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Design and Optimization of a Renewable Energy Based Microgrid System on Reni Island

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Abstract

Remote island communities in Indonesia often face limited access to reliable and affordable electricity due to geographic isolation and dependence on expensive, carbon-intensive diesel generators. This study investigates a hybrid renewable energy-based microgrid system tailored for Reni Island that uses photovoltaic modules, a diesel generator, and a battery energy storage system. Using HOMER Pro software, the system was modeled and optimized using local meteorological data and load profiles to assess its techno-economic feasibility. The optimal configuration—a PV–BESS–Inverter system (5 kWp PV and BESS)—was selected after simulating multiple architectures. Technically, the system is highly feasible, supplying an annual electricity demand of 4,315 kWh with a total generation of 4,816 kWh. The system achieved a 100% renewable energy fraction. Economically, it is viable, with a Net Present Cost (NPC) of IDR 204.14 million, a Cost of Energy of IDR 3,008/kWh, and a payback period of 12 years and 6 months. Environmentally, it is sustainable, eliminating diesel fuel consumption and reducing CO_2 emissions by approximately 11,330 kg annually compared to a generator-only system. These findings demonstrate that the chosen hybrid microgrid is a technically feasible, economically viable, and environmentally sustainable solution for remote electrification. The novelty of this work lies in its context-specific system design using real-world constraints and the absence of historical demand data, offering a scalable model for electrifying underserved archipelagic regions.

Keywords: cost of energy, hybrid microgrid, NPC, photovoltaic, Reni Island

1. Introduction

The increasing global demand for sustainable and decentralized energy systems has driven significant advancements in microgrid technologies, particularly those integrating renewable energy sources (Rehiara *et al.*, 2023). Microgrids provide a resilient, flexible alternative to conventional centralized power systems, especially in remote or isolated regions with limited access to national electricity grids (Hernández-Mayoral *et al.*, 2023; Rehiara *et al.*, 2025b; Shim *et al.*, 2022). The implementation of renewable energy-based microgrids has gained momentum due to their potential to reduce greenhouse gas emissions, lower operational costs, and improve energy security (Agupugo *et al.*, 2024; Muleta & Badar, 2023). This is especially pertinent in archipelagic and island regions, where conventional infrastructure is economically and logistically impractical. In such settings, microgrids emerge as a viable and environmentally responsible electrification solution (Rehman *et al.*, 2017; Sarwar *et al.*, 2022; Yan *et al.*, 2017).

Numerous studies have emphasized optimizing microgrid design and operation to achieve economic efficiency and sustainability. A Markovian modeling approach was introduced to manage the stochastic behavior of photovoltaic (PV) generation, and branch-and-cut algorithms were applied to address combinatorial design challenges (Abdulkarim *et al.*, 2017). HOMER software was utilized to identify optimal microgrid configurations, effectively balancing economic viability with ecological performance (Syafii *et al.*, 2021). The use of simulation tools and analytical techniques has been supported by integrating software-based solutions with optimization methods to enhance system reliability and efficiency (Babatunde *et al.*, 2019; Siddaraju *et al.*, 2022). The technical and economic viability of microgrids across various off-grid contexts has been further demonstrated through a range of studies (Er *et al.*, 2024; Yan *et al.*, 2024; Zhang *et al.*, 2024).

Hybrid systems combining PV, wind, and storage components have been evaluated by researchers (Cultura & Dalde, 2015; Vertudes *et al.*, 2025), highlighting the role of component diversification in improving system robustness and cost-effectiveness (Akulker & Aydin, 2023; Alluraiah & Vijayapriya, 2023; Zhou & Xu, 2023). In addition, systems incorporating demand-side management and smart control technologies have been explored, indicating a shift toward more intelligent and adaptive microgrid configurations (Hai *et al.*, 2023; Khawaja *et al.*, 2023). The integration of climate data into the design process, enables more precise modeling for island-based systems with unique weather patterns (Shi *et al.*, 2023).

