In-depth evaluation and enhancement of a PV-wind combined system: A case study at the Engineering Faculty of Wahid Hasyim University

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ABSTRACT

Energy sustainability is crucial for mitigating climate change and reducing dependence on fossil fuels. This research evaluates a hybrid renewable energy system combining photovoltaic (PV) technology and wind turbines to meet the electricity demand of Wahid Hasyim University's Faculty of Engineering, totalling 555,000 VA. Using HOMER Pro software, the study identifies the optimal configuration based on technical, economic, and environmental aspects. The hybrid system integrating PV, wind turbines, batteries, and converters achieves the lowest Net Present Cost (NPC) of $214,877 and a Levelized Cost of Energy (LCOE) of $0.0185/kWh, outperforming grid-only systems. Environmentally, the system significantly reduces carbon dioxide (CO2) emissions, from 559,226 kg/yr in conventional systems to 62,452 kg/yr. Solar energy contributes 56% of electricity generation, leveraging stable solar radiation of 4.28–5.54 kWh/m²/day. Additionally, an annual surplus of 156,350 kWh can be sold back to the grid, enhancing operational efficiency. This study demonstrates that hybrid renewable energy systems deliver long-term cost efficiency and significantly mitigate climate impacts. It provides a sustainable energy model for campuses in Indonesia and worldwide, particularly in regions with abundant solar resources.

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1. INTRODUCTION

In recent decades, energy sustainability has become one of the main focuses in various sectors, including higher education. This issue is becoming increasingly relevant along with the increasing global demand for energy, climate change, and the need to reduce dependence on fossil energy resources [1]-[3]. Campuses worldwide are beginning to respond to this challenge by turning to renewable energy technologies, which support sustainability and create a pilot model for the surrounding communities. In this context, Wahid Hasyim University (UNWAHAS) has the opportunity to become a pioneer in the application of innovative and efficient renewable energy solutions, especially on the Faculty of Engineering (FT) Campus, which requires an electricity supply of 555,000 VA.

Electrical energy is an essential need to carry out various campus activities, ranging from laboratory operations and classrooms to other supporting facilities [4]. However, high conventional energy consumption is often associated with negative impacts on the environment, such as carbon emissions and unsustainable exploitation of natural resources [5]. Therefore, integrating renewable energy systems, such as photovoltaic (PV) and wind turbines, is a strategic solution to overcome this problem. By harnessing the potential of available solar and wind energy, the campus can not only reduce its carbon footprint but also optimize long-term operational costs [6].

PV technology and wind turbines have their advantages that complement each other. PV systems, which utilize solar energy, offer consistent energy production in regions with high sunlight intensity [7]. On the other hand, wind turbines can generate electricity efficiently in areas with adequate wind speeds, especially at night or in certain weather conditions when sunlight is less than optimal [8], [9]. The combination of these two technologies forms a hybrid system that can improve the overall reliability and efficiency of energy supply [10].

Optimizing PV systems and wind turbines is not a simple task. Various factors must be considered, including the potential of local resources, technological efficiency, installation and maintenance costs, and environmental impact [11]. In addition, implementing these solutions requires in-depth technical analysis, such as optimal capacity calculations, performance simulations, and economic evaluations. This study uses HOMER Pro software as a simulation tool to model and evaluate the performance of PV hybrid systems and wind turbines [12]. This approach allows for a comprehensive analysis of various configurations and operational scenarios to find the best solution [6], [13]. Here is a table summarizing some relevant studies to understand the latest developments related to renewable energy optimization using HOMER Pro software. All references in Table 1 are current publications that can be easily accessed:

