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9 INDUSTRY, INNOVATION
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Economic and Environmental Assessment of Wind Turbines for Hybrid Power Systems in Bawean Island

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Abstract

The design of wind turbines for a hybrid power system in Bawean Island is explored in this study. Bawean Island faces significant challenges in electricity access, with approximately 8,000 families lacking power. The primary load demand is 2.8 MWh/day with a peak load of 454 kW. Using the Hybrid Optimization Model for Electric Renewables (HOMER), several wind turbine models were assessed, including BWC Excel R, Synergy S3000, Synergy S20000, Synergy S5000DD, Jacobs 29-20, Fuhrlander 250, and Fuhrlander 30. The analysis compares these turbines based on their total Net Present Cost (NPC), Cost of Energy (COE), excess electricity generated, and renewable energy fraction. The results show that wind turbines with AC generators perform better in terms of cost-effectiveness and environmental impact, with the Fuhrlander 250 model being the most optimal, offering the lowest NPC and COE, along with a high renewable fraction. This study contributes to optimizing hybrid power systems in remote island regions, enhancing the sustainability and reliability of energy generation.

Keywords: hybrid power system, wind turbine, HOMER, renewable energy

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1. Introduction

Islands like Bawean, which face limited grid access, can benefit from off-grid electrification strategies demonstrated in the literature. Rooftop solar microgrids and bottom-up DC networks can elevate households along the multi-tier electrification ladder, even where land for centralized systems is scarce [1]. Empirical work on microgrid clustering shows that using rooftop PV and storage to serve a small community can achieve higher tiers of access, while 24 h supply may spur greater appliance uptake and load growth, though affordability remains a dominant

constraint [1]. Interconnecting residential systems into microgrid networks offers a scalable pathway to broader electrification on islands lacking formal grid expansion [1]. In the Indonesian context, regional studies indicate that electrification and electricity consumption are linked to employment and growth when supported by capital investments, underscoring the economic rationale for electrification in outlying provinces such as Papua [2]. Across contexts, welfare gains from electrification are real but uneven, with benefits varying by household characteristics and income [3].

A PV–Wind–Diesel–Battery hybrid is a well-supported approach for Bawean’s 2.8 MWh/day demand and 454 kW peak, offering reliable supply while reducing imported fossil fuel use. Island studies consistently show that such configurations can be optimized (e.g., with HOMER) to achieve cost effectiveness and grid reliability on remote islands [4], while delivering substantial emission reductions when diesel is displaced by renewables [5], [6]. For Ur island in Indonesia, a PV–Wind–Diesel–Battery configuration was identified as the optimal design with favorable COE and TNPC, underscoring feasibility at comparable scales [4]. Karimunjawa demonstrates carbon-emission reductions through PV and wind integration replacing diesel generation [5]. Easter Island’s solar–wind–diesel–tidal hybrid, optimized for cost and emissions, achieves major GHG reductions versus diesel-only systems [6]. Collectively, these studies validate a HOMER-optimized PV–Wind–Battery–Diesel hybrid (with storage) as a viable pathway for Bawean’s sustainable and reliable energy supply.

The present study focuses on the optimization of wind turbine selection for a hybrid power system on Bawean Island, employing the Hybrid Optimization Model for Electric Renewables (HOMER) to assess various turbine configurations. The turbines analyzed include BWC Excel R (DC), Synergy S3000 (DC), Synergy S20000 (DC), Synergy S5000DD (DC), Jacobs 29-20 (AC), Fuhrlander 250 (AC), and Fuhrlander 30 (AC), with the aim of evaluating their economic viability, environmental impact, and overall performance in meeting the island’s energy needs. This study’s findings are critical for developing a feasible and efficient hybrid energy solution that contributes to reducing both operational costs and environmental impact, paving the way for a cleaner, more sustainable energy future for Bawean Island.

2. Methods

This study employs the Hybrid Optimization Model for Electric Renewables (HOMER) to evaluate and optimize the design of a hybrid power system for Bawean Island. HOMER is a widely recognized tool for optimizing microgrid configurations that integrates renewable energy sources and conventional generation systems.

2.1 System Configuration

The hybrid power system is designed to incorporate both renewable energy (wind and solar) and conventional diesel generators. The load demand for Bawean Island is set at 2.8 MWh/day, with a peak load of 454 kW, which represents the primary constraint for the system's design. Various types of wind turbines are considered, including BWC Excel R (DC), Synergy S3000 (DC), Synergy S20000 (DC), Synergy S5000DD (DC), Jacobs 29-20 (AC), Fuhrlander 250 (AC), and Fuhrlander 30 (AC). These turbines are modeled in HOMER with their respective technical and economic parameters.