Reni Island is a small and remote island situated within the Ayau District, Raja Ampat Regency, in the province of Southwest Papua, Indonesia. Geographically, the island is located at coordinates 0°35'2.52"N North latitude and 131°11'31.03" East longitude. Despite its modest size and isolation, Reni Island is home to a community of approximately 439 residents. The island, which currently lacks access to electricity, faces significant socio-economic limitations as a result. To address this, the current study proposes a comprehensive, renewable energy-based microgrid system designed to meet the island's energy demands in a technically feasible, economically viable, and environmentally sustainable manner. Drawing on prior work that emphasized the importance of location-specific data in system modeling (Dashtdar *et al.*, 2022), this research focuses on tailoring microgrid solutions to Reni Island's distinct geographic and socio-economic characteristics.

Optimization continues to be regarded as a core strategy in the deployment of renewable-based microgrids, particularly in off-grid environments such as Reni Island. The application of Markovian models has been revisited because the inherent variability of solar output is particularly pronounced in tropical maritime climates (Abdulkarim *et al.*, 2017). Robust optimization algorithms have been incorporated (Kharrich *et al.*, 2022; Sahu *et al.*, 2022), ensuring computational efficiency while maintaining system flexibility. Through these methods, generation-demand profiles can be accurately simulated, enhancing the adaptability of microgrid systems to fluctuations caused by weather conditions.

The use of tools such as HOMER has proven effective in the multi-criteria evaluation of system configurations (Revathi & Prabhakar, 2022; Siddaraju *et al.*, 2022; Syafii *et al.*, 2021). By integrating environmental and economic metrics, these systems are ensured to remain both sustainable and cost-effective. Optimization of storage and converter components has been conducted using linear programming and metaheuristic techniques (Babatunde *et al.*, 2019; Mahmud *et al.*, 2022), leading to improvements in overall system reliability. These methodologies have been further refined (AlKassem *et al.*, 2022; Elkholy *et al.*, 2022; Kharrich *et al.*, 2021), allowing for better-informed decision-making in the design and operation of microgrids for underserved regions.

Despite the growing body of literature, there is still a notable gap in studies that focus on the implementation challenges of microgrid systems in small island environments. It has been emphasized that many existing models fail to consider logistical obstacles such as equipment transportation, limitations in local capacity for operation and maintenance, and heightened exposure to extreme weather events (Arcos-Aviles *et al.*, 2021; Xiang *et al.*, 2021). Such limitations compromise the real-world applicability of generalized frameworks to remote island communities such as Reni Island.

Additionally, while decision-support tools like HOMER and various optimization algorithms have been widely validated (Siddaraju *et al.*, 2022; Syafii *et al.*, 2021), their underlying assumptions often include consistent economic conditions and readily available consumption data. However, in contexts like Reni Island, characterized by limited economic activity and an absence of historical electricity usage patterns, these assumptions are not valid. The need to adapt such tools for areas lacking established infrastructure or baseline data has been identified (Bouchekara *et al.*, 2021; Çetinbaş *et al.*, 2021; Tsao & Thanh, 2021). Furthermore, the integration of geospatial and socio-economic datasets has been recommended to provide better contextualization for microgrid planning and development in isolated and underserved regions (Huang *et al.*, 2021; Shboul *et al.*, 2021).

This research is intended to bridge existing gaps by developing a context-sensitive microgrid system specifically tailored to the energy landscape of Reni Island. The methodology has been informed by previous works (Elsaraf *et al.*, 2021; Soundarya *et al.*, 2021; Tran *et al.*, 2021), who stress the need for holistic approaches that combine technical, environmental, and economic factors. The novelty of this study lies in its integrative design framework, supported by simulation and optimization tools, to develop a scalable microgrid model for communities with no prior access to electricity.

The proposed microgrid design includes renewable energy source sizing and system configuration, cost-benefit analyses, and a comprehensive environmental impact assessment. This approach is based on multidisciplinary methods advocated in prior studies, which recommend harmonizing engineering design with policy, economic, and environmental dimensions (Islam *et al.*, 2021; Mohseni *et al.*, 2021; Shezan *et al.*, 2021). Then, the goal is to provide a feasible roadmap for electrification in remote island communities through the implementation of a technically robust and contextually informed microgrid system.

