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Sustainable Energy Transition in Remote Islands: Evaluating Wind–Solar Hybrid Systems to Support Commercial Green Tourism on Kei Kecil Island

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Abstract

This study aims to analyze the techno-economic feasibility of a hybrid microgrid system designed to support commercial green tourism infrastructure on Kei Kecil Island, Southeast Maluku. The research focuses on evaluating the investment feasibility of adding a 99 kW wind power plant to an existing system comprising photovoltaic (PV), diesel generators, and batteries. The methodology employs HOMER Pro simulation to assess key financial indicators and environmental impacts, with a particular emphasis on carbon emission reduction. Simulation results indicate that the proposed hybrid scenario offers a highly profitable investment strategy, characterized by a high return on investment (ROI) and a rapid payback period of under five years. These findings confirm that integrating wind energy not only significantly increases the renewable energy fraction but also suppresses the cost of energy to a competitive level compared to conventional generation. The novelty of this study lies in the specific analysis of wind turbine intervention on a brownfield architecture in a remote island setting, distinguishing it from typical greenfield design studies. This research provides a significant contribution to policymakers and investors as a validation model for energy transition supporting sustainable tourism in archipelagic regions.

Keywords: techno-economic analysis; green tourism; microgrid hybrid wind turbine; PV.

1. Introduction

The increasing need for electrical energy in Indonesia, especially in remote archipelagic areas, demands a more sustainable and environmentally friendly energy diversification strategy. So far, the electricity supply in many isolated areas remains highly dependent on fossil-based diesel power plants, which are vulnerable to global market price fluctuations [1], [2]. This dependence carries various multidimensional risks, ranging from high operational costs due to logistics complexity to negative environmental impacts in the form of massive greenhouse gas emissions [3], [4]. This condition urges the acceleration of energy transition through the integrated use of new renewable energy within smart hybrid microgrid systems [5], [6]. One strategic implementation is the development of hybrid power plants combining local potentials, such as wind power and solar power, to drastically reduce diesel fuel consumption [7], [8]. This integrative approach is expected not only to improve generation cost efficiency but also to strengthen national energy security in outer regions.

The application of hybrid solar power plants to support commercial green tourism, such as the case study on Kei Kecil Island, holds high economic and strategic urgency [9], [10]. Although hybrid systems offer potential operational cost savings and improved supply reliability, their success heavily depends on accurate technical analysis of intermittent local resource characteristics [11], [12]. However, most of the existing literature focuses more on designing new systems and rarely evaluates technical interventions in currently running systems. To bridge this research gap, this study focuses on the techno-economic feasibility analysis of adding wind power capacity to an existing system (photovoltaic (PV)-diesel-battery) using HOMER Pro simulation [13], [14]. This research aims to validate whether the addition of wind turbines can significantly improve cost efficiency and environmental performance in operating tourism infrastructure. Comprehensive evaluation is conducted on vital

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indicators such as annual cost savings, return on investment, and payback period as a basis for investment decision-making [15], [16].

Table 1. Comparative literature review

Reference	Methods/software	levelized cost of energy (LCOE)/cost of energy (COE)	NPC	Key results
[17]	Techno-economic analysis of grid-connected systems (PV/wind/battery) using HOMER Pro.	$0.134/kWh	$11.9 Million	Analyzed a hybrid system (PV/wind/battery) connected to the grid to improve the voltage profile on Tumbatu Island, Zanzibar. Optimal configuration has been shown to reduce COE by 20.2% compared to other scenarios.
[18]	The design of a stand-alone microgrid system (PV/Wind/Battery/Diesel) uses HOMER Pro.	$0.198/kWh	$5.98 Million	Designed a stand-alone hybrid system for a wastewater treatment plant in İzmir, Turkey. The optimal scenario (PV/wind/diesel/battery) was identified as the most feasible with a renewable fraction of 77.2%.
[19]	Hybrid system optimization (PV/wind/biogas/battery/grid) using HOMER Pro and the multi-criteria decision-making (MCDM) CRITIC-PROMETHEE II METHOD.	$0.312/kWh	$1.41 Million	Analyzed six hybrid system scenarios, including biogas from human waste, for a school in Malawi. The MCDM method is used to select the optimal configuration (PV/wind/biogas/battery) to reduce electricity bills and grid dependence.
[20]	Optimization of on-grid hybrid systems (PV/wind) using HOMER Pro.	$0.021/kWh	$11.9 Million	Analyze on-grid PV/wind systems to supply electricity to cement plants in Kuwait. The proposed optimal system can achieve a renewable fraction of 51.5% and shows significant cost savings.
[21]	Evaluate the energy, economics, and environment of on-grid (PV/wind) systems using HOMER Pro.	$0.0382/kWh	$1.04 Million	Analyze the feasibility of an on-grid PV/wind system at a site in Colombia. The proposed system proved economically feasible (7.8-year payback period) and reduced 1,174 tons of CO_2 per year.

