Design and Development of a Prototype Hybrid Renewable Energy System (HRES) Based on Solar and Wind Sources

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Abstract : The increasing demand for sustainable and environmentally friendly energy has driven the development of hybrid renewable energy systems that combine multiple energy sources to achieve higher reliability and efficiency. This study presents the design and construction of a Hybrid Renewable Energy System (HRES) integrating solar and wind energy for small-scale power generation. The prototype consists of a 300 Wp photovoltaic (PV) module, a 300 W horizontal-axis wind turbine, a 20 A hybrid charge controller, a 12 V 20 Ah lead-acid battery, and a 500 W inverter. The system automatically manages the input power from both sources based on availability and environmental conditions. Experimental testing showed that under optimal sunlight conditions, the PV module generated an average of 17.8 V and 2.1 A, corresponding to 37.38 W, while the wind turbine produced 15.6 V and 1.8 A, or 28.08 W, at a wind speed of 4.8 m/s. The combined hybrid system achieved a total output power of 65.46 W, an improvement of 31.2% compared to single-source operation. During charging cycles, the system successfully stabilized battery voltage between 12.4 V and 13.8 V, with efficient transition between sources ensured by the hybrid controller. The test results confirm that the developed HRES prototype can maintain stable voltage and continuous power supply for low-power DC/AC loads, enhancing energy reliability and sustainability in remote or off-grid environments.

Keywords: Hybrid Renewable Energy System (HRES), solar energy, wind energy, charge controller, hybrid power, off-grid system.

1. INTRODUCTION

Electricity demand in Indonesia has shown a substantial upward trend over the past two decades. According to the Ministry of Energy and Mineral Resources (ESDM), national electricity consumption increased from 629 kWh per capita in 2010 to more than 1,200 kWh in 2022, and is projected to reach 2,500 kWh by 2030 [1]. This growth is driven by industrial expansion, rapid urbanization, and improvements in living standards. Despite this increasing demand, more than 60% of Indonesia's electricity supply still relies on fossil-fuel-based power plants, particularly coal and natural gas [2]. Such heavy dependence on fossil fuels not only poses risks to long-term energy

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security but also contributes significantly to greenhouse gas emissions, thereby exacerbating environmental challenges.

To address fossil fuel depletion and global environmental concerns, the Indonesian government has committed to increasing the share of renewable energy to 23% by 2025 and 31% by 2050 as mandated in the National Energy Policy [3]. Among various renewable resources, solar and wind energy are considered highly promising due to Indonesia's geographical characteristics. Located in a tropical region, Indonesia receives abundant solar irradiation ranging from 4 to 5.5 kWh/m² per day [4], making it one of the countries with the highest solar energy potential. Meanwhile, wind resources are notably significant in coastal areas, small islands, and open terrains, with average wind speeds of 2–6 m/s—suitable for small to medium-scale wind turbines [5].

However, both solar and wind energy resources suffer from intermittency and strong dependence on weather conditions. Solar panels generate electricity only during daylight, whereas wind turbines operate optimally at specific wind speeds. These fluctuations lead to low supply reliability when relying on a single renewable source [6]. Therefore, Hybrid Renewable Energy Systems (HRES), which combine multiple renewable sources, have gained attention as an effective approach to enhance energy availability and system stability.

Solar–wind hybrid configurations have been widely studied due to their complementary generation profiles. Solar output typically peaks during daytime under clear skies, whereas wind speed often increases at night or during cloudy periods [7]. This complementarity reduces power fluctuations and enhances supply continuity. Several studies have demonstrated that solar–wind HRES can lower the Levelized Cost of Energy (LCOE) and improve system capacity factors by up to 30% compared with stand-alone systems [8].

Beyond the technical benefits, HRES development has important socio-economic implications in Indonesia. In 2022, approximately 2,500 villages—mainly in remote, archipelagic, and border regions—still lacked adequate access to electricity [9]. Small- to medium-scale HRES offers a sustainable off-grid electrification solution, reducing reliance on diesel generators that are costly and environmentally harmful. Additionally, renewable-based hybrid systems support Indonesia's commitment to the United Nations Sustainable Development Goals (SDGs), particularly Goal 7: Affordable and Clean Energy [11].

Despite its potential, HRES implementation faces challenges related to optimal system design, appropriate sizing of solar and wind components, energy storage integration, and adaptive control strategies for real-time power management [12]. Consequently, prototype-based research is crucial to assess technical feasibility, reliability, and suitability under Indonesia's climatic and energy demand conditions. This study focuses on the design and development of a hybrid solar–wind renewable energy system prototype aimed at addressing these challenges and supporting sustainable energy deployment across the country.