This study establishes the following goal, objectives, and hypothesis to precisely address the identified research gaps. The overarching goal is to design and validate an optimal, sustainable microgrid configuration that provides reliable electricity for Reni Island. This is achieved through the following specific objectives: to model and simulate multiple architectural combinations of PV, wind turbines, battery storage, and diesel generators using HOMER software (1); to identify the most economically viable configuration by minimizing the Net Present Cost (NPC) and Cost of Energy (CoE) (2); and to evaluate the environmental impact of the proposed system by quantifying its renewable fraction and CO_2 emissions (3). The central hypothesis of this work is that a hybrid microgrid architecture dominated by solar PV and battery storage will prove to be the most economically and environmentally optimal solution for Reni Island, outperforming systems that rely on fossil fuel generators and achieving near-total energy independence with minimal environmental impact. Consequently, this study aims to provide a feasible, evidence-based roadmap for the electrification of remote island communities through a technically robust and contextually informed microgrid system.

2. Methodology

2.1 Microgrid Components

The hybrid microgrid system designed for Reni Island incorporates several key components, including 250 W PV Panel (Sharp ND-250QCS, Sharp Energy Solutions Corporation, Japan), wind turbines (Homer generic model), a battery energy storage system (PowerSafe OPzV 1000, EnerSys Delaware Inc., USA), an 11 kW solar inverter (Isuna 11000T, Shenzhen Sinexcel Electric Co., Ltd., China), and a backup of 10 kW diesel generator (Homer generic model). Each of these components plays a crucial role in maintaining energy reliability, sustainability, and operational efficiency.

The proposed hybrid microgrid system for Reni Island includes photovoltaic (PV) modules, wind turbines, a 10 kW diesel generator, an inverter, and associated control systems. The PV component utilizes PV panel modules rated at 5 kW, with a total installed cost of IDR 10,500,000 per kW. The wind turbine employed is a 3 kW generic unit mounted at a hub height of 17 meters. Power conversion is handled by an 11 kW Solar Inverter, characterized by a high efficiency of 97.45%. The diesel generator serves as the main backup energy source during periods of low solar irradiance and weak wind conditions. The generator is rated at 10 kW, ensuring sufficient capacity to meet peak load demands. The complete system is integrated and modeled using HOMER Pro V3.18.4 software (HOMER Energy by UL, 2025) to ensure optimized sizing and performance under varying load and weather conditions.

2.1.1 Photovoltaic Systems

Photovoltaic systems convert solar radiation directly into electricity using semiconductor materials. The output of a PV module (P_{pv}) depends on the irradiance and temperature at the installation site. The theoretical power output is given in Equation 1 as follows (Babatunde *et al*., 2019; Syafii *et al*., 2021):

$$P_{pv} = P_{pv}^{rated} \frac{G}{Gst}\left(1 - \gamma\left(T - T_{ref}\right)\right) \tag{1}$$

Where P_{pv}^{rated}, G, γ, and T are the rated power, irradiance, the temperature coefficient, and the cell temperature, respectively.

2.1.2 Wind Turbines

Wind turbines convert kinetic energy from wind into electrical energy using rotor blades and a generator. The power extracted is governed using Equation 2, where ρ is air density, A is swept area, v is wind speed, and C_p is the power coefficient, as follows (Babatunde *et al*., 2019; Syafii *et al*., 2021):

$$P_{wind} = 0.5\rho A v^3 C_p \tag{2}$$

2.1.3 Diesel Generator

Given the intermittent nature of photovoltaic (PV) output, a supplementary energy source is essential to ensure load reliability. This role is fulfilled by incorporating a diesel generator and battery storage system. The fuel consumption of the diesel generator is modeled as shown in Equation 3 (Siddaraju *et al*., 2022).

$$F_{DG} = XP_{oDG} + YP_{rDG} \tag{3}$$

where F_{DG}, P_{oDG}, P_{rDG}, X, and Y represent the fuel consumption, the generator's operational output, its rated capacity, the slope and intercept of the generator's fuel consumption curve, respectively.