The novelty of this research lies in its specific focus on the techno-economic evaluation of retrofitting an operational brownfield microgrid, rather than designing a greenfield system from scratch. While existing literature (Table 1) extensively covers comparative potential studies or optimal sizing for new installations, there is a distinct lack of research analyzing the technical and financial implications of intervening in an active hybrid architecture [22], [23]. This study bridges that gap by modeling the integration of a 99 kW wind power plant into an established system comprising PV, diesel, and battery storage on Kei Kecil Island [24]. The primary objective is to assess whether such an intervention can be economically justified to support commercial-scale green tourism infrastructure without compromising grid stability. Using HOMER Pro simulations, this research provides a rigorous validation model for clean energy investments, focusing on critical financial metrics such as internal rate of return and return on investment (ROI) under real-world constraints. Consequently, the findings are intended

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to serve as a strategic reference for upgrading energy infrastructure in remote archipelagic regions, moving beyond theoretical feasibility to practical investment viability [25].

2. Methods

This study can be seen in Figure 1 illustrates the schematic diagram of the hybrid system modeled using HOMER Pro software with a brownfield configuration to serve tourism electrical loads on Kei Kecil Island. Technically, this system integrates generation components across two main buses: the AC bus hosts the existing 250 kW diesel generator and the proposed 99 kW wind turbines, while the DC bus accommodates the 100 kWp PV array and 264 kWh Battery bank connected by a 250 kW bi directional converter [26]. To ensure methodological transparency and simulation accuracy, the model operates on a 60-minute time step using the cycle charging (CC) dispatch strategy, which prioritizes battery charging by the diesel generator running at full load for maximum fuel efficiency [27]. Furthermore, the validity of financial indicators (net present cost (NPC) and LCOE) is upheld through the application of rigorous macroeconomic parameters, including a nominal discount rate of 10% and an annual inflation rate of 3.5% over a 25-year project lifetime. Operational cost analysis also accounts for energy market realities by setting the industrial diesel price at $1.10 per liter, accompanied by a fuel price escalation assumption of 5% per year to anticipate future fossil energy cost increases [28]. This combination of integrated technical architecture and conservative economic assumptions is designed to yield a realistic and justifiable investment evaluation.

