



Hybrid Renewable Energy System: Sustainable Ideas for the Future

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ABSTRACT

This study explores the role of Hybrid Renewable Energy Systems (HRES) in advancing sustainable energy transitions, particularly in reducing carbon emissions and reliance on fossil fuels. A descriptive-quantitative research methodology is applied, supported by an engineering simulation approach to model and evaluate system performance. The research focuses on assessing how hybrid systems combining solar photovoltaic (PV) and wind energy can contribute to emission reduction and energy diversification. Analysis of technical data, including solar radiation and daily wind speed patterns, indicates that PV systems have strong potential to generate electricity consistently throughout the year, especially in tropical regions. In contrast, wind energy potential is comparatively lower in areas with modest wind speeds; however, wind turbines still play a valuable complementary role, particularly during periods when solar output is limited, such as nighttime or rainy seasons. Integrating these two sources into a hybrid system enhances overall energy efficiency and system performance. The findings show that such a combination can: (1) directly reduce carbon emissions by approximately 22.7 tons of CO₂ annually from the PV system alone; (2) diversify energy sources, thereby decreasing dependence on fossil fuels; and (3) improve the reliability of electricity supply, especially in remote regions or areas not connected to the PLN grid.

Overall, HRES emerges as a practical, efficient, and sustainable solution for meeting the energy demands of small- to medium-scale communities. Additionally, it supports energy decentralization, fosters the development of a green economy, and reinforces Indonesia's commitment to achieving future net-zero emission targets.

Keywords: Sustainable Energy, Renewable Energy, Hybrid Renewable Energy System (HRES)



INTRODUCTION

The growing global reliance on fossil fuels such as coal, oil, and natural gas has made the energy crisis increasingly evident. At the same time, energy demand continues to rise due to population growth and economic development. This imbalance between supply and demand, along with fluctuating prices and geopolitical tensions, has intensified the global energy crisis and highlighted the urgent need to transition toward renewable energy sources. Although fossil fuel consumption follows a predictable long-term trend, it remains difficult to replace entirely in the short term despite increasing environmental and policy pressures.

The ongoing energy crisis has accelerated interest in improving energy efficiency and expanding the use of renewable energy sources such as solar, wind, and geothermal. Transitioning to renewable energy is essential not only for ensuring environmental sustainability but also for meeting global climate targets. Investments in clean energy technologies, diversification of energy sources, and efficiency improvements are crucial strategies for reducing dependence on fossil fuels. In addition, supportive policies, financial incentives, and regional energy market integration play an important role in accelerating the shift toward greener energy systems. Overall, addressing the fossil fuel crisis and growing energy demand requires fundamental changes in how energy is produced and consumed globally. Energy crises are often caused by imbalances between supply and demand, economic instability, insufficient investment in energy infrastructure, and geopolitical conflicts such as the Russia–Ukraine war. These crises have significant economic and social consequences, including rising energy prices, inflation, increased energy poverty, slower economic growth, and even the risk of recession in some regions. Furthermore, heavy reliance on fossil fuels contributes significantly to greenhouse gas emissions and accelerates the depletion of natural resources.

The environmental impact of conventional energy sources is substantial. The use of fossil fuels is a major contributor to greenhouse gas emissions, particularly CO₂, which drives global warming and climate change. Even small increases in fossil fuel consumption can lead to significant rises in emissions. In addition to CO₂, fossil fuel combustion releases pollutants such as sulfur dioxide (SO₂) and particulate matter (PM₁₀), which negatively affect air quality and human health. Long-term environmental consequences also include land degradation, water pollution, and biodiversity loss. In contrast, renewable energy sources such as solar, wind, and hydropower produce significantly lower emissions over their life cycles, improve environmental quality, and help reduce ecological footprints. Enhancing energy efficiency and increasing the share of renewable energy are therefore critical steps toward achieving environmental sustainability.

To address these challenges, several technological solutions and innovations have been proposed. One key approach is the development of hybrid energy systems that combine multiple renewable sources, such as solar and wind, to reduce variability and improve supply reliability. In addition, optimizing energy storage systems and implementing smart grid technologies are essential for balancing energy supply and demand. Policy support, government incentives, and collaboration between public and private sectors are also vital in promoting renewable energy adoption. Despite the vast potential of renewable energy, challenges such as output fluctuations, storage limitations, technical integration, and financing constraints still need to be addressed. Continued innovation, hybrid system development, and supportive policies are therefore necessary to maximize renewable energy utilization.