2.1.4 Battery Storage System

To mitigate PV intermittency—particularly during non-generating periods such as nighttime or overcast days—the battery bank plays a critical role (Hannan *et al*., 2021; Ling & Mulani, 2024). It stores surplus energy produced by both the PV system and diesel generator for later use during demand shortfalls. The system's storage capacity, B_s is determined using Equation 4 (Babatunde *et al*., 2019), which incorporates the energy demand D_L, battery autonomy duration B_{Ad}, battery round-trip efficiency ηB_a, depth of discharge D_{oBD}, and nominal voltage V_{sn}.

$$B_s = \frac{D_L B_{Ad}}{\eta B_a D_{oBD} V_{sn}} \tag{4}$$

To ensure battery operation remains within safe limits, Equations 5 and 6 define constraints on battery sizing to prevent overcharging or deep discharging, and Equation 7 further restricts the state of charge, where $B_{s\,min}$, B_s, and $B_{s\,max}$ are the minimum, current, and maximum battery sizes, respectively; $D_o D_{max}$ is the maximum depth of discharge; $S_o C_{min}$, and $S_o C_{max}$ are the minimum and maximum allowable state of charge. $S_o C(i)$ to remain within specified minimum and maximum boundaries to ensure battery longevity and operational efficiency (Babatunde *et al*., 2019).

$$B_{s\,min} \leq B_s \leq B_{s\,max} \tag{5}$$

$$B_{s\,min} = (1 - D_o D_{max}) B_s = S_o C_{min} B_s \tag{6}$$

$$S_o C_{min} \leq S_o C(i) \leq S_o C_{max} \tag{7}$$

2.1.5 Charging and Discharging of Battery

Depth of Discharge (DoD) is a metric that indicates how much energy has been withdrawn from a battery, expressed as a percentage of the battery's total capacity. It measures the extent to which a battery has been emptied. The DoD is critically linked to battery lifespan. Most batteries, especially lithium-ion, degrade faster when regularly cycled to a high DoD.

State of Charge (SoC) is the inverse of DoD. It indicates the current available energy level in a battery, expressed as a percentage of its total capacity. It measures how "full" the battery is. In essence, SoC tells you the remaining energy, while DoD tells you the consumed energy. Both are crucial for managing and maintaining battery health in applications like electric vehicles, solar energy storage, and consumer electronics.

Theoretically, both SoC and DoD have minimum and maximum values in the range of 0% to 100%, and the two variables are inversely related, as shown in Equation 8 (Hannan *et al.*, 2021; Ling & Mulani, 2024).

$$S_oC(\%) + D_oD(\%) = 100\% \quad (8)$$

Therefore, in practice, to manage and maintain battery health, the operating ranges for SoC and DoD are often designed to be within narrower limits, such as 20% to 90% for SoC (which corresponds to 10% to 80% for DoD).

2.2 Greenhouse Gas

Greenhouse gas (GHG) emissions result from the release of heat-trapping gases into the atmosphere, leading to the greenhouse effect. While this effect is a natural process, human activities—primarily the burning of fossil fuels for energy, deforestation, and industrial agriculture—have drastically increased the concentration of key GHGs like carbon dioxide (CO_2), Sulfur dioxide (SO_2), and nitrous oxide (NO_x). This enhanced greenhouse effect is the main driver of global warming and climate change, causing profound impacts such as rising sea levels, more extreme weather events, and disruptions to ecosystems and agriculture.