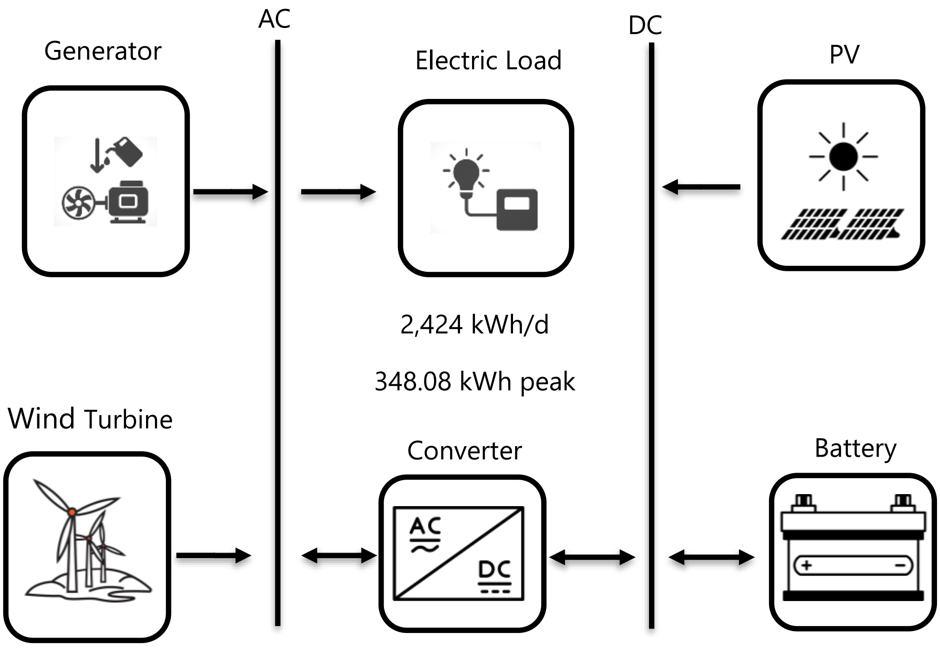

Figure 1. Scheme of hybrid wind and solar power plant

Figure 2 presents a high-resolution satellite image of the case study site on Kei Kecil Island, specifically located at coordinates 5.63° S and 132.73° E. The geographical characteristics of this archipelago present dual logistical challenges: high reliance on costly maritime diesel fuel shipments and the risk of supply disruptions due to adverse weather [29]. However, from a renewable energy technical perspective, the open coastal topography offers significant advantages in the form of unobstructed wind fetch and low surface roughness, conditions highly ideal for maximizing wind turbine capacity factors. Therefore, the selection of this location is considered highly

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relevant and representative for analyzing the application of hybrid energy systems (wind and solar) as a resilient standalone infrastructure solution to support sustainable commercial green tourism in outer regions [30].