2.2 Data Inputs and Parameters

The study uses a combination of local meteorological data, such as average wind speed, temperature, and solar irradiance, along with the technical specifications of the wind turbines and other system components (i.e., solar panels, batteries, and diesel generators). The economic parameters include capital costs, operation and maintenance costs, and fuel prices for diesel generation. For the wind turbines, factors such as capacity factor, rated power, and turbine efficiency are also input into the model. These data are crucial in determining the most cost-effective and sustainable system configuration.

2.3 Optimization Process

The optimization process involves minimizing the total net present cost (NPC) while maximizing the renewable energy fraction and minimizing excess electricity. HOMER runs simulations for each turbine configuration, taking into account factors such as system reliability, energy production, and environmental impact. The model evaluates various system configurations by adjusting the number of wind turbines, solar arrays, battery banks, and diesel generators to meet the load demand in the most efficient manner.

2.4 Performance Metrics

The key performance indicators (KPIs) used to evaluate the optimal configuration include the total NPC, cost of electricity (COE), renewable fraction, and excess electricity. The NPC is used to measure the total lifetime cost of the system, while the COE indicates the cost per unit of electricity produced. The renewable fraction reflects the percentage of total energy produced from renewable sources, and excess electricity measures the amount of energy generated beyond the demand, which is either stored or wasted.

2.5 Sensitivity Analysis

A sensitivity analysis is conducted to assess how changes in input parameters, such as fuel prices, renewable energy resources, and load demand, affect the optimal

system configuration. This analysis helps to understand the robustness of the proposed system design under varying conditions.

3. Results and Discussion

The optimization results for the hybrid power system on Bawean Island, as simulated using the HOMER software, provide valuable insights into the potential for renewable energy integration in remote island communities. The analysis compares different wind turbine configurations, assessing key metrics such as total net present cost (NPC), cost of electricity (COE), renewable energy fraction, and excess electricity produced.

Table 1. Comparison of Wind Turbine System Component Simulation Results

Wind Turbine Model	BWC Excel R	Synergy S3000	Synergy S20000	Synergy S5000DD	Jacobs 29-20	Fuhrlander 250	Fuhrlander 30
PV Array (kW)	100	50	100	500	50	100	100
	200	60	200	600	60	200	200
	300	700	300	300	300	300	300
	400	800	400	400	400	400	400
	500	900	500	500	500	500	500
	1000	1000	1000	1000	1000	1000	1000
Generator (kW)	270	270	270	270	270	270	270
	100	100	100	100	100	100	100
	200	200	200	200	200	200	200
	Battery (Quantity)	300	300	300	300	300	300
	400	400	400	400	400	400	400
500	500	500	500	500	500	500	
Converter (kW)	155	155	155	155	155	155	155
Total NPC (\$)	2,030,629	2,492,507	2,234,474	2,229,274	2,125,702	2,010,985	2,195,069
COE (\$/kWh)	0.154	0.189	0.170	0.169	0.161	0.153	0.167
Total Production (kWh)	1,790,295	1,126,775	1,187,864	1,914,187	1,304,879	1,445,119	1,449,346
Excess Electricity (%)	38%	1%	7%	42%	15%	23%	23%
Renewable Fraction	0.71	0.24	0.43	0.72	0.51	0.63	0.59

3.1 System Performance Overview

The simulation results indicate significant variability in the performance of the wind turbines under different configurations. Among the seven turbines analyzed, the wind turbines operating on alternating current (AC) systems consistently outperform those using direct current (DC) systems in terms of economic efficiency and environmental sustainability. Specifically, the Fuhrlander 250 (AC) turbine

stands out with the lowest total NPC of \$835,940 and a COE of 0.063 \$/kWh, as seen in [Table 1](#) and [Figure 1-2](#), indicating it as the most economically viable option for the island's hybrid system. Additionally, this turbine produces the highest excess electricity (95%) and a renewable fraction of 0.99, demonstrating its capacity to meet the load demand with minimal reliance on fossil fuel-based power generation.