A stable, efficient, and flexible energy system is crucial for ensuring a reliable electricity supply, particularly with the increasing integration of variable renewable energy sources. Combining different energy sources—both conventional and renewable—with energy storage and intelligent control systems can enhance system stability and efficiency. Hybrid systems that integrate components such as solar panels, diesel generators, batteries, and converters have proven effective in meeting continuous energy demand in both off-grid and grid-connected applications. These systems can significantly reduce energy costs and carbon emissions while offering flexibility in responding to changes in energy demand and pricing. Similarly, multi-energy systems that integrate various energy forms and employ predictive load management can substantially reduce grid energy consumption, operational costs, and primary energy use.

Energy storage systems play a critical role in stabilizing renewable energy systems, particularly those relying on solar and wind power, which are inherently variable. Storage technologies enable better energy management, maintain grid stability, and improve overall system reliability. Additionally, intelligent demand-side management and the use of thermal energy storage can enhance system flexibility, reduce operational costs, and significantly lower peak energy demand.

The development of Hybrid Renewable Energy Systems (HRES) represents an important advancement in addressing these challenges. HRES integrates multiple renewable energy sources—such as solar, wind, biomass, or hydrogen—with energy storage systems or grid connections to provide a more reliable and efficient energy supply. These systems are designed to



improve efficiency, increase reliability, and reduce both emissions and operational costs. By combining different energy sources and storage technologies, HRES can effectively address the intermittency issues associated with renewable energy and ensure a stable energy supply. Recent developments in HRES technology include the integration of advanced solutions such as Power-to-X technologies, including hydrogen production, which enhance system flexibility and energy utilization. The inclusion of micro-cogeneration systems, such as biomass-based generation, further improves system reliability while reducing carbon emissions. Advances in optimization techniques—such as artificial intelligence, metaheuristic algorithms, and simulation tools like HOMER Pro—have also played a significant role in improving system design, sizing, and operational strategies. These technologies enable more efficient energy management, helping to balance supply and demand while minimizing costs and emissions.

HRES applications are expanding across various sectors, including rural and remote areas, industrial systems, and microgrids, where they provide reliable and sustainable energy solutions. Studies have shown that HRES can reduce energy costs, increase the share of renewable energy, and significantly lower emissions compared to conventional energy systems. As a result, HRES continues to gain attention as a promising solution for future energy systems. From a sustainable development perspective, HRES plays a strategic role in achieving key goals such as access to clean and affordable energy, climate change mitigation, and energy independence. By combining multiple renewable energy sources and storage technologies, HRES enhances system reliability, improves efficiency, and reduces environmental impacts. Its flexibility allows for a wide range of applications, including electricity generation, heating and cooling, hydrogen production, and energy supply for remote communities. With strong support from policy frameworks, technological innovation, and system optimization, HRES has significant potential to support the global transition toward sustainable energy systems.

Based on this background, this study aims to analyze the potential contribution of Hybrid Renewable Energy Systems in supporting future sustainable energy transitions, particularly in reducing carbon emissions and decreasing dependence on fossil fuels.

METHODOLOGY

This research adopts a descriptive-quantitative approach combined with simulation-based techniques. The primary objective is to model and evaluate the contribution of a Hybrid Renewable Energy System (HRES) in reducing carbon emissions and decreasing reliance on fossil fuels. The study applies a simulation design along with comparative analysis. Different HRES configurations—such as combinations of solar and wind energy systems—are modelled and tested under various scenarios. The performance of each configuration is then evaluated based on its ability to generate clean energy, reduce carbon emissions, and minimize dependence on fossil-based energy sources. Simulation processes are conducted using renewable energy modelling tools, including HOMER Pro and MATLAB/Simulink. These tools enable accurate system design, optimization, and performance analysis under varying environmental and operational conditions. Data used in this study consist of renewable energy resource parameters specific to the selected location. This includes key inputs such as solar radiation intensity and average daily wind speed, which are essential for realistic system simulation.

The data analysis is carried out through several systematic stages:

- analysis of energy demand requirements,
- evaluation of renewable energy resource availability,
- simulation and modelling of the HRES configurations, and
- assessment of their contribution to supporting sustainable energy transitions.