Table 1. State of the art

References	Research focus	Key results
[14]	Techno-economic analysis of renewable energy systems	The downward trend in LCOE costs from \$0.91/kWh to \$0.70/kWh.
[13]	PV-Wind hybrid system optimization	Optimal design for remote communities with the use of renewable energy.
[15]	PV-Wind system design for energy savings in hotels	Cost savings of up to 25% and reduction of CO_2 emissions.
[16]	This study optimizes a PV-wind-diesel microgrid for lower costs and emissions.	PV-wind-diesel HRES costs \$0.1616/kWh, \$1.8M total, 81% PV, 557,749 kg CO_2.
[17]	COE, NPC, and CO_2 emissions analysis	Case III PV-battery cuts NPC to \$19.2M, COE \$0.034/kWh, cuts emissions ~63%.
[18]	Cost and environmental performance	A Coruña's HRES is best (\$1.39M NPC, \$0.199/kWh), Madrid worst (\$2.61M NPC, \$0.374/kWh).
[19]	Life cycle cost and emissions	A 32 kW solar hybrid system for a healthcare centre in Bangladesh costs \$33,818 (NPC) with a \$0.022/kWh energy cost.
[20]	Cost and environmental impact analysis	Off-grid HRES with fuel cells cuts 653 kg CO_2 but costs \$4.58M (NPC), \$0.5238/kWh (LCOE).
[21]	Cost and emissions analysis	Lead-acid HRES costs \$6.02M, \$0.47/kWh; cheaper Li-ion is more optimal, cutting 1.06M kg CO_2.
[22]	Economic and environmental evaluation	Optimized HRES (PV, wind, biogas, diesel) costs \$1.71M, \$0.347/kWh, aiding hybrid system design.
[23]	Performance, cost, and emissions	Renewables supply 29.2%, cutting NPC to \$1.39M, COE to \$0.246/kWh, with 14% IRR and 6.7-year payback.
[24]	Optimization (GWO)	100% renewable microgrid cuts GHG by 82%, LCOE: \$0.3588–\$0.2491/kWh (LCOE).
[9]	Techno-economic parameters on NPC and COE	Optimal WT/PV microgrid costs \$679.6K–\$838.8K, COE \$0.189–\$0.232/kWh.
[25]	Techno-economic evaluation of an isolated microgrid for Kanur, India	Optimal PV/WT/DG system costs \$569.3K, COE \$0.157/kWh, with 28.6% excess energy.

These studies demonstrate the importance of technology-based and simulation-based approaches in designing efficient and sustainable renewable energy systems. By utilizing software such as HOMER Pro, analysis can be carried out comprehensively to evaluate various technology configurations and operational scenarios. On-grid and optimization algorithms are significant trends in developing renewable energy systems [15]. As a campus committed to sustainability, UNWAHAS has excellent potential to become a pilot model for implementing renewable energy systems in Indonesia. This research aims to explore the optimization strategy of the combination of PV and wind turbines to meet the electricity needs of the FT UNWAHAS Campus efficiently and sustainably. By adopting a data-driven approach and the latest technology, this study is expected to provide practical recommendations that can be applied at UNWAHAS and other educational institutions with similar challenges. As a first step, this research will map the potential of solar and wind energy around the FT UNWAHAS Campus. Meteorological data, such as sunlight intensity and wind speed, will be collected and analyzed to determine the technical feasibility of PV systems and wind turbines. In addition, HOMER Pro software-based simulations will be used to model the performance of hybrid systems, including estimated energy production, efficiency, and carbon emissions. The results of this simulation will be compared with conventional energy scenarios to evaluate the economic and environmental benefits of the proposed solution.

The novelty of our research presents a novel approach by focusing on optimizing renewable energy systems specifically designed for educational institutions in Indonesia, with the Faculty of Engineering Campus at Wahid Hasyim University as the case study. Unlike previous studies, which predominantly emphasize applications in industrial sectors, rural areas, or commercial entities ([13]-[16], [22]), this study addresses the unique challenges and opportunities of university campuses. These campuses have distinct energy demands and serve as sustainability role models for surrounding communities. This research is groundbreaking in its geographic focus, as it evaluates a tropical site characterized by high solar radiation but low wind speeds. This specific meteorological profile drives the development of a PV-dominant hybrid system optimized for tropical conditions.