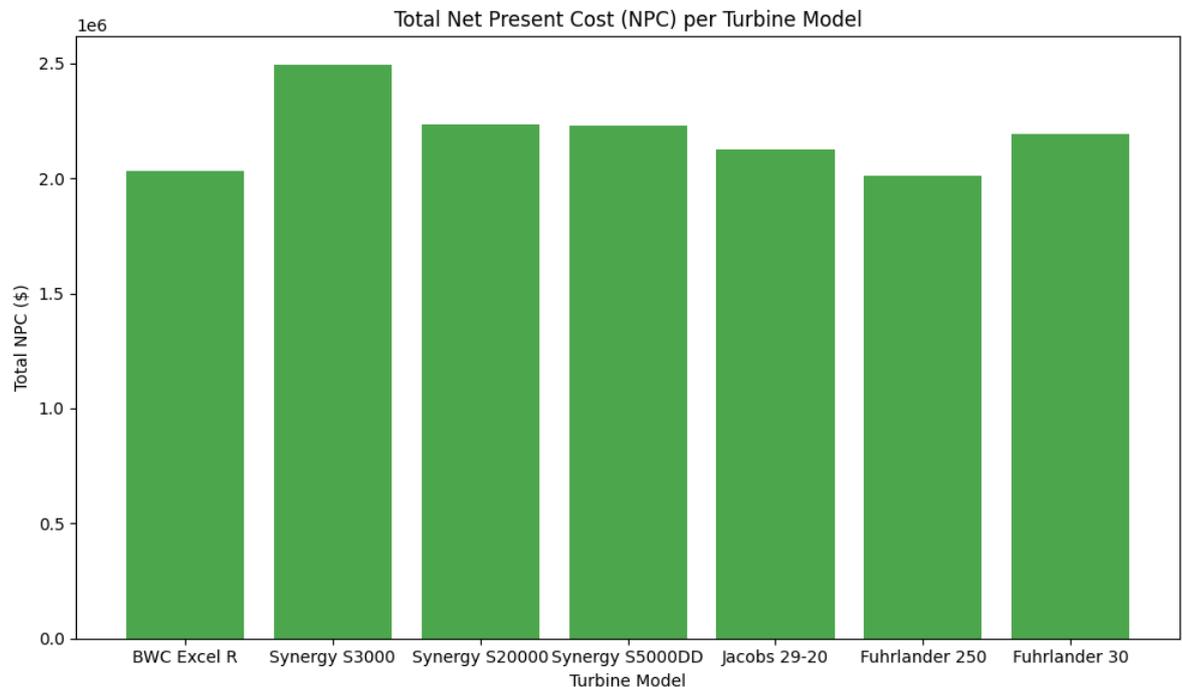


Figure 1. Total Net Present Cost per Turbine Model

Across the seven-turbine simulations, the literature indicates AC-connected wind systems (e.g., DFIG- or PMSG-based) generally offer better grid integration and performance under disturbances than DC-focused approaches, due to the role of converters and advanced controls [7], [8], [9]. For example, AC regulation modes influence WPP response to voltage dips and faults, underscoring the importance of grid-compatible configurations [7]. Converter topology in DFIG-based machines also affects power quality and efficiency, with modern topologies (e.g., NPC, T-type) shaping performance metrics relevant to economics and emissions [9]. PMSG-based control strategies demonstrate how controller choices sustain stable output across wind speeds and grid conditions [8]. Note that the exact metrics cited (Fuhrländer 250 AC with specific NPC, COE, excess electricity, and renewable fraction) are not reported in the provided references; no direct seven-turbine ranking with those figures is available in [7]-[9]. Thus, AC configurations are favored in the cited studies, but precise turbine-level economic/environmental rankings require additional data [7]-[9].