In quantifying emission reductions, one common method calculates the tons of CO_2 saved by a cleaner system. This reduction is based on the useful energy output (P_{out}) over its operating time (t), multiplied by specific emission conversion factors (V), as formulated in Equation 9 (Rehiara *et al.*, 2025a; Rehiara & Setiawidayat, 2025). The emission factors used in HOMER are average values of CO_2, SO_2, and NO_x in the USA, which are about 570, 1.19, and 0.64 g/kWh, respectively (UL Renewables, n.d.).

$$\Delta CO_2 = P_{out}\, V\, t \quad (9)$$

2.3 Data Collection

Meteorological data such as solar radiation and wind speed were collected from the National Aeronautics and Space Administration (NASA) databases for the location of Reni Island, Ayau District (coordinates 0°35'2.52" N and 131°11'31.03" E). The annual average solar radiation is 5.62 kWh/m²/day, while the average wind speed is 4.22 m/s and the renewable energy potential is presented in Table 1, while the location of Reni Island is presented in Figure 1. The daily electricity demand profile for the Reni Island microgrid is approximately 11.26 kWh/day with a peak load of 2.97 kW.

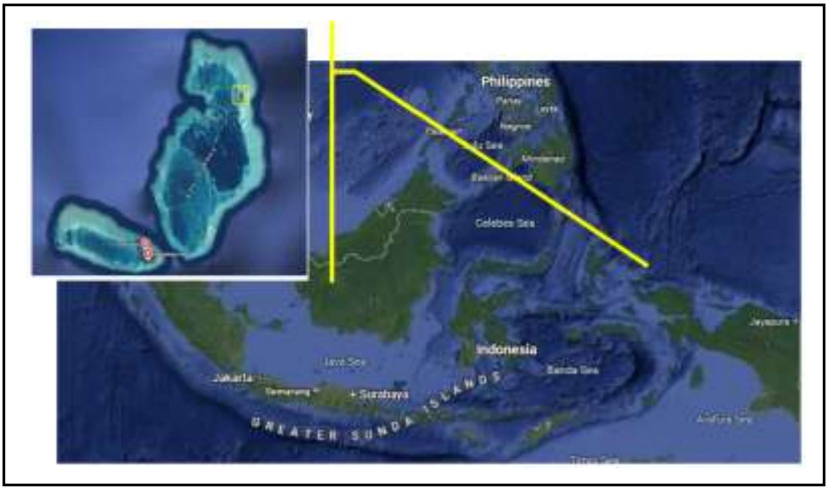

Figure 1. Reni Island location

2.4 Analytical and Statistical Methods

System optimization was carried out using HOMER Pro software, focusing on minimizing the Net Present Cost (NPC) and the Cost of Energy (CoE), while also assessing the Payback Period (PP) for financial feasibility. These parameters form the foundation for evaluating the long-term viability of hybrid renewable energy systems, where taken from NASA (n.d.) and summarized in Table 1.

Table 1. Renewables potencies

Month	Clearness Index	Daily Radiation (kWh/m2/day)	Wind Speed (m/s)
Jan	0.558	5.58	4.31
Feb	0.555	5.74	4.41
Mar	0.553	5.81	4.13
Apr	0.570	5.83	3.41
May	0.577	5.60	3.65
Jun	0.554	5.19	4.17
Jul	0.555	5.27	4.90
Aug	0.561	5.58	5.28
Sep	0.561	5.80	4.35
Oct	0.577	5.96	4.16
Nov	0.574	5.76	3.88
Dec	0.544	5.35	3.94
Avg	0.562	5.62	4.22

2.4.1 Net Present Cost

The Net Present Cost (NPC) represents the total cost of installing and operating the microgrid system over its lifetime, discounted to present value. It includes capital expenditures, replacement costs, operation and maintenance (O&M) costs, fuel costs, and the residual salvage value. A lower NPC indicates a more economically viable project. The NPC is calculated in Equation 10 as follows (Babatunde *et al.*, 2019; Siddaraju *et al.*, 2022).

$$NPC = CC + RC + O\&M + FC + Sal \tag{10}$$

Where CC, RC, $O\&M$, FC, and Sal are capital cost, replacement cost, operation and maintenance cost, fuel cost (mainly for diesel backup), and residual value of components at the end of the project lifespan.

2.4.2 Payback Period

The Payback Period is a fundamental capital budgeting tool that measures how quickly the initial investment is recovered through the net income or savings generated by a system. Valued for its straightforward calculation and intuitive meaning, it is a simple yet important financial indicator for assessing investment risk. A shorter payback period suggests faster capital recovery and reduced investment risk, making the project more attractive.