Compared to prior studies, such as [16] and [22], which reported higher Net Present Costs (NPC) and levelized costs of energy (LCOE) for hybrid systems; this research achieves significant cost-efficiency with an NPC of $214,877 and an LCOE of $0.0185/kWh, making it highly suitable for campus applications where budgets are a critical concern. Furthermore, the system's environmental benefits are notable, with carbon dioxide emissions reduced to just 62,452 kg/year and nitrogen oxide emissions to 132 kg/year, surpassing the results of studies like [16] and [20], which incorporated more complex multi-energy systems. Additionally, this study identifies an economic opportunity to resell 156,350 kWh/year of surplus energy to the grid, an aspect not extensively explored in previous research, such as [14], [15], [20], which primarily focused on self-consumption.

This study's methodology leverages HOMER Pro to conduct a comprehensive techno-economic and environmental impact analysis, similar to prior works like [16] and [19]. However, its focus on balancing the unique energy requirements of university campuses with sustainable outcomes sets it apart. By pioneering a renewable energy system tailored for educational institutions in tropical regions, this research provides a scalable and replicable model for similar contexts, bridging a significant gap in renewable energy applications.

2. METHOD

2.1. Load profile

Figure 1(a) illustrates a hybrid energy system that integrates various renewable energy sources, namely solar panels (PV) and wind turbines, with battery-based energy storage systems and connections to the power grid and electrical loads. This diagram shows the relationship between the main components, namely solar panels that generate electrical energy from sunlight, wind turbines that convert wind energy into electrical energy, and batteries that store energy for use when needed [20]. The system is also connected to the grid to ensure the availability of additional energy when needed. The electricity load exemplified in the diagram is 2,442.25 kWh per day, with a peak load of 348.08 kW, which reflects the daily and peak energy needs on campus. AC/DC converters function to convert energy from AC (wind turbine) and DC (solar panel) sources into energy that suits the needs of the system [26], [27].

Figures 1(b) and 1(c) presented below show the electricity consumption profile throughout the year. Figure 1(b) first illustrates the variation in monthly energy consumption, while Figure 1(c) presents a statistical analysis of hybrid energy production, including annual maximum values, daily averages, and minimum values. This analysis shows the potential to reduce operational costs and carbon footprint by utilizing more dominant renewable energy [28]. In this research methodology, a similar approach will be applied to design and optimize renewable energy systems that meet the electricity needs of the Faculty of Engineering, UNWAHAS Campus. Through simulations using HOMER Pro software, this study aims to evaluate various system configurations and identify the best solutions in terms of energy efficiency, cost savings, and carbon emission reduction [31].

2.2. Energy calculations and renewable energy system costs

In this section, the main formulas used to analyze the performance and economic evaluation of the proposed renewable energy system will be explained, namely the combination of PV panels and wind turbines [29], [30]. The calculation in question includes the estimated energy produced by the PV system and wind turbines, the battery capacity required for energy storage, the overall efficiency of the system, and economic analysis through the calculation of the levelized cost of energy (LCOE) and net present cost (NPC) [31, [32]. These formulas have a crucial role in the design and optimization of hybrid systems to ensure that the proposed energy solutions can meet the energy needs of the Faculty of Engineering UNWAHAS Campus efficiently and sustainably [19], [33]. Table 2 follows the formulas used in the calculation of the performance and economic evaluation of the renewable energy system.