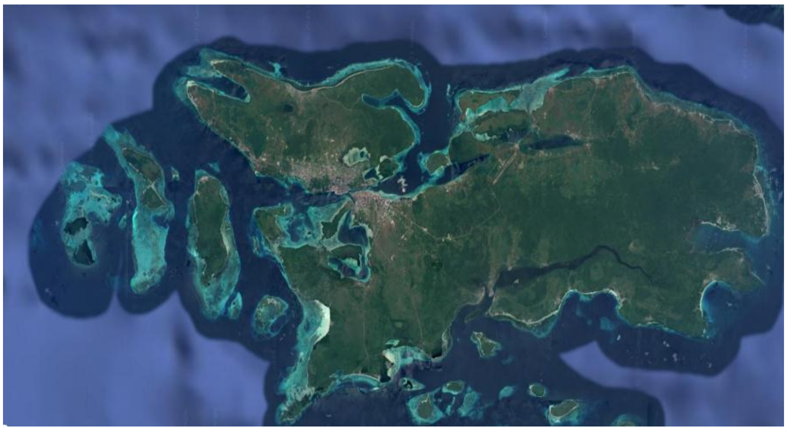

Figure 2. The condition of the Kei Kecil Island that became a case study

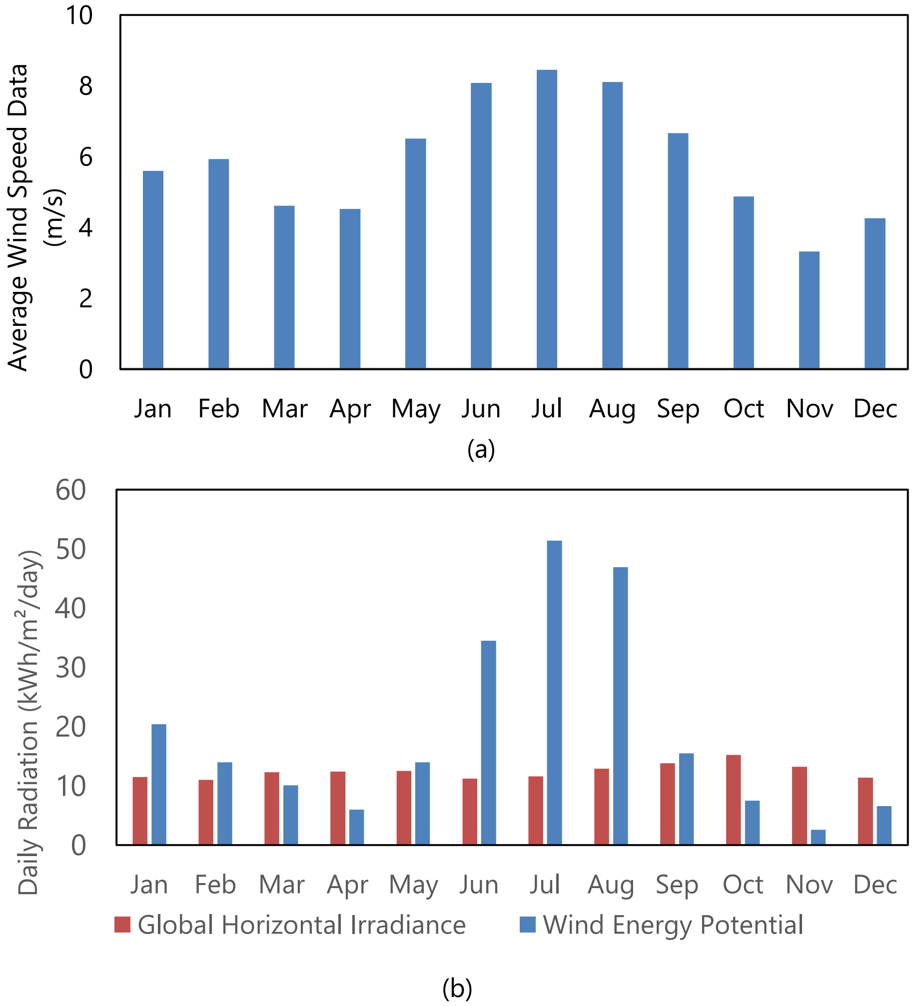

Figure 3. (a) Average wind speed data and (b) Global horizontal irradiance and wind energy potential

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The techno-economic feasibility of the hybrid system on Kei Kecil Island is critically determined by the availability characteristics of local natural resources, as comparatively visualized in Figure 3 based on National Aeronautics and Space Administration (NASA) power satellite data from the last 5-year period. Figure 3 (a) displays the average wind speed profile, which exhibits sharp seasonal fluctuations driven by monsoon patterns. Wind speeds reach their highest intensity in July (>7.4 m/s) during the East Monsoon but experience a significant decline to their lowest point in November (<4.0 m/s) during the transition period.

In contrast, Figure 3 (b) presents the daily radiation data, which remains relatively stable throughout the year, ranging from 4.65 kWh/m²/day in the rainy season (February) to a peak of 6.32 kWh/m²/day in October. This pattern indicates that solar potential can be relied upon as a consistent base load supply. These contrasting yet complementary resource characteristics where wind peaks mid-year and solar remains stable year-round serve as key variables in the simulation to determine the energy management strategy and optimal battery capacity required to guarantee 24-hour electricity supply reliability.

3. Techno-Economic Performance Metrics for Hybrid Renewable Energy Systems

To comprehensively evaluate the performance of hybrid renewable energy systems, a techno-economic analysis is conducted using a set of quantitative indicators. These parameters describe the financial feasibility, energy efficiency, and environmental benefits of the system throughout its operational lifetime. NPC represents the total life-cycle cost of the system, discounted to its present value. It includes all expenses related to capital investment, component replacement, operation and maintenance, and fuel consumption, minus the residual (salvage) value of components at the end of the project. The equation is expressed as follows [31].

$$\text{NPC} = \text{Capital Cost} + \text{Replacement Cost} + \text{O\&M Cost} + \text{Fuel Cost} - \text{Salvage} \quad (1)$$

The capital cost covers the initial investment, the replacement cost represents periodic component renewals, and the O&M cost accounts for the routine operation and maintenance of the system. Fuel cost applies to hybrid systems utilizing fossil fuels or biomass, while the salvage value indicates the remaining worth of system components after the project's lifespan. COE describes the average cost of producing one kWh of electricity. It is calculated by dividing the total annualized cost of the system by its total energy production per year, as shown in equation (2) [32].

$$\text{COE} = \frac{\text{Total Annual Cost}}{\text{Total Energy Production}} \quad (2)$$

A lower COE reflects a more cost-efficient and productive system, making it a key indicator for comparing different configurations or technologies. Moreover, ROI measures the economic profitability of the project by comparing the net annual savings to the initial investment. The formula is written in equation (3) [33].

$$\text{ROI} = \frac{\text{Net Annual Savings}}{\text{Initial Investment}} \times 100\% \quad (3)$$

Net annual savings represent the difference between the operational costs of the existing (conventional) system and those of the proposed renewable configuration. A higher ROI indicates a more financially attractive project. Moreover, simple payback period defines the time required to recover the initial investment from the annual cost savings generated by the system. It is given as follows [34].