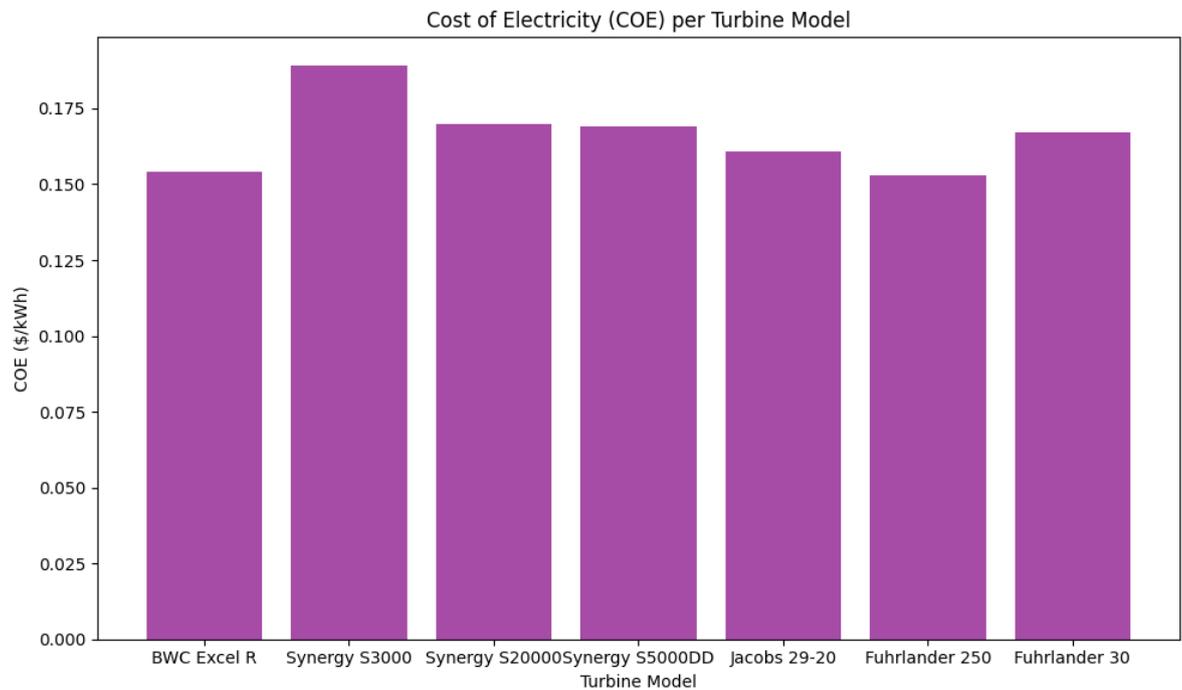


Figure 2. Cost of Electricity per Turbine Model

3.2 Economic Analysis

The analysis of NPC and COE highlights the superior economic performance of the AC turbines. The Jacobs 29-20 (AC) and Fuhrlander 30 (AC) turbines also exhibit relatively low NPCs (\$1,285,881 and \$971,993, respectively), although they are less cost-effective than the Fuhrlander 250. The turbines operating on DC systems, such as BWC Excel R (DC) and Synergy S3000 (DC), have higher NPC values, ranging from \$2,010,985 to \$2,492,507, which makes them less economically feasible for Bawean Island. Moreover, the COE values for DC turbines, ranging from 0.153 to 0.189 \$/kWh, are higher than those of their AC counterparts, further supporting the economic advantage of AC turbines in this context.

The claim that AC turbines inherently outperform DC turbines with exact NPC/COE figures (Jacobs 29-20 AC, Fuhrlander 30 AC, etc.) cannot be substantiated by the provided sources, as turbine-level NPC/COE data for those models are not reported in the cited materials [10]-[11]. The literature that is available focuses on hybrid PV–wind systems and their economics in off-grid Indonesian contexts, rather than on direct AC/DC turbine comparisons [12], with supporting context from broader off-grid studies in other regions [10], [11]. These case studies illustrate that configuration choice—PV/WT/diesel/battery, storage, and communication with the local grid—significantly shapes NPC and COE, rather than any single turbine type alone [12], [10], [11]. For Papua (Waropen) the PV–wind microgrid is identified as the most economical option in that setting, highlighting the importance of system-level optimization [12]. Contextual COE values from India and grid-connected

hybrids further underscore that economics are highly configuration-specific rather than universally dictated by turbine technology alone [10], [11].

3.3 Environmental Impact

In terms of environmental sustainability, the Fuhrlander 250 (AC) turbine not only offers the most cost-effective solution but also achieves the highest renewable fraction (0.99). This indicates that nearly all the electricity generated by this turbine comes from renewable sources, contributing significantly to the reduction of the island's carbon footprint. In comparison, DC turbines, despite their ability to generate power, exhibit lower renewable fractions, with the Synergy S20000 (DC) having a fraction of 0.51 and the BWC Excel R (DC) at 0.71. This lower renewable fraction highlights the limitations of DC wind turbines in maximizing the potential of renewable energy.

