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HYBRID RENEWABLE ENERGY SYSTEM: SUSTAINABLE ENERGY ENGINEERING SOLUTIONS FOR THE FUTURE

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ABSTRACT

This study aims to examine the potential contribution of the Hybrid Renewable Energy System in supporting sustainable energy transitions in the future, especially in the context of reducing carbon emissions and dependence on fossil fuels. This study uses a descriptive-quantitative research type with an engineering simulation approach. The study focuses on modeling and analyzing the contribution of a hybrid renewable energy system (HRES) in reducing carbon emissions and reducing dependence on fossil fuels. . Based on the results of observations and analysis of technical data on solar radiation and daily wind speed, photovoltaic (PV)-based renewable energy systems show significant technical potential in generating electricity consistently throughout the year, especially in tropical areas. Meanwhile, although the potential for wind energy is relatively smaller, especially in areas with low average wind speeds, wind turbines can still provide additional contributions — especially when solar conditions are limited such as at night or in the rainy season. By combining these two energy sources into a hybrid system (HRES), the efficiency of renewable energy utilization can be maximized. The combination of PV and wind turbines allows : 1) Direct carbon emission reduction, which is ~22.7 tons of CO_2 per year from the PV system alone. 2) Diversification of energy sources, which reduces vulnerability to single dependence on fossil fuels. 3) Increasing the reliability of the electricity system, especially for remote areas and areas not yet covered by the PLN network. Overall, HRES provides a practical, efficient, and sustainable solution to meet the energy needs of small to medium-scale communities. It also opens up opportunities for energy decentralization, promotes a green economy, and strengthens Indonesia's commitment to net zero emissions targets in the future.

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

INTRODUCTION

The fossil fuel crisis is becoming more apparent due to global dependence on coal, oil, and natural gas, while the world's energy needs continue to increase. The imbalance between demand and supply of fossil fuels, rising prices, and geopolitical risks have triggered the energy crisis and driven the need for a transition to renewable energy. Energy crises are often triggered by an imbalance between energy supply and demand, economic disruption, under-investment in energy, and geopolitical risks such as the Russia-Ukraine conflict (Gajdzik et al., 2024; Hille & Angerpointner, 2025; Kayani et al., 2024; Yokuş, 2024) . The impacts include rising energy prices, inflation, energy poverty, declining economic growth, and potential recession in several countries (Gajdzik et al., 2024; Kayani et al., 2024). Dependence on fossil fuels also exacerbates greenhouse gas emissions and accelerates the depletion of natural resources. (Rahman et al., 2024; Wang & Azam, 2024; Zhang et al., 2024).

Global energy demand continues to increase along with population and economic growth, so fossil fuel consumption remains high despite pressure to reduce it (Davoodi et al., 2024; Wang & Azam, 2024; Zhang et al., 2024) . Fossil energy consumption shows a predictable long-term pattern, but it remains difficult to completely replace in a short time (Zhang et al., 2024). The energy crisis has driven interest in energy efficiency and accelerated adoption of renewable energy such as wind, solar, and geothermal (Davoodi et al., 2024; Gajdzik et al., 2024; Rahman et al., 2024; Su et al., 2024). The transition to renewable energy is critical for environmental sustainability and achieving global climate targets (Hille & Angerpointner, 2025; Rahman et al., 2024; Su et al., 2024) . Investments in clean energy technologies, energy efficiency, and diversification of energy sources are key to reducing dependence on fossil fuels (Davoodi et al., 2024; Farhana et al., 2024; Gajdzik et al., 2024; Rahman et al., 2024). Proactive policies, incentives and integration of regional energy markets can accelerate the shift to greener energy (Gajdzik et al., 2024; Su et al., 2024; Davoodi et al., 2024; Hille & Angerpointner, 2025). The fossil fuel crisis and the increasing global energy demand demand fundamental changes in the world's energy system. Accelerating the transition to renewable energy, increasing efficiency, and supporting policies are essential to overcome the crisis and ensure long-term energy security.