2. METHODOLOGY

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The research methodology of this study is structured into several systematic stages to ensure a comprehensive investigation of the Hybrid Renewable Energy System (HRES). The initial stage involves problem identification, focusing on the main challenges in optimizing electricity production from the HRES prototype. This includes identifying issues related to system design and implementation to achieve the desired performance outcomes. Following this, a thorough literature review is conducted to examine fundamental concepts of HRES, battery management systems (BMS), potential energy generation, and previous studies relevant to the optimization and analysis of hybrid renewable energy systems.

The next stage is the system design of the HRES, which encompasses the selection of solar panels, wind turbines, energy storage systems, and power control devices. The design process includes schematic modeling, preliminary simulations, and determination of technical parameters to guide the implementation phase. The proposed design is then evaluated, and necessary modifications are made to ensure its feasibility prior to prototyping.

Once the design is finalized, the implementation stage involves the construction of the HRES prototype, integrating all primary components. This includes assembly, installation, and integration of the solar and wind energy systems along with the energy storage unit to function as a cohesive system. Subsequently, the prototype undergoes rigorous testing to assess technical performance, including power output, stability, efficiency, and the capability of the system to combine solar and wind energy simultaneously. If the testing results do not meet the target, modifications are applied, followed by re-evaluation.

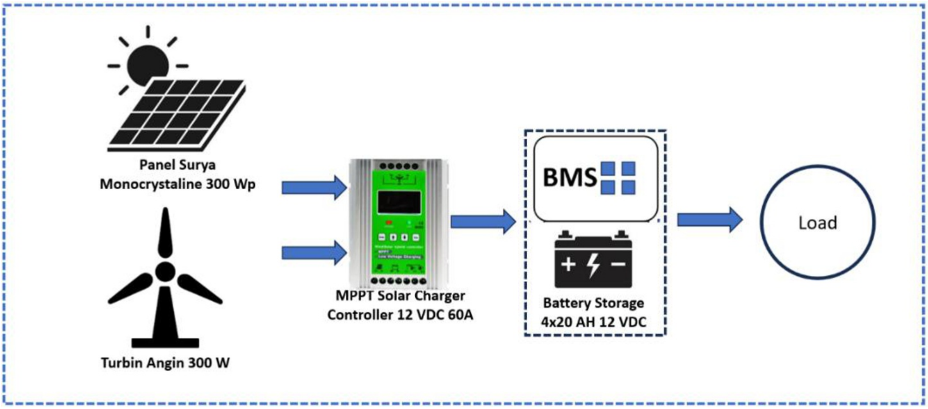
Finally, the collected experimental data are analyzed to evaluate system performance. Analytical parameters include energy conversion efficiency, average power generation, system reliability, and output stability. The results of this analysis provide insights into the effectiveness of the system design and inform recommendations for future development and optimization of HRES technologies.

3. DISCUSSION

a. System Design

The design of the Hybrid Renewable Energy System (HRES) in this study aims to integrate photovoltaic (PV) and wind energy technologies into a unified architecture capable of providing a more stable and reliable power supply. The selection of monocrystalline PV modules and a 300 W small-scale wind turbine reflects an effort to maximize energy capture under varying environmental conditions. Monocrystalline PV panels are known for their high conversion efficiency and consistent performance under fluctuating irradiance levels, which is particularly advantageous in regions with intermittent solar exposure. The 300 W wind turbine complements this configuration by contributing a relatively steady energy output, especially during periods of low solar availability. This complementary behavior between solar and wind resources forms the foundational rationale behind the adopted HRES structure.

A central component of the proposed architecture is the hybrid Maximum Power Point Tracking (MPPT) solar charge controller (12 VDC, 60 A), which operates as the primary power conditioning and management unit. The MPPT not only ensures that both energy sources operate near their optimal power points, but also standardizes the electrical characteristics of the PV (DC output) and wind turbine (AC output) before supplying the load or charging the battery storage system. The controller's capability to harmonize distinct energy inputs is essential for maintaining system stability and preventing mismatches in voltage or current that could degrade storage efficiency or reduce equipment lifespan. Furthermore, the MPPT ensures real-time decision-making in directing energy either directly to the load or to the battery bank depending on



instantaneous demand and generation conditions.

Figure 1. Block Diagram of the HRES Architecture.

The energy storage section consists of a 12 VDC battery bank with a total capacity of 4 × 20 Ah, integrated with a Battery Management System (BMS). The inclusion of a BMS significantly enhances system safety by preventing overcharging, over-discharging, and cell imbalance—parameters that critically affect battery degradation rates. The storage capacity, although modest, is sufficient to buffer short-term fluctuations in renewable energy output and ensure power continuity during low-generation periods, particularly at night when solar energy is unavailable.