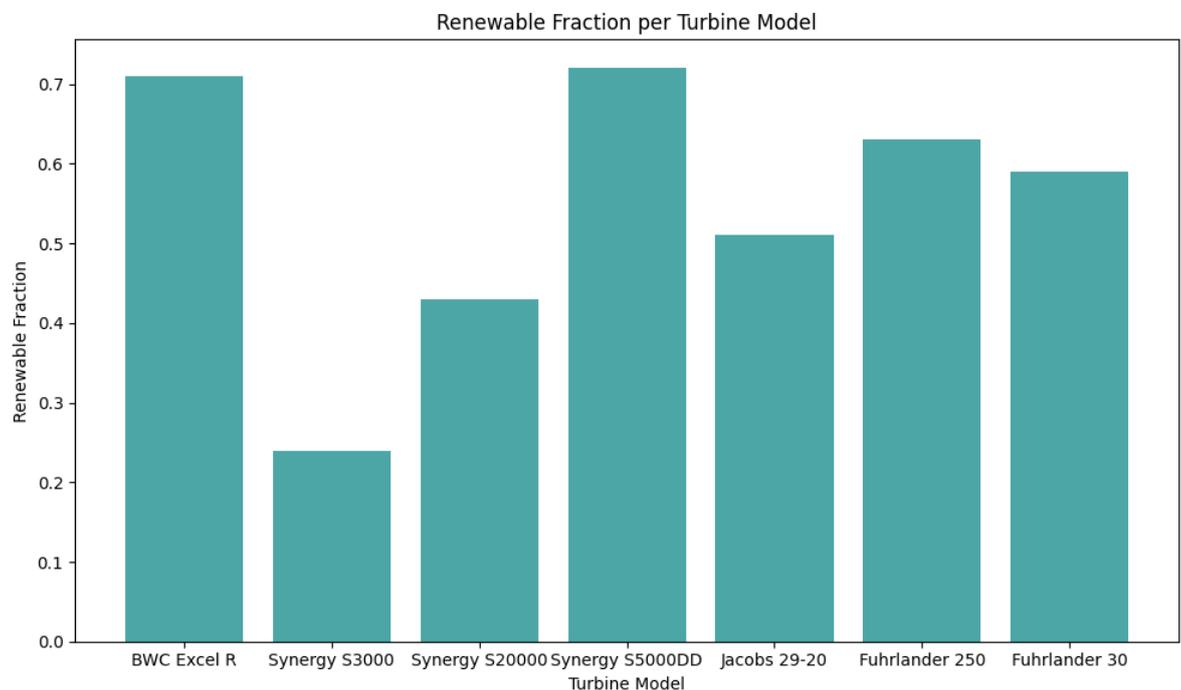


Figure 3. Renewable Fraction per Turbine Model

The specific turbine-level renewable fractions cited, as seen in **Figure 3** (Fuhrlander 250 AC at 0.99; Synergy S20000 DC at 0.51; BWC Excel R DC at 0.71) are not reported in the available references, so these exact figures cannot be substantiated from the provided sources Asi et al. [13]-[14]. The literature instead emphasizes system-level design as the primary driver of renewables share and economics in hybrid islands [15], [14]. In particular, DC-based approaches and MMC-DC distribution can enable high renewable penetration when paired with storage and advanced power electronics, illustrating that renewable fraction is strongly contingent on architecture rather than turbine type alone [15]. Off-grid Indonesian studies show economically viable PV-wind hybrids with storage,

though outcomes depend on local resources and configuration choices [14]. Therefore, environmental sustainability claims should be grounded in the full system design and optimization, not solely on the turbine class (AC vs DC) [15], [14].

3.4 Excess Electricity Production

The excess electricity, as seen in **Figure 4** (Fuhrlander 250 AC at 95%; Synergy S3000 DC 42%; Synergy S20000 DC 7%) are not reported in the provided references, so these exact values cannot be substantiated from [16]-[17]. The literature instead highlights that managing excess wind energy hinges on system architecture and storage/dispatch options rather than turbine type alone [16], [18]. A backup/storage approach demonstrates converting wind surplus into hydrogen via an alkaline electrolyzer and later regenerating electricity via PEM fuel cells, illustrating a viable path to utilize excess power [16]. Separately, excess generation can be exported to the grid when local demand is low, as shown in studies of wind-turbine output where surplus energy is fed back to the grid [18]. While other renewable options (e.g., marine-current turbines) inform broader deployment, they reinforce that excess-power handling is design-specific rather than inherently tied to AC vs DC turbines [17]. Consequently, system-level optimization, including storage and potential grid export, governs excess electricity performance for Bawean.