$$\text{Payback Period} = \frac{\text{Initial Investment}}{\text{Annual Savings}} \quad (4)$$

This metric provides a straightforward measure of investment recovery time, with shorter payback periods signifying better economic viability. Moreover, solar power plant energy production (E_{PLTS}) is calculated based

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on the installed capacity, solar radiation intensity, and system performance ratio (PR). The formula is expressed as follows [35].

$$E_{PLTS} = P_{pv} \times GHI \times PR \quad (5)$$

where P_{pv} is the installed PV capacity (kWp), GHI is the global horizontal irradiance (kWh/m^2/year), and PR represents the system's overall performance ratio, typically ranging from 0.7 to 0.85.

Wind power plant energy production (E_{PLTB}) is determined using wind energy potential (WEP), installed turbine capacity, and performance ratio. It can be formulated in the following expression [31], [36].

$$E_{PLTB} = P_{PLTB} \times WEP \times PR \quad (6)$$

here, P_{PLTB} is the rated capacity of the wind turbine system (kWp), WEP represents the available wind energy potential (kWh/m^2/year), and PR denotes the performance ratio that reflects aerodynamic and mechanical efficiency.

Renewable fraction (RF) measures the contribution of renewable energy sources to the total system load. It indicates how much of the total energy demand is met by renewable generation, calculated as follows [37].

$$RF = \frac{E_{ren}}{E_{load}} \times 100\% \quad (7)$$

A higher RF value signifies a greater reliance on renewable sources and a reduced dependency on fossil fuels. CO_2 emissions avoided quantifies the environmental benefit of using renewable energy by estimating the amount of CO_2 emissions avoided compared to a conventional system. The relationship is given by the following equation [38].

$$CO_2 = E_{renewable} \times EF \quad (8)$$

where $E_{renewable}$ is the energy generated by renewable sources (kWh) and EF is the emission factor (kg CO_2/kWh), typically around 0.6 kg CO_2/kWh for systems replacing diesel generation.

Overall, these techno-economic metrics provide a comprehensive framework for assessing the performance of hybrid renewable energy systems. By integrating technical, economic, and environmental aspects, this approach enables researchers and decision-makers to identify optimal system configurations that balance sustainability, efficiency, and cost-effectiveness.

4. Results and Discussion

4.1. Simulation results from HOMER

Cost structure analysis and load implications of the initial investment structure detailed in Table 2 provide fundamental insights into the system's economic feasibility. The dominance of the energy storage cost (Tesla Powerwall 2.0) at $200,000 comprising over 60% of the total generation component costs indicates that the primary bottleneck in achieving higher renewable penetration is not the cost of solar panels or wind turbines, but the cost of storage. The sharp disparity between the low capital cost of the diesel generator ($15,000) and the high cost of batteries explains why a fully renewable system remains economically unfeasible. However, this substantial upfront investment in battery and wind infrastructure ($60,000) serves as the key variable in suppressing long-term operational costs, thereby enabling the achievement of an NPC of $2.298 million and a competitive levelized COE of $0.1284/kWh.

The technical challenges in the system design are underscored by the load profile in Table 3. With a total consumption of 884,852 kWh/year consisting entirely of AC primary load (no deferrable load), the system faces high demand rigidity. The absence of deferrable loads implies that the system lacks demand-side management

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flexibility, necessitating that all load fluctuations are met instantly by power supply. This condition is the underlying cause for retaining the diesel generator within the energy mix; it functions as a grid stabilizer during sudden load spikes that cannot be solely addressed by the battery discharge rate.

The effectiveness of this strategy is reflected in the energy mix composition in Table 4. Comparative analysis reveals that the AWS HC 3.3 kW wind turbine possesses a specific productivity far superior to PV. Despite equivalent installed capacities (100 kW), wind contributes 25% to total energy production, outperforming PV's 16.1%. This phenomenon occurs because the wind profile at the study site (see Figure 3) offers longer availability duration extending into the night, unlike PV which is limited to daylight hours. Although the effective renewable fraction reaches 37,6%, the continued dominance of the diesel generator at 58.9% is a deliberate economic compromise designed to maintain a high ROI of 19.6% and a short payback period (4.15 years), avoiding battery oversizing that would erode project economics.