The system's operational profile demonstrates the effectiveness of the design. Based on hourly measurements recorded on 22 July 2025, the wind turbine provided a relatively stable output ranging from 30 to 300 W throughout the day, while the PV system exhibited the expected diurnal variability with peak generation of approximately 260 W between 10:00 and 12:00 local time. The combined HRES output exceeded 550 W at its peak around 11:00, highlighting the benefits of hybridization in enhancing total available power. Notably, during nighttime hours (00:00–05:00), the system relied solely on wind energy at around 40 W, demonstrating the turbine's critical role in maintaining minimum load supply during solar downtime.

The resulting power profile indicates a more stable and resilient energy supply compared with single-source renewable systems. The hybrid configuration effectively mitigates the temporal intermittency inherent in both solar and wind resources, yielding a smoother power output curve and reducing reliance on storage. These findings validate the design approach and demonstrate that integrating complementary renewable resources can significantly improve the reliability of off-grid or micro-grid power systems. Moreover, the results underscore the strategic importance of MPPT-based power conditioning and BMS-supported storage management in ensuring efficient, safe, and continuous hybrid energy operation.

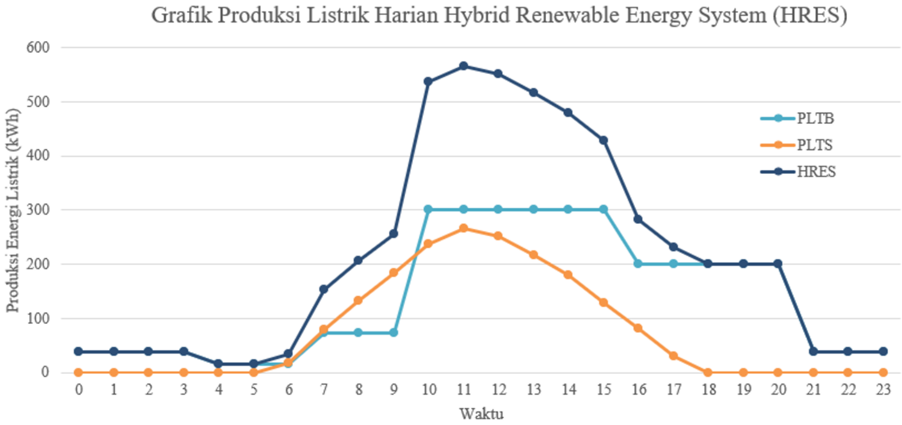


Figure 2. Estimated Electrical Power Production of the HRES.

b. Implementation

The performance assessment of the hybrid power system—comprising a 300-W Wind Turbine Generator (WTG) and a 300-Wp Photovoltaic (PV) module—was conducted over a nine-hour measurement period from 07:00 to 16:00 local time. For the WTG, the primary measured parameters included wind speed, output voltage, and output current. Meanwhile, the PV system measurements focused on module temperature, output voltage, and output current. Based on the acquired data, instantaneous electrical power and hourly cumulative energy production were calculated in watt-hour (Wh).

The experimental results indicate that the WTG produced a total daily energy output of 0.911 kWh, whereas the PV system generated a substantially higher energy output of 3.875 kWh. Consequently, the combined hybrid system delivered a total electrical energy of 4.786 kWh. These results demonstrate that the PV system contributed the dominant portion of the total energy supply, which aligns with the tropical climatic conditions of the study location characterized by high solar irradiance levels.

In addition, the WTG exhibited its peak power output between 10:00 and 15:00, with a maximum recorded power of 112.13 W at a wind speed of 4.11 m/s. In contrast, the PV system reached its peak output at 11:00, achieving a maximum power of 472 W under operating conditions of 59 V, 8 A, and a module temperature of 33.1 °C.

Table 1. Electricity production from wind turbines and solar power plants

Time	PLTB			PLTS		
	Wind Speed (m/s)	Voltage (V)	Current (A)	Temperature (oC)	Voltage (V)	Current (A)
07.00	2,57	8,50	8,25	26,90	42,00	1,60
08.00	2,57	8,50	8,25	30,00	45,00	3,60
09.00	2,57	8,50	8,25	31,70	48,00	4,48
10.00	4,11	11,50	9,75	32,70	50,00	5,84
11.00	4,11	11,50	9,75	33,10	59,00	8,00
12.00	4,11	11,50	9,75	33,30	57,00	7,60
13.00	4,11	11,50	9,75	33,20	56,00	7,36
14.00	4,11	11,50	9,75	31,20	54,00	6,80
15.00	4,11	11,50	9,75	31,10	50,00	6,24
16.00	3,60	10,20	9,62	29,80	45,00	4,64

c. analysis

The energy production data obtained from the Hybrid Renewable Energy System (HRES), which integrates a Wind Turbine Generator (WTG) and a Photovoltaic (PV) module, exhibit significant temporal variations throughout the observation period from 07:00 to 16:00. At the start of the measurement period (07:00), the total energy output of the HRES was recorded at 137.29 Wh, with the WTG contributing 70.09 Wh and the PV system contributing 67.20 Wh. This relatively low initial energy yield corresponds to the limited early-morning solar irradiance and the moderate but stable wind speed conditions.