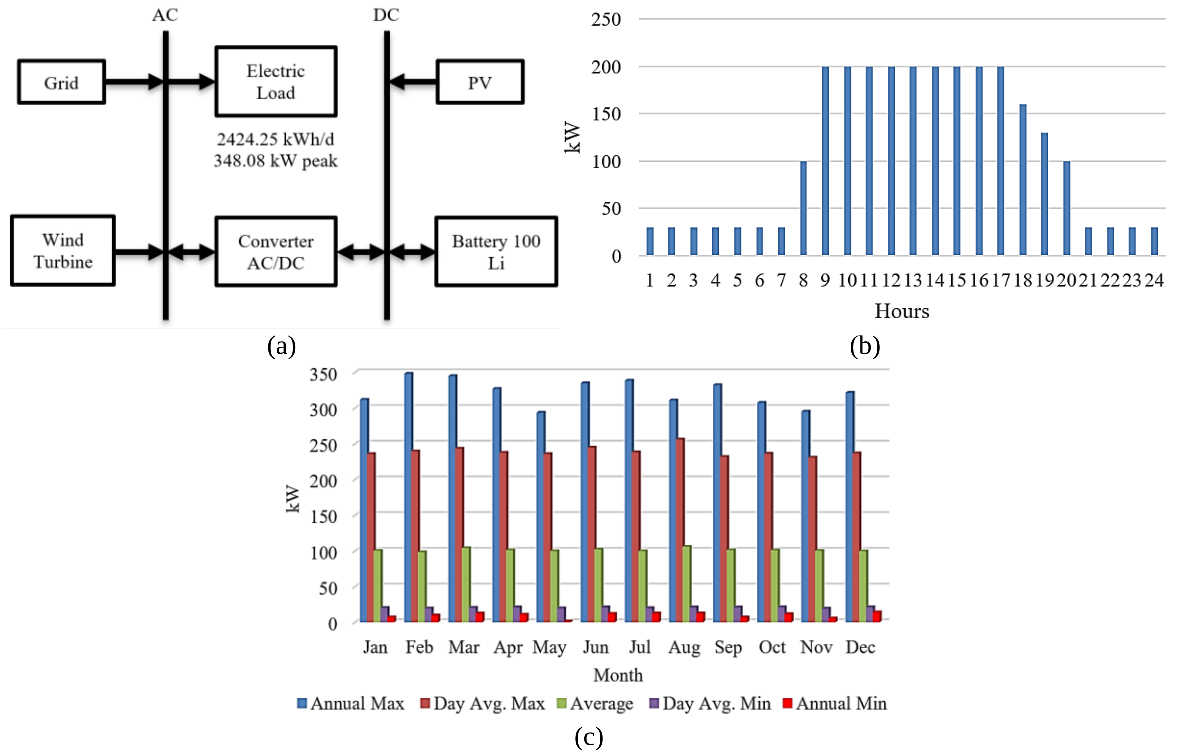

Figure 1. Overview of the hybrid energy system: (a) schematic of the hybrid PV-wind turbine, (b) daily load, and (c) seasonal load

Table 2. Formulas about calculation and energy system costs

References	Formula		Description

[34], [35]	$P_{PV} = Y_{PV} \times f_{PV} \times \left(\frac{NPC}{G_{T,STC}}\right) \times [1 + \alpha_p \, (T_c - T_{c,STC})]$
	where PPV = Output power from PV (watts);
	YPV = PV system power drop factor (watts);
	fPV = PV system derating factor;
	GT = Received solar irradiation at a given time (W/m²);
	GT, STC = Solar irradiation under standard conditions (1000 W/m²);
	αP = PV power temperature coefficient (%/°C);
	Tc = Current PV cell temperature (°C); and
	Tc, STC = Cell temperature under standard conditions (25°C).
		(1)	Calculate the energy produced by a PV system.

[35, [36]	$P_{WTG} = P_{WTG,STP} \times \left(\frac{\rho}{\rho_0}\right)$ Where: PWTG = Output power from PV (watts); PWTG, STP = PV installed capacity (watts); ρ0 = PV system downgrade factor; and ρ = Radiation received at a given time(W/m²).	(2)	Calculate the power generated by a wind turbine.
[37], [38]	$E_{wind} = P_{wind} \times t$ Where E_{wind} = Energy generated by wind turbines (kWh)	(3)	Calculate the energy produced by a wind turbine over some time.
[35], [39]	$C_{Battery} = \frac{E_{load} \times DOD}{SOC}$ Where $C_{Battery}$ = Battery capacity (kWh); Eload = Total energy required by load (kWh); DOD = Depth of discharge (the depth of energy discharge from the battery, e.g., 0.8 to 80%); SOC = State of charge (the state of charge of the battery initially, usually 1 for a full charge); and	(4)	Calculate the battery capacity needed to store energy.
	$LCOE = \frac{NPC}{E_{total}}$ where LCOE = Total system cost (USD); and Etotal = Total energy produced (kWh)	(5)	LCOE signifies the average expense of generating a single unit of energy throughout the system's lifespan. It is a critical metric for evaluating energy projects' economic feasibility and contrasting various energy sources.
[5], [40]	$NPC\ (USD) = \sum_{t=0}^{N} \frac{C_t}{(1+r)^t}$ Where C_t: Total cost in year t; r: Interest rate (%); and N: Project age (years)	(6)	NPCs allow for a comprehensive view of the total cost of a project in present value, facilitating comparative analysis among a wide range of investment options.