Table 2. Component price data

Component	kW	Price
LONGi Ssolar LR6-60PH	100	$20,000
AWS HC 3.3 kW wind turbine	99	$60,000
Generator CAT-250kW-60Hz-PP	250	$15,000
Schneider inverter altivar ATV630 250kW	250	$15,558
Tesla Powerwall 2.0	264	$200,000

Table 3. Load profile of annual electricity consumption for hybrid solar power plant simulation on Kei Kecil Island

Consumption	kWh/year	%
AC primary load	884,852	100
DC primary load	0	
Deferrable load	0	
Total	884,852	100

Table 4. Contribution of solar energy, wind energy, and generators to annual consumption

Energy Contribution	kWh/year	%
LONGi solar LR6-60PH	150,551	16.1
AWS HC 3.3kW wind turbine	234,488	25
Generator CAT-250kW-60Hz-PP	551,969	58.9
Total	936,968	100

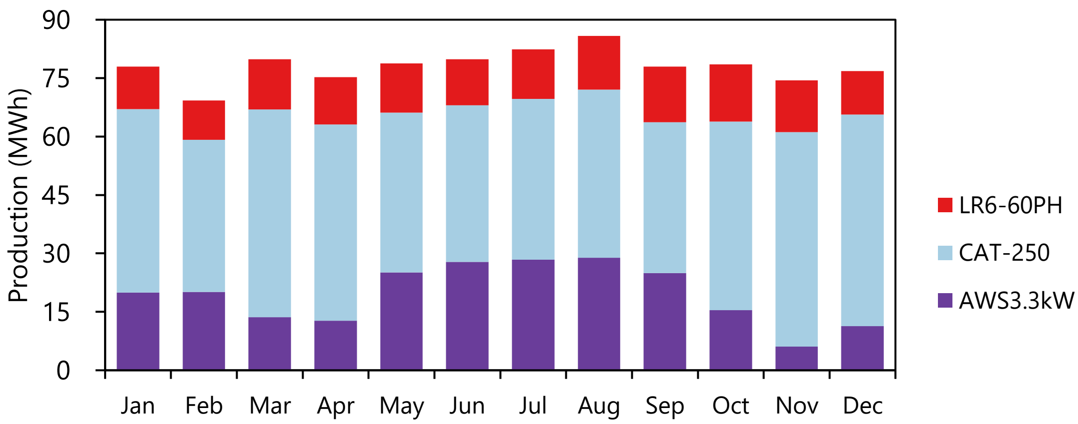

Figure 4. Electrical energy production from Kei Kecil Island

Figure 4 illustrates the monthly production dynamics of the hybrid system, which generates a total of 940 MWh annually. This stacked bar chart details the interaction between three key components. The AWS 3.3 kW wind turbines contribute 235 MWh (25.0%), exhibiting strong seasonality with significant output observed from May to September and peaking in July–August, consistent with the regional seasonal wind patterns. In contrast, the solar power plants (LR6-60PH) provide a relatively stable energy supply throughout the year, contributing 195 MWh (20.7%), with a slight production increase during the dry season (June–August) due to higher global horizontal irradiance (GHI). Consequently, the diesel generator (CAT-250) remains the dominant supplier, generating 510 MWh (54.3%). Its role is particularly critical as a stabilizer during months with lower renewable yields specifically February, April, and November where it ramps up operations to guarantee supply reliability and cover production shortfalls from the fluctuating renewable sources.

4.2. Economic analysis

Comprehensive techno-economic feasibility and strategic implementation analysis based on simulation parameters utilizing a conservative discount rate of 4.75% and an inflation rate of 3% over a 25-year project lifetime, the hybrid system optimization project on Kei Kecil Island demonstrates robust commercial viability. financially, the project is estimated to have a total NPC of $2.298 Million and a highly competitive LCOE of $0.1284 per kWh. This superior performance is mainly reflected in the very high ROI, which reaches 19.6%, and a rapid simple payback period of only 4.15 years. This implies that investors can achieve a break-even point in less than one fifth of the project's operational life, rendering the initial investment in 99 kW wind turbines and energy storage a low-risk, high-impact business decision (Table 5).