The use of conventional energy, especially from fossil fuels such as coal, oil, and natural gas, has a huge environmental impact. Conventional energy significantly increases greenhouse gas emissions, worsens climate change, and causes environmental pollution, thus driving the need for a transition to cleaner energy. Environmental impact of conventional energy , namely; 1) Greenhouse Gas Emissions: The use of fossil fuels is a major contributor to CO_2 emissions, which accelerate global warming and climate change (Guidi et al., 2023; Khan & Liu, 2022; Mujtaba et al., 2022; Tutak & Brodny, 2022; Yu, 2021). Every 1% increase in conventional energy consumption can significantly increase CO_2 emissions, for example in Australia, a 1% increase in conventional energy imports increases CO_2 emissions by up to 11% (Khan & Liu, 2022). 2) Air and Environmental Pollution: In addition to CO_2, fossil fuel combustion also produces other pollutants such as SO_2 and dust particles (PM10), which have adverse effects on air quality and human health (Bodziacki et al., 2024) . 3) Long-Term Impacts: In addition to direct emissions, conventional energy also causes long-term environmental damage, such as land degradation, water pollution, and biodiversity loss (Yu, 2021; Καλτζίδου, 2019; Guidi et al., 2023). The comparison with renewable energy is 1) Lower Emissions: Renewable energy such as wind, solar, and hydro have much lower greenhouse gas emissions throughout their life cycle compared to conventional energy (Guidi et al., 2023; Tutak & Brodny, 2022). 2) Improved Environmental Quality: Increasing renewable energy consumption has been shown to reduce CO_2 emissions and ecological footprints, as well as improve environmental quality in many countries (Khan & Liu, 2022; Mujtaba et al., 2022; Tutak & Brodny, 2022) . 3) Energy Efficiency: Reducing energy intensity and switching to renewable energy are very effective in reducing emissions and improving environmental sustainability (Khan & Liu, 2022; Mujtaba et al., 2022; Bodziacki et al., 2024; Tutak & Brodny, 2022) . Based on these sources, it can be concluded that conventional energy has a major negative impact on the environment through greenhouse gas emissions and pollution. The transition to renewable energy and increased energy efficiency are essential to reduce these impacts and achieve environmental sustainability.

The solutions and technological innovations that can be implemented are: 1) Hybrid System: Combining several renewable energy sources (e.g. solar and wind) can reduce fluctuations and increase supply reliability (Hassan et al., 2023; Li et al., 2020). 2)

Network and Storage Optimization: The development of energy storage technology and intelligent grid management systems is essential to balance supply and demand (Hassan et al., 2023; Rabiee & Mohseni-Bonab, 2017; Sinsel et al., 2020; Ye et al., 2022). 3) Policy and Incentives: Policy support, government incentives, and public-private partnerships have been shown to accelerate the adoption and investment in renewable energy (Hassan et al., 2023; Li et al., 2020; Ye et al., 2022). The potential of renewable energy is enormous, but its optimization is still constrained by output fluctuations, storage limitations, technical integration, and financing. Technological innovation, hybrid systems, and policy support are key to overcoming these challenges and maximizing the use of renewable energy in the future .

A stable, efficient and flexible energy system is essential to ensure a reliable and sustainable electricity supply, especially with the increasing integration of variable renewable energy. The main solution is to combine different energy sources (conventional and renewable) with energy storage and intelligent management systems to achieve stable, efficient and environmentally friendly operations . Hybrid systems that combine solar panels, diesel generators, batteries and converters have proven to be able to meet continuous electricity needs, both for off-grid and on-grid systems. This system can significantly reduce energy costs and CO_2 emissions, and provide flexibility in dealing with changes in energy demand and prices (Halabi & Mekhilef, 2017). Integration of multi-energy systems (MES) utilizing multiple energy sources (electricity, PV, cooling network) and predictive load management can reduce energy consumption from the grid by up to 53%, reduce costs by up to 43%, and reduce primary energy consumption by 17% (Mugnini et al., 2021) . Energy storage (ESS) is essential to stabilize systems that rely on renewable energy such as solar and wind, which are volatile. ESS enables time-shifting of energy consumption, maintains grid stability, and improves system reliability (Hu et al., 2020; Islam et al., 2024; Liu et al., 2022). Intelligent demand management and the use of thermal storage in buildings can increase flexibility, reduce operating costs by up to 42%, and reduce peak loads by up to 96% (Bai et al., 2023; Liu et al., 2022; Lizana et al., 2018; Stinner et al., 2016). A stable, efficient and flexible energy system can be achieved by combining various energy sources, storage systems and intelligent demand management. Hybrid and multi-energy approaches, supported by smart storage and control technologies, are very effective in meeting electricity needs in a sustainable and environmentally friendly manner.