This metric is formally defined as the ratio of the total renewable investment cost (RIC) to the annual income or savings from the system (Inc_{annual}). The Payback Period (PP) is expressed as in Equation 11, where RIC, and Inc_{annual} are renewable investment cost, and annual income or savings from the system (Babatunde *et al.*, 2019; Siddaraju *et al.*, 2022). While this calculation provides a quick snapshot, it is important to note a key limitation: the basic Payback Period does not account for the time value of money or cash flows beyond the payback point, which can lead to an oversimplified view of a project's true profitability.

$$PP = \frac{RIC}{Inc_{annual}} \tag{11}$$

2.4.3 Cost of Energy

The Cost of Energy (CoE) is the average cost per kilowatt-hour (kWh) of electricity produced by the system over its lifetime. It is a critical metric for comparing the competitiveness of renewable energy systems with conventional energy sources. If the CoE is lower than the cost of supplying electricity through conventional systems, the project is considered economically feasible. CoE also helps in policy-making and investment decisions by identifying the most cost-effective energy solutions for remote and off-grid applications. The CoE is calculated using Equation 12, where TAC and $KWhTP$ are the total annualized cost of the system and the total electrical energy generated by the system in KWh (Babatunde *et al.*, 2019; Siddaraju *et al.*, 2022).

$$CoE = \frac{TAC}{KWh_{TP}} \tag{12}$$

In this study, all these economic indicators were derived from HOMER Pro system simulations, based on real-site data, component costs, and performance parameters. They provide a comprehensive basis for assessing the techno-economic viability of the proposed PV/Wind/BESS-based hybrid microgrid system.

2.5 Optimization Configuration

The HOMER software distinguishes between simulation, which models a specific system's performance, and optimization, which identifies the best possible system configuration. The optimal system is defined as the one that meets all user-defined constraints at the lowest Net Present Cost (NPC). To find this, HOMER automatically simulates thousands of configurations by varying key decision variables—such as the size of the PV array, the number of wind turbines and batteries, and generator sizes—and then ranks the feasible solutions based on cost (UL Renewables, n.d.).

The modeler defines the optimization search by specifying multiple possible values for each decision variable of interest. HOMER then evaluates every possible combination of these values, discards any configurations that violate the set constraints, and presents the results. The core output is the single, least-cost system overall, but HOMER can also display the best option within different architectural. This process efficiently determines the most cost-effective system design from a vast array of possibilities.

3. Results and Discussion

3.1 System Configurations

The proposed hybrid microgrid system for Reni Island comprises several integrated components, each contributing to the overall performance, reliability, and sustainability of the energy supply shown in Figure 2, while the capacity and cost are also given in Figure 2.