3. RESULTS AND DISCUSSION
3.1. Result of economic LCOE and NPC

Table 3 of economic results and emissions presented provides a comprehensive overview of the performance of various energy system configurations. In terms of economics, Table 3 shows that pure grid-based systems (grid) have the highest net present cost (NPC) of $887.949 and a levelized cost of energy (LCOE) of $0.090/kWh. In contrast, a hybrid configuration that integrates photovoltaic (PV) panels, wind turbines, batteries, and converters has the lowest NPC of $214,877 and an LCOE of $0.0185/kWh. This confirms that hybrid systems provide the best cost efficiency in the long run. In addition, the hybrid system's operating cost (OC) is also much lower, at only $8,744, compared to the grid-based system, which reaches $79,637.

In terms of environmental sustainability, Table 4 reveals that pure grid-based systems produce the highest carbon dioxide (CO_2) emissions of 559.226 kg/yr and nitrogen oxide (NO_X) emissions of 1.186 kg/yr. In contrast, a hybrid configuration that combines PV, wind turbines, batteries, and converters produces only 62,452 kg/yr of CO_2 emissions and 132 kg/yr of NO_X, with zero unburned hydrocarbons (UHCs) emissions and dust particles (PM). This significant reduction in emissions reflects the advantages of environmentally friendly renewable energy technology.

Table 3. Results of economic schemes

Architecture	PV(kW)	Wind (kW)	Grid (kW)	Battery (Strings)	Converter (kW)	NPC ($)	LCOE($)	OC ($)
Grid	0	0	999,999	0	0	887,949	0.0900	79,637
Wind-grid	0	50	999,999	0	0	542,809	0.0506	48,638
Wind-battery-grid-converter	0	50	999,999	1	21.8	543.706	0.0519	47,235
PV-grid-converter	500	0	999,999	0	223	480,108	0.0444	37,004
PV-grid-battery-converter	500	0	999,999	6	204	452,580	0.0448	29,667
PV-wind-grid-converter	500	50	999,999	0	191	251,317	0.0198	17,320
PV-wind-grid-battery-converter	500	50	999,999	6	188	214,877	0.0185	8,744

Table 4. Emissions produced by the system

Architecture	CO_2 (kg/yr)	CO (kg/yr)	SO_2 (kg/yr)	NO_X (kg/yr)	Unburned hydrocarbons (UHCs) (kg/yr)	Particulate matter (PM) (kg/yr)
Grid	559,226	0	2,424	1,186	0	0
Wind-grid	344,008	0	1,491	729	0	0
Wind-battery-grid-converter	332,682	0	1,442	705	0	0
PV-grid-converter	262,862	0	1,140	557	0	0
PV-grid-battery-converter	204,879	0	888	434	0	0
PV-wind-grid-converter	130,211	0	565	276	0	0
PV-wind-grid-battery-converter	62,452	0	271	132	0	0

3.2. Electrical production results

Based on the data analysis in Figure 2, this location's average monthly wind speed ranges from 2.72 m/s to 4.00 m/s. This value indicates that the potential of wind energy is minimal, as wind speeds remain low throughout the year, even in months with high radiation. On the other hand, the average daily radiation is in the range of 4.28 kWh/m²/day to 5.54 kWh/m²/day, with the highest value occurring in a month that also has a relatively high temperature, which is 25.54 °C. Consistent radiation throughout the year shows that this location is well-suited for solar energy applications. With small fluctuations, the average daily temperature ranges from 23.89 to 26.01 °C, signaling a stable tropical climate.