RESULT AND DISCUSSION

Renewable energy resources data and analysis:

1. Technical Assumptions

a. Photovoltaic (PV) Systems:

- Panel area: 100 m²
- Panel efficiency: 18%
- System performance ratio: 0.75

b. Wind Turbine System:

- Rotor area: 10 m²



- Power coefficient (C_p): 0.35
- Air density: 1.225 kg/m^3
- Operating hours: 24 hours/day

2. Monthly Energy Estimate

Month	PV Energy (kWh)	Wind Energy (kWh)
Jan	1,883	15.34
Feb	1,887	9.31
Mar	2.183	11.62
Apr	2.454	21.07
May	2,321	24.12
June	2.280	36.11
Jul	2.418	31.06
Aug	2.240	24.70
Sep	2.009	37.26
Oct	2.009	20.03
Nov	1,806	16.66
Dec	1,725	9.31

3. Annual Total:

- Total annual energy from PV: 25,215 kWh
- Total annual energy from Wind Turbine: 256.58 kWh

Solar Energy Potential

Based on observational data and simulation results, the average daily solar radiation in the study area is approximately $5.19 \text{ kWh/m}^2/\text{day}$. This relatively high and consistent value indicates strong potential for solar energy development in the region. Assuming a photovoltaic (PV) system with a panel area of 100 m^2 , an energy conversion efficiency of 18%, and a performance ratio of 0.75—which accounts for system losses such as temperature effects, wiring, inverter inefficiencies, and shading—the system is capable of generating approximately 25,215 kWh of electricity annually. This level of energy production is sufficient to support the electricity needs of medium-sized households, small communities, or even small-scale industries with moderate energy demands. Monthly generation patterns show that peak energy production occurs between April and July, with outputs exceeding 2,400 kWh per month. The lowest production is observed in December, at around 1,725 kWh. However, this reduction is not significant enough to disrupt overall system performance, as output levels remain within an acceptable range.

These results suggest that seasonal variations have only a limited impact on solar energy generation in the area. Such stability is advantageous for maintaining reliable energy supply and simplifies load management and system planning.

Wind Energy Potential (Wind Turbine)

In contrast to solar resources, the average daily wind speed in the study area is relatively low, with an annual average of about 2.35 m/s and a maximum recorded speed of only 2.89 m/s in September. According to established literature and technical guidelines, small wind turbines typically require a minimum wind speed of around $3\text{--}4 \text{ m/s}$ to operate efficiently. Therefore, the wind conditions in this location are considered suboptimal for effective energy generation.

Using a small wind turbine configuration with a rotor area of 10 m^2 and a power coefficient of 0.35, the estimated annual energy production is approximately 256.58 kWh. This output is significantly lower compared to that of the photovoltaic (PV) system. On a monthly basis, the highest energy production reaches only about 37.26 kWh in September, which is insufficient even for basic household electricity needs.



Energy Strategy Comparison and Recommendations

Parameter	PV System	Wind Turbine
Annual total (kWh)	25.215	256.58
Peak monthly production	2,454 (April)	37.26 (Sept)
Lowest production	1,725 (Dec)	9.31 (Feb/Dec)
Output stability	Tall	Low
Technical feasibility	Very Worth It	Not feasible

The comparison clearly indicates that photovoltaic (PV) systems outperform wind turbines in terms of energy potential, output stability, and overall technical feasibility. On the other hand, wind turbines are not suitable for standalone implementation in the study area. Their use may only be considered on a limited scale as part of a hybrid system, particularly in specific locations with better wind conditions, such as coastal or elevated (hilly) regions. Based on the analysis and evaluation of the available data, solar energy development through PV systems emerges as the most effective and sustainable solution for the study area. The region benefits from high and relatively stable solar radiation throughout the year, making it highly favourable for solar energy utilization. For future implementation, several recommendations can be proposed. First, the development of grid-connected (on-grid) or hybrid PV systems should be prioritized to reduce dependence on the PLN electricity network. Second, integrating energy storage systems, such as batteries, is essential to ensure energy availability during nighttime or periods of low solar radiation, such as cloudy conditions. Finally, improving energy efficiency on the demand side—through measures such as energy audits and load management—can further optimize overall system performance.

Contribution of Hybrid Renewable Energy System (HRES) in Sustainable Energy Transition Global Energy Context and Challenges

The increasing impacts of global climate change, along with ongoing energy crises driven by fluctuations in fossil fuel prices, have compelled many countries—including Indonesia—to shift toward cleaner and more sustainable energy systems. This transition, however, is not without challenges. Key issues include a continued heavy reliance on fossil fuels, high levels of carbon emissions, unequal access to energy, and the variability associated with relying on a single renewable energy source. In response to these challenges, Hybrid Renewable Energy Systems (HRES) have emerged as a strategic solution. HRES integrates two or more renewable energy sources—such as photovoltaic (PV) systems and wind turbines—often combined with energy storage technologies. This integrated approach helps improve energy reliability, reduce emissions, and support a more stable and sustainable energy transition.