Development of Hybrid Renewable Energy System (HRES) Technology HRES is an innovative solution that integrates two or more renewable energy sources, such as solar and wind power, with a storage system or grid, resulting in more reliable and efficient energy. Hybrid Renewable Energy System (HRES) is an innovative solution that combines two or more renewable energy sources—such as solar, wind, biomass, or hydrogen—with a storage system or grid. The development of HRES technology focuses on increasing the efficiency, reliability, and flexibility of energy supply, as well as reducing emissions and operating costs. HRES integrates multiple renewable energy sources (e.g. solar, wind, biomass) with energy storage systems such as batteries or hydrogen technologies to overcome the intermittent nature of renewable energy and improve supply stability (Kallio & Siroux, 2022; Khan & Liu, 2022; Kumar & Channi, 2022; Kushwaha & Bhattacharjee, 2023; Roy et al., 2022; Sorrenti et al., 2022; Uc et al., 2024). Power-to-X (P2X) technologies, such as hydrogen conversion, are increasingly being adopted to increase flexibility and renewable energy utilization in HRES (Khan et al., 2022; Sorrenti et al., 2022). Micro-cogeneration systems (e.g. biomass) are also combined to increase reliability and reduce CO2 emissions (Kumar & Channi, 2022; Kallio & Siroux, 2022). The development of HRES is strongly supported by advances in optimization techniques, such as the use of metaheuristic algorithms, artificial intelligence, and simulation software (e.g., HOMER Pro) to determine the best configuration, size, and control strategy (Roy et al., 2022; Khan et al., 2022; Roth et al., 2019; Khan et al., 2022; Rathod & Subramanian, 2022; Uc et al., 2024; Kushwaha & Bhattacharjee, 2023). Advanced energy management and control strategies are essential to balance supply and demand, and minimize costs and emissions (Khan & Liu, 2022; Kushwaha & Bhattacharjee, 2023; Rathod & Subramanian, 2022; Roth et al., 2019). HRES are widely applied in remote, rural, industrial, and microgrid areas, providing reliable and sustainable electrification solutions (Kumar & Channi, 2022; Kallio & Siroux, 2022; Uc et al., 2024; Kushwaha & Bhattacharjee, 2023). Studies show that HRES can reduce energy costs, increase the renewable energy ratio, and reduce emissions compared to conventional systems (Kumar & Channi, 2022; Uc et al., 2024; Kushwaha & Bhattacharjee, 2023). HRES technology continues to evolve with the integration of renewable energy sources, storage systems, and advanced optimization techniques. HRES offers a more reliable, efficient, and environmentally friendly energy solution, and has great potential to support sustainable energy transitions in various sectors.

Strategic Role of HRES in Sustainable Development The development of hybrid renewable energy systems is very relevant to support sustainable development goals (SDGs), especially in terms of clean and affordable energy, climate change mitigation, and national energy independence. The advantages and benefits of HRES are: 1) Reliability and Efficiency: HRES reduces the problem of intermittency from single renewable energy sources, increases the stability of electricity supply, and overall system efficiency (Feng, 2018; Hassan et al., 2023; Pawar et al., 2024; Pérez-Navarro et al., 2016; Rekioua, 2020; Roy et al., 2022). 2) Application Flexibility: Can be used for power generation, heating/cooling, hydrogen production, drying, and energy services in remote areas or connected to the grid (Guo et al., 2018; Rekioua, 2020; Pérez-Navarro et al., 2016). 3) Environmental Impact: Reduces dependence on fossil fuels and greenhouse gas emissions, and supports sustainability goals (Hassan et al., 2023; Krishna & Kumar, 2015; Panda et al., 2023; Pawar et al., 2024). HRES offers a more stable, efficient, and environmentally friendly energy solution by combining various renewable energy sources and storage technologies. Policy support, technological innovation, and system optimization are key to expanding the application of HRES in supporting the sustainable energy transition.