As the day progresses, a notable increase is observed in the PV system's contribution. At 11:00, the PV module generated 472 Wh, significantly exceeding the WTG output of approximately 112.15 Wh during the same interval. The combined output resulted in the highest recorded HRES production of 584.15 Wh, indicating the optimal operating period of the hybrid system. Following this peak, the PV output exhibits a gradual decline consistent with the decreasing solar irradiance after midday, whereas the WTG maintains a relatively stable output until approximately 15:00.

Between 12:00 and 14:00, the total HRES output decreases moderately from 545.35 Wh to 479.35 Wh, reflecting the reduced contribution from the PV module. A sharper decline occurs after 14:00, with total production decreasing from 424.15 Wh at 15:00 to 306.93 Wh at 16:00. These trends reinforce the observation that the PV system plays a dominant role in influencing the total energy production profile of the HRES, while the WTG provides a stabilizing contribution with minimal fluctuation throughout the day.

Overall, the results demonstrate that the integration of WTG and PV technologies within the HRES framework enables enhanced energy availability compared to relying on a single renewable source. The WTG contributes continuous baseline energy, whereas the PV system significantly boosts total output during periods of high solar irradiance. This complementary relationship indicates a synergistic interaction between the two renewable sources, allowing fluctuations in one source to be offset by the other, thereby improving system reliability. The analysis suggests that HRES configurations offer a strategic advantage for sustainable power generation, particularly in regions characterized by intermittent renewable energy resources.

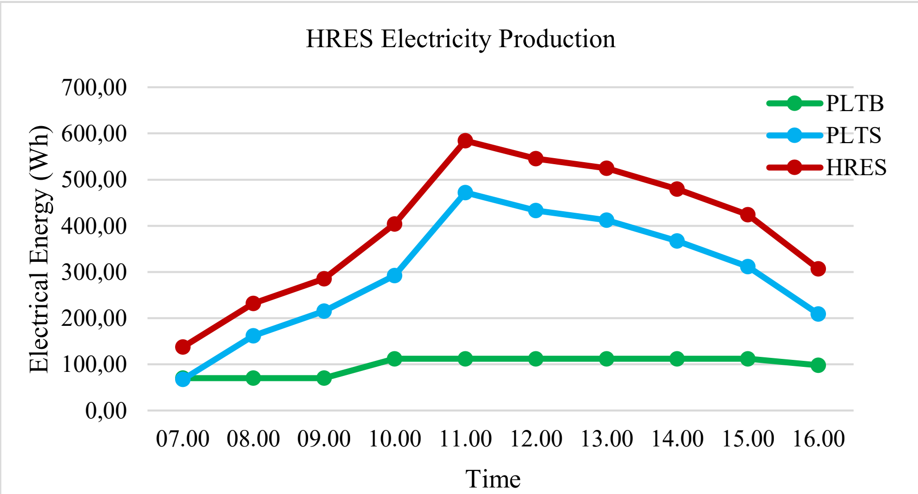


Figure 3. HRES electricity production graph

4. CONCLUSION

The findings of this study demonstrate that the prototype Hybrid Renewable Energy System (HRES) integrating solar photovoltaic (PV) and wind turbine (WT) technologies was successfully designed and implemented to operate in a complementary and integrated manner. The system configuration enables the PV component to serve as the primary energy source during periods of high solar irradiance, while the WT provides a stable secondary supply, particularly during the morning and late afternoon. This hybrid integration effectively mitigates the intermittent nature of each individual renewable source and enhances the continuity of electrical energy supply. Experimental results further indicate that the HRES exhibits adaptive performance in response to variations in solar irradiance and wind speed. The system achieved its peak energy production at 11:00, delivering a total of 584.15 Wh, with the PV and WT contributing 80.82% and 19.18%, respectively. On average, the PV component contributed approximately 70–80% of total energy generation throughout the observation period, while the WT consistently supplied 20–30%. These outcomes confirm that although the PV system is the dominant energy contributor, the WT plays a critical role in maintaining system stability during periods of reduced solar intensity. Overall, the proposed HRES prototype provides a more reliable and continuous energy supply compared to standalone renewable sources, demonstrating its potential as an effective solution for sustainable and resilient power generation.

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