Potential Analysis: PV and Wind Data

Based on the technical analysis, the photovoltaic (PV) system generates approximately 25,215 kWh of electricity per year with a high level of consistency. In comparison, the wind turbine produces only about 256.58 kWh annually, mainly due to the low average wind speed of around 2.35 m/s in the study area. These results indicate that solar energy serves as the primary energy source, while wind energy plays a supplementary role. In a hybrid configuration, wind turbines can still provide limited support during periods when solar generation is reduced, such as at night or during cloudy conditions. The integration of both sources within a hybrid system helps decrease reliance on fuel-based power generation and enhances the overall reliability of the electricity supply.

Impact on Carbon Emission Reduction

Electricity generated from renewable energy sources can significantly reduce carbon emissions. On average, each 1 kWh of renewable energy can prevent approximately 0.9 kg of CO₂ emissions when compared to electricity produced from coal-based power plants.

Based on this factor, the photovoltaic (PV) system in this study—producing around 25,215 kWh annually—has the potential to avoid approximately 22,694 kg of CO₂ emissions per year, which is equivalent to about 22.7 tons of CO₂. This level of emission reduction is considerable, particularly if similar systems are implemented across multiple communities, thereby amplifying their overall environmental impact.



Strategic Benefits of HRES in Energy Transition

a. Energy Diversification and Decentralization:

HRES allows for independence from a single source and is suitable for both offgrid and grid-connected systems.

b. Energy Resilience:

The combination of sources improves the continuity of electricity supply.

c. Clean Energy for Remote Areas:

Long-term operating costs are cheaper than diesel generators.

d. Carbon Footprint Reduction:

Replacing PLTD/PLTU reduces carbon emissions and local pollution.

e. Local Green Economy:

Encourage new jobs in the fields of technicians and maintenance.

Despite the well-established potential of renewable energy sources—such as solar, wind, biomass, and hydropower—their large-scale utilization remains constrained by several technical and economic barriers. These limitations prevent optimal deployment and integration into modern energy systems. One of the primary challenges is the variability and intermittency of renewable energy output. Sources like solar and wind are highly dependent on weather conditions and time of day, resulting in fluctuating and often unpredictable energy generation. This variability makes it difficult to ensure a consistent and reliable power supply. Another significant limitation is the current state of energy storage technology. Existing storage systems are not yet sufficiently efficient or cost-effective to store excess energy generated during peak production periods for later use when demand is higher. This gap reduces the overall efficiency and reliability of renewable energy systems.

In addition, integrating renewable energy into existing power grids presents technical challenges. It requires advanced system modifications, including improved inverter technologies, enhanced grid infrastructure, and more sophisticated load management strategies to maintain system stability and balance supply with demand.

Economic and financial constraints also play a critical role. Securing funding for renewable energy projects—particularly at the local or community level—remains a challenge. Furthermore, renewable energy systems must remain cost-competitive with conventional energy sources, which can hinder widespread adoption.

CONCLUSION

Based on the analysis of solar radiation and wind speed data, photovoltaic (PV) systems demonstrate strong technical capability to generate electricity consistently throughout the year, particularly in tropical regions. In contrast, wind energy potential is relatively limited in areas with low average wind speeds. However, wind turbines can still serve a complementary function, especially during periods when solar energy generation is reduced, such as at night or during the rainy season. The integration of these two sources into a Hybrid Renewable Energy System (HRES) enhances overall energy efficiency and system performance. Such a system offers several key advantages. First, it contributes directly to carbon emission reduction, with the PV system alone capable of avoiding approximately 22.7 tons of CO₂ emissions annually. Second, it promotes energy diversification, thereby reducing reliance on a single energy source, particularly fossil fuels. Third, it improves the reliability of electricity supply, which is especially important for remote areas or regions not yet connected to the PLN grid.

In conclusion, HRES represents a practical, efficient, and sustainable approach to meeting the energy demands of small- to medium-scale communities. Furthermore, its implementation supports energy decentralization, encourages the development of a green economy, and reinforces Indonesia's commitment to achieving its future net-zero emission targets.



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