The relationship between the variables suggests that daily radiation tends to be higher in months with higher temperatures, indicating significant solar intensity. However, no strong correlation was found between wind speed and daily radiation, as wind speeds remained low even on moons with high radiation. Wind speed also did not affect the temperature significantly, indicating that the winds in these locations were local and not strong enough to bring about significant changes to the climate. With low wind energy potential and high solar radiation, as shown in Figure 2, the main recommendation is to prioritize the development of solar power generation systems at these sites. The average temperature stability also supports the optimal performance of solar panels, making solar energy a more efficient and sustainable solution than wind energy.

Table 5 shows the data on electricity production and consumption in a system with a breakdown of the amount of energy in kWh per year and its percentage. In terms of production, this system produces a total energy of 1,171,775 kWh per year. The most significant contribution comes from solar panels, which produce 655,884 kWh annually, or about 56% of total production. The second most important energy source is wind turbines, which generate 417,074 kWh annually, or 35.6%. Meanwhile, the grid contributes an additional 98,817 kWh per year, equivalent to 8.43% of total production.

In terms of consumption, the total energy used in the system is 1,041,202 kWh per year. Most energy consumption is used for the AC primary load, which reaches 884,852 kWh annually or about 85% of the total consumption. No energy is consumed for DC primary load or deferrable load. An energy surplus of 156,350 kWh per year is resold to the grid, which accounts for 15% of total consumption.

This analysis shows the system has an energy surplus, with production exceeding consumption by 130,573 kWh per year. The system relies heavily on renewable energy sources, of which 91.6% of the total output comes from solar panels and wind turbines. This shows that this system is designed to maximize the use of renewable energy with minimal contribution from the power grid.

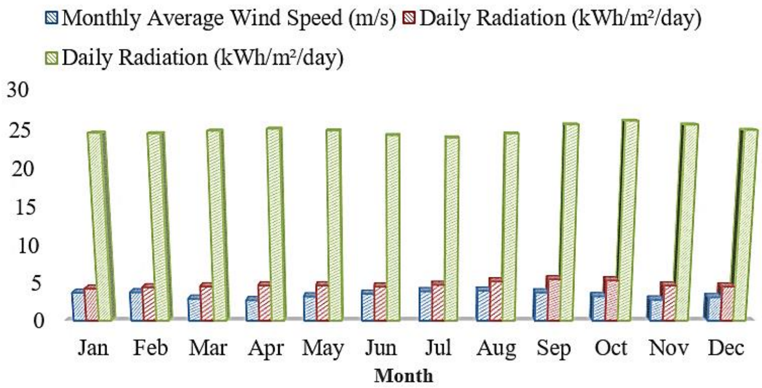

Figure 2. Meteorology data

Table 5. Electrical production and consumption in the system

Production	kWh/year	Percentage (%)	Consumption	kWh/year	Percentage (%)
PV	655,884	56.0	AC primary load	884,852	85.0
Wind turbine	417,074	35.6	DC primary load	0	0
Grid	98,817	8.43	Deferrable load	0	0
Total	1,171,775	100	Grid sales	156,350	15.0
			Total	1,041,202	100

Figure 3 shows that electricity production in the system shows a seasonal pattern consistent with annual contributions. Solar panels dominated output with a monthly average of around 54.66 MWh, peaked in July and August with 70-80 MWh per month, and declined to 50-60 MWh in December and January. Wind turbines showed stability throughout the year with a monthly average of 34.76 MWh, slightly higher in July and August (around 40 MWh). Meanwhile, the grid (grid) made a steady small contribution of 8.23 MWh monthly. The total monthly production of the system averaged 97.65 MWh, with peak production in July-August (110-120 MWh) and minimum in December-January (80-90 MWh).

