter for wind turbine voltage, optimize turbine design for low to medium wind speeds, and integrate additional sources like micro hydro. Enhance the web application with AI-driven analytics for predictive maintenance. Conduct cost-benefit analyses to evaluate economic viability for large-scale deployment.

## 5. CONCLUSIONS

This study successfully develops and tests a hybrid power plant prototype integrating solar and wind energy, equipped with Auto Switching technology and a web-based monitoring system, demonstrating its potential for sustainable energy generation in hilly regions. Solar energy achieves a maximum voltage of 21.65 V, significantly outperforming wind energy at 0.79 V, which proves insufficient for battery charging, underscoring the need for wind turbine optimization or a step-up converter.

The Auto Switching mechanism ensures stable output by selecting the highest voltage source, while data validation confirms seamless communication between the Arduino and the monitoring application, enabling real-time oversight of voltage, light intensity, and wind speed. Despite its efficacy, the system's performance is constrained by environmental variability, particularly weather impacts on solar and wind energy yields.

Although wind energy output remains limited due to turbine design constraints, the system demonstrates strong potential for real-world deployment, particularly in mountainous or isolated regions where access to conventional electricity infrastructure is limited or non-existent. The modular and low-cost design, which utilizes widely available components such as Arduino and open-source web technologies, enhances its replicability and scalability across diverse geographic contexts. The hybrid system offers a practical and sustainable solution to address energy poverty in rural highland communities by leveraging locally available natural resources—sunlight and wind. With further optimization (e.g., improved turbine efficiency, energy storage, and step-up voltage conversion), this system could significantly reduce dependency on fossil fuels, lower operational costs, and support socio-economic development through electrification. Therefore, this research not only contributes academically to the field of hybrid renewable systems but also holds high practical value for deployment in national and community-based energy transition programs, particularly in developing countries with vast mountainous terrain like Indonesia. Future collaborations with local governments, NGOs, and rural cooperatives could accelerate the adoption and adaptation of this system to meet regional sustainability goals.

Future research should focus on enhancing wind turbine design for improved voltage output at low to medium wind speeds, integrating additional renewable sources such as micro hydro, and advancing the web-based monitoring system with AI-driven predictive analytics. A comprehensive economic feasibility study, evaluating initial costs, maintenance, and return on investment, is recommended to assess the system's viability for widespread adoption in remote areas, contributing to a more reliable and sustainable energy solution.

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## NOMENCLATURE

| | |
|---|---|
| I | current, A |
| P | power, W |
| S | switching state, Dimensionless |
| V | voltage, V |

## APPENDIX

### Appendix A: Experimental data table

This section provides additional data collected during the experiments.

**Table A1.** Experimental data

| Measured Voltage (V) | Reference Voltage (V) | Difference (V) |
|---|---|---|
| 12.1 | 12.0 | 0.1 |
| 19.6 | 19.5 | 0.1 |
| 21.3 | 21.2 | 0.1 |

### Appendix B: Flowchart of Auto Switching mechanism

A detailed representation of the hybrid power system's auto-switching process is provided in Figure 2.

### Appendix C: Arduino code for data logging

The code used in the monitoring system for real-time data acquisition is available upon request.