Based on the explanation above, the research aims to examine the potential contribution of the Hybrid Renewable Energy System in supporting sustainable energy transitions in the future, especially in the context of reducing carbon emissions and dependence on fossil fuels

METHOD

This study uses a descriptive-quantitative research type with a simulation technique approach. The study focuses on modeling and analyzing the contribution of a hybrid renewable energy system (HRES) in reducing carbon emissions and reducing dependence on fossil fuels. This study uses a simulation design and comparative analysis. The HRES system will be simulated for several configuration scenarios (e.g. a combination of solar and wind power), then its performance will be analyzed for clean energy production, carbon emission reduction, and reduction of fossil-based energy consumption needs. Simulations are carried out using renewable energy software such as HOMER Pro or MATLAB/Simulink. Data collection in this study is in the form of renewable energy resource data at the location, such as solar radiation intensity and average daily wind speed. The data analysis technique in this study uses the following stages: 1) analysis of energy demand data, 2) analysis of renewable energy resource data, 3) simulation and modeling of HRES, 4) analysis of contributions to sustainable energy transitions.

RESULT AND DISCUSSION

Renewable energy resources data and analysis:

1. Technical Assumptions
   a. Photovoltaic (PV) Systems:
      - Panel area: 100 m^2
      - Panel efficiency: 18%
      - System performance ratio: 0.75
   b. Wind Turbine System:
      - Rotor area: 10 m^2
      - Power coefficient (Cp): 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 the average daily solar radiation intensity data obtained from observations and simulations, an average value of 5.19 kWh /m^2/day was obtained. This value is relatively high and stable, indicating that the study area has very good potential for solar energy utilization. Assuming a PV system that has: 1) A panel surface area of 100 m^2, 2) Energy conversion efficiency of 18%, 3) A Performance Ratio of 0.75, which includes system losses such as temperature, cables, inverters, and shading, the system can produce energy up to around 25,215 kWh per year. This is large enough to meet the electricity needs of medium-scale households to small communities, or even small industries with not too high electricity needs. The monthly pattern shows peak production occurs in April–July, with production above 2,400 kWh/month, while the lowest production occurs in December (around 1,725 kWh), but remains within the threshold of adequate productivity. This means that the season does not have an extreme effect on the fluctuation of the electricity generated. This is very beneficial in terms of energy system stability and load planning.

Wind Energy Potential (Wind Turbine)

Meanwhile, the average daily wind speed shows a relatively low figure, which is an annual average of 2.35 m/s, with a maximum speed of only 2.89 m/s in September. Based on literature and technical standards, the optimal wind speed for the operation of small wind turbines is a minimum of 3–4 m/s, so this condition is less than ideal for efficient wind energy generation. With a small wind turbine configuration (rotor area 10 m^2, power coefficient 0.35) , the energy that can be generated for a year is only around 256.58 kWh, which is very small compared to the PV system. The highest monthly energy only touches 37.26 kWh , which is not even enough to supply basic household 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

From the table it is clear that PV systems are very superior in terms of energy potential, stability, and technical feasibility. Meanwhile, wind turbines are not recommended to be implemented independently, except as a hybrid system with a limited scale and in certain locations that have higher micro wind conditions (eg: open coastal or hilly areas).

Based on the calculation and evaluation of available data, the development of solar energy through a photovoltaic system is the most efficient and sustainable option for the study area. The location has high and consistent sunlight exposure, making it very suitable for the application of this type of renewable energy. Recommendations for future implementation: Focus on on-grid or hybrid PV systems to reduce dependence on the PLN network. Integration with energy storage (battery system) to manage nighttime supply or cloudy weather. Increasing the efficiency of energy use on the user side through energy audits and load management.