Overall, total annual production of 1,171,775 MWh came from PV (56%), wind turbines (35.6%), and grids (8.43%). This production distribution aligns with the system's design and relies heavily on renewable energy, reaching 91.6% of total production. The surplus energy generated during the months with peak production, especially in the summer, allows the system to resell 15% of total annual consumption to the grid. Thus, the system meets the internal energy needs and generates excess energy that the external power grid can utilize.

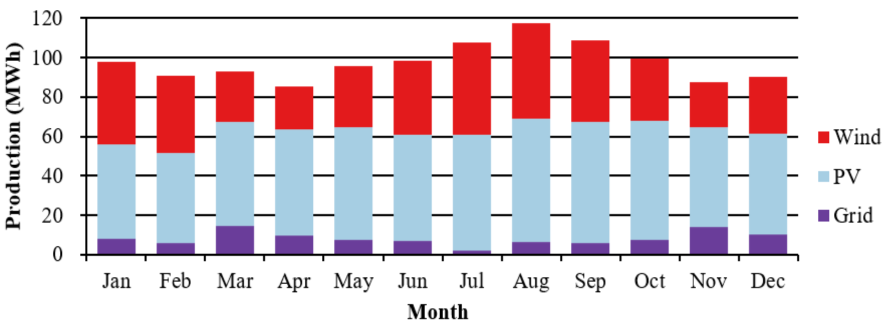

Figure 3. Monthly power production

3.3. Recommendations and implications

The techno-economic analysis supports prioritizing hybrid energy systems, particularly those integrating PV panels and wind turbines with battery storage and converters. These systems achieve superior cost efficiency, reduced operational costs, and enhanced environmental sustainability. The low LCOE and NPC values and significant emission reductions underline the viability of transitioning from conventional grid-based systems to renewable energy solutions.

Given the site's high solar radiation and stable tropical climate, solar energy should be the primary focus of future energy development efforts. The steady wind contribution complements solar energy, ensuring reliable and diversified energy production. By capitalizing on renewable resources, the hybrid system meets energy demands and provides economic and environmental benefits, making it a model for sustainable energy planning.

4. CONCLUSION

This study demonstrates the effectiveness of renewable energy-based hybrid systems in delivering both economic and environmental benefits. By integrating solar panels, wind turbines, batteries, and converters, the system offers a cost-effective and sustainable alternative to conventional grid-based energy. The analysis confirms that such configurations can optimize energy use in regions with high solar potential, as evidenced by the favorable performance of the proposed system. The hybrid approach also supports energy self-sufficiency and resource optimization by utilizing locally available energy sources. These findings contribute to the growing body of evidence supporting hybrid renewable systems as a strategic solution for sustainable energy development.

The implications of this research extend beyond the case study site, suggesting that similar systems could be effectively adapted to other regions with comparable solar and wind profiles. The substantial reduction in emissions reinforces the potential of hybrid systems to contribute to climate change mitigation and cleaner air. Moreover, the results point to the importance of policy support and technological innovation, particularly in energy storage to further improve performance and scalability. Future studies are encouraged to explore adaptive strategies for hybrid integration in diverse geographic and socio-economic contexts. Overall, this research underscores the strategic value of hybrid renewable energy systems in achieving long-term energy resilience and sustainability.

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AUTHOR CONTRIBUTIONS STATEMENT

This journal uses the Contributor Roles Taxonomy (CRediT) to recognize individual author contributions, reduce authorship disputes, and facilitate collaboration.

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C : **C**onceptualization
M : **M**ethodology
So : **So**ftware
Va : **Va**lidation
Fo : **Fo**rmal analysis
I : **I**nvestigation
R : **R**esources
D : **D**ata Curation
O : Writing - **O**riginal Draft
E : Writing - Review & **E**diting
Vi : **Vi**sualization
Su : **Su**pervision
P : **P**roject administration
Fu : **Fu**nding acquisition

CONFLICT OF INTEREST STATEMENT

The authors declare no conflict of interest.

DATA AVAILABILITY

The data used to support the research findings are available from the corresponding author upon request.

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