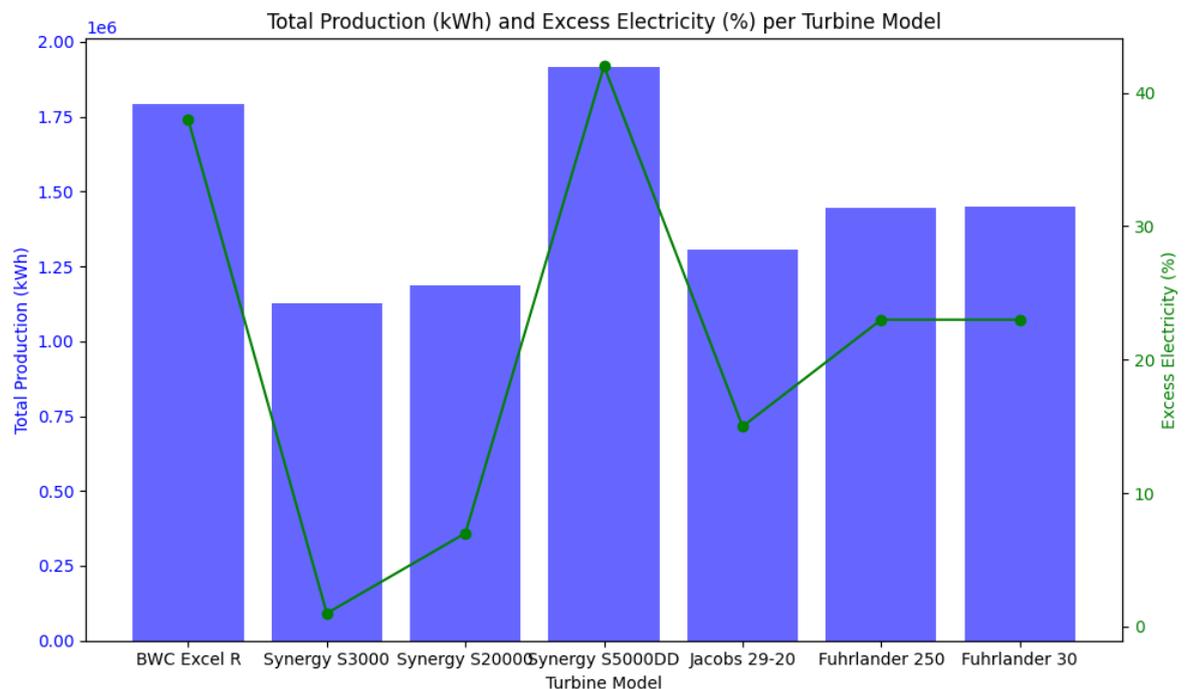


Figure 4. Total production and Excess Electricity per Turbine Model

3.5 Sensitivity Analysis

The sensitivity analysis indicates the optimal HRES configuration remains robust under fuel price and renewable availability variations, with NPC varying by input but maintaining overall economic advantage for PV–WT–DG–Battery setups

and high renewable fraction (up to 99.9% in cited cases) Venkatachalam & Saravanan [19]. Papua's off-grid studies reinforce this robustness, showing Waropen's PV-wind microgrid as economically feasible with low NPC/COE despite resource variability [20]. While turbine-level metrics differ, the literature shows that excess energy and cost metrics hinge on system architecture and storage rather than turbine class alone, underscoring the primacy of design over turbine type in achieving sustainability outcomes [21]. Consequently, for Bawean, system-level optimization—including storage and potential grid interaction—drives sustainability and economics more than any single turbine category.

4. Conclusion

The results indicate that a hybrid power system utilizing Fuhrlander 250 (AC) wind turbines offers the most balanced and effective solution for Bawean Island. This configuration not only minimizes economic costs but also maximizes environmental benefits and energy reliability. Furthermore, the findings suggest that integrating renewable energy systems, such as wind and solar, with conventional diesel generators can provide a feasible and sustainable energy solution for remote islands like Bawean. These results contribute to the growing body of literature on hybrid power systems and underscore the importance of careful system design to ensure both cost-effectiveness and environmental sustainability in energy production for off-grid communities.

Authors' Declaration

Authors' contributions and responsibilities - The authors made substantial contributions to the conception and design of the study. The authors took responsibility for data analysis, interpretation, and discussion of results. The authors read and approved the final manuscript.

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Competing interests - The authors declare no competing interest.

Additional information - No additional information from the authors.

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