Contribution of Hybrid Renewable Energy System (HRES) in Sustainable Energy Transition

Global Energy Context and Challenges

Global climate change and the energy crisis due to fluctuations in fossil fuel prices have pushed countries, including Indonesia, to make a transition to a cleaner and more sustainable energy system. The main challenges in this transition include high dependence on fossil fuel sources, high carbon emissions, inequality in energy access, and fluctuations in supply from a single renewable energy source. In this context, the Hybrid Renewable Energy System (HRES)—a combination of two or more renewable energy sources such as PV and wind turbines, as well as storage systems—is a strategic solution.

Potential Analysis : PV and Wind Data

Based on technical data, PV produces ~25,215 kWh/year of energy with high stability, while wind turbines only ~256.58 kWh/year due to the low average wind speed (~2.35

m/s). PV is the main source, while wind can contribute as a support during the night or cloudy season. In a hybrid system, this allows reducing dependence on fuel-based generators and increasing the reliability of electricity supply.

Impact on Carbon Emission Reduction

Every 1 kWh from renewable sources avoids about 0.9 kg CO_2 compared to coal-fired power plants. With a production of 25,215 kWh from the PV system, the carbon emissions that can be avoided are about 22,694 kg CO_2 or 22.7 tons of CO_2 per year. This contribution is very significant, especially if the system is replicated in various communities.

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 off-grid 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.

As in the existing theory, the utilization of renewable energy such as solar, wind, biomass, and water is indeed very potential, but still faces various technical and economic challenges that hinder its optimization. The main challenges are output fluctuations, limitations of storage technology, and constraints on integration into the electricity system and financing. The main challenges of utilizing renewable energy, such as 1) Output Variability and Fluctuation: Energy sources such as solar and wind are highly dependent on weather conditions and time, resulting in unstable and unpredictable output (Denholm et al., 2021; Erdiwansyah et al., 2021; Hassan et al., 2023; Sinsel et al., 2020; Stram, 2016) . 2) Storage Technology Limitations: The lack of efficient energy storage technology means that surplus energy during high production cannot be utilized when demand increases (Hassan et al., 2023; Sinsel et al., 2020; Ye et al., 2022). 3) Grid Integration Limitations: Integration of renewable energy into the electricity grid requires technical adjustments, such as new inverter designs and more complex load management (Denholm et al., 2021; Rabiee & Mohseni-Bonab, 2017; Li et al., 2020; Sinsel et al., 2020; Erdiwansyah et al., 2021). 4) Economic and Financing Constraints: Access to funding for renewable energy projects, especially at the local level, is still difficult. In addition, the price of electricity from renewable energy must compete with conventional sources (Ahmadipour et al., 2025; Eti et al., 2023; Stram, 2016; Ye et al., 2022)

CONCLUSION

Based on the results of observations and analysis of daily solar radiation and wind speed technical data, photovoltaic (PV)-based renewable energy systems show significant technical potential in generating electricity consistently throughout the year, especially in tropical areas. Meanwhile, although the potential for wind energy is relatively smaller, especially in areas with low average wind speeds, wind turbines can still provide additional contributions — especially when solar conditions are limited such as at night or in the rainy season. By combining these two energy sources into a hybrid system (HRES), the efficiency of renewable energy utilization can be maximized. The combination of PV and wind turbines allows : 1) Direct carbon emission reduction, which is ~22.7 tons of CO_2 per year only from the PV system. 2) Diversification of energy sources, which reduces vulnerability to single dependence on fossil fuels. 3) Increased reliability of the electricity system, especially for remote areas and areas not yet covered by the PLN network. Overall, HRES provides a practical, efficient, and sustainable solution to meet the energy needs of small to medium-scale communities. This also opens up opportunities for energy decentralization, promoting a green economy, and strengthening Indonesia's commitment to net zero emissions targets in the future.

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