The robustness of this economic model is further validated through multidimensional sensitivity analysis. In a scenario of energy market volatility, should diesel fuel prices rise from the current baseline to $1.50/liter (anticipating subsidy removal), the project's ROI is projected to surge to 24.8%. This finding confirms that the hybrid system functions effectively as a hedging mechanism against fossil energy inflation. However, the analysis also identifies vulnerability regarding climate variability; a 15% decrease in average wind speed particularly during critical transition months like October and November would necessitate increased diesel dispatch, implying a rise in LCOE to $0.139/kWh. Furthermore, given that batteries constitute the largest CAPEX component, a future 20% reduction in storage technology costs is predicted to have the most significant impact on reducing the overall NPC.

While the simulated indicators are promising, the transition to physical implementation faces complex practical challenges that must not be overlooked. First, logistics in remote archipelago regions pose risks of cost overruns due to the complexity of supplying sensitive components like wind turbines and Li-ion batteries via maritime routes. Second, a technical skill gap exists; the local workforce, typically accustomed to mechanical diesel engines, requires intensive training to manage digital energy management systems (EMS) and advanced inverters to prevent system downtime. Third, the financial barrier of high upfront capital ($2.298 Million) demands creative financing schemes, such as public private partnerships (PPP), given local budget constraints. Finally, battery lifecycle management in a hot tropical climate requires strict cooling system planning and the allocation of a sinking fund for battery replacement in year 10, ensuring long-term energy supply sustainability.

Table 5. Techno-economic and environmental performance of hybrid wind and solar power plants on Kei Kecil Island

Metric	Result
Total NPCs	$2.298 Million
COE	$0.1284
ROI	19.6%
Simple payback	4.15 years
Solar power plant production	150,511 kW/year
Wind power plant production	234,488 kW/year
Renewable Factions	37.6%
CO_2 emissions	431,542 kg/year

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4.3. Literature Comparation

Based on the simulation results, the proposed hybrid system on Kei Kecil Island consistently shows very superior financial performance as a green tourism infrastructure investment, demonstrating an ROI of 19.6% and a rapid payback period of 4.15 years. This profitability performance far outperforms comparative case studies that report similar metrics, such as on-grid studies in Colombia that record a payback period of 7.8 years [21]; a disparity primarily driven by the high avoided cost of fuel in Kei Kecil ($1.10/liter) which amplifies operational savings compared to the lower energy costs in the Colombian context. However, when compared to international literature, the LCOE of this study ($0.1284/kWh) is in a moderate but very competitive position for its class. Industrial-scale on-grid projects in the Middle East, such as in Kuwait, show that the LCOE can be reduced to as low as $0.021/kWh [20], mainly because grid-tied systems avoid the significant capital expenditure required for battery energy storage. Conversely, stand-alone microgrid studies in Turkey and Malawi reported much higher LCOEs (ranging from $0.198–$0.312/kWh) [18], [19], often due to less optimal resource complementarity which necessitates system oversizing. This distinction emphasizes that although the Kei Island study is the most optimal in the context of profitability (ROI), the ROI is strongly influenced by external factors such as project scale, system configuration (on-grid vs. stand-alone), capital costs (especially batteries), as well as reliability assumptions. Thus, this comparison shows that the results on Kei Kecil Island are already very relevant and superior for the national microgrid context but still cannot be directly equated with international on-grid studies that utilize different technical and financial baselines.

5. Conclusion

Based on the results of the technoeconomic analysis of hybrid power plants (solar power plants and wind power plants) on Kei Kecil Island, it is evident that the integration of renewable energy components specifically the addition of 99 kW of wind turbines significantly enhances system performance from economic, technical, and environmental perspectives. The proposed system scenario proves to be the most ideal investment choice due to its superior financial performance, demonstrated by a very high ROI of 19.6% and a rapid simple payback period of only 4.15 years. Technically, this optimized system significantly boosts clean energy production, supported by the contribution of solar PV (150,511 kWh/year) and wind turbines (234,488 kWh/year). This technical synergy achieves a renewable fraction of 37.6% and results in a competitive COE of $0.1284 per kWh. Although the system still produces CO_2 emissions of 431,542 kg/year due to the role of diesel generators, its financial indicators confirm high feasibility. Thus, it can be concluded that the implementation of wind power plants to the hybrid system on Kei Kecil Island is a highly feasible and profitable strategy for commercial green tourism infrastructure investment.

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