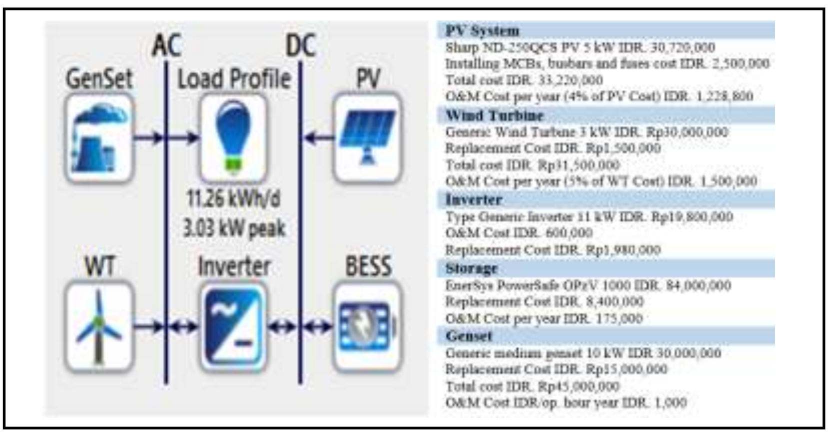

Figure 2. Microgrid components and sizing

The photovoltaic (PV) system includes 20 units of PV panel rated at 5 kW with a total capital cost of IDR 30,720,000. Additional installation components such as miniature circuit breakers (MCBs), busbars, and fuses add IDR 2,500,000, bringing the total PV system cost to IDR 33,220,000. The PV system incurs an annual operation and maintenance (O&M) cost of IDR 1,228,800, calculated at 4% of its capital value. Complementing solar energy production, a 3 kW generic wind turbine (WT) is incorporated at a cost of IDR 30,000,000, with a replacement cost of IDR 1,500,000 and an annual O&M cost of IDR 1,500,000, equivalent to 5% of the turbine's cost. These components are essential for enhancing renewable energy penetration and mitigating variability in solar irradiance.

Supporting the conversion and storage of generated energy, the system includes an 11 kW solar inverter priced at IDR 19,800,000, with a replacement cost of IDR 19,800,000 and no associated O&M costs, ensuring efficient DC-to-AC conversion for grid compatibility. The storage system utilizes the battery energy storage system (BESS), which offers robust performance and durability. The battery system has a capital cost of IDR 84,000,000 and an annual O&M cost of IDR 175,000 with a replacement cost of IDR 8,400,000, equivalent to 10% of its capital cost. Additionally, a 10 kW diesel generator (GenSet) is included in the configuration as a backup energy source to ensure system reliability during periods of low renewable generation with total cost IDR 45,000,000 and O&M cost 1,000/operational hour. This combination of solar, wind, storage, and conventional backup power provides a comprehensive, resilient, and cost-effective microgrid solution for off-grid electrification on Reni Island.

The PV panel which is based on HOMER data, has a 0.25 kW output, a temperature coefficient of -0.485 %/°C, and an efficiency of 15.3%, with a temperature rating of 4.75°C. While the battery parameters are as follows: Nominal Voltage is 2 V, Nominal Capacity is 2.81 kWh, and Maximum Capacity is 1400 Ah. Additionally, the Capacity Ratio is 0.202, Rate Constant is 2.05 per hour, and Roundtrip efficiency is 95%. The battery also has a Maximum Charge Current of 464 A, Maximum Discharge Current of 1090 A, and Maximum Charge Rate of 1 A/Ah. The String Size is 24, resulting in a terminal voltage of 48 V.

3.2 Optimal Microgrid Design

The simulation and optimization results indicate that the most economically and environmentally viable microgrid configuration for Reni Island is a PV–BESS–Inverter system, consisting of photovoltaic (PV) panels integrated with a battery energy storage system (BESS) and an inverter. This configuration achieved the lowest Net Present Cost (NPC) of IDR 204.14 million and the lowest Cost of Energy (CoE) of IDR 3,008/kWh, while also achieving a 100% renewable energy fraction. This result underscores the system's effectiveness in enabling zero-emission electricity generation and highlights its environmental sustainability, as presented in Table 2. Although several simulated architectures included a diesel generator (GenSet) as a backup power source to enhance system reliability, the optimization results demonstrate that its inclusion is not economically or environmentally justified for the specific conditions of Reni Island. Systems incorporating a GenSet exhibited higher NPC and CoE values and produced additional CO_2 emissions. Consequently, the PV–BESS–Inverter architecture was selected as the optimal configuration because it reliably meets the island's energy demand while maintaining a fully renewable energy supply.

Table 2. Optimal convergence of Reni Island's microgrid

Cost			System				
NPC (Mil. IDR)	CoE (IDR)	OC (Mil. IDR/yr)	Capital (Mil. IDR)	Ren Frac (%)	Total Fuel (L/yr)	CO_2 (kg/yr)	Arch.
204.14	3,008	5.80	108.37	100.00	-	-	1-4-5
226.82	3,343	5.40	137.71	99.94	1	2	1-3-4-5
259.74	3,828	7.34	138.50	100.00	-	-	1-2-4-5
274.65	4,048	6.73	163.45	100.00	-	-	1-2-3-4-5
384.37	5,664	12.33	180.73	85.64	215	563	2-3-4-5
501.90	7,397	14.10	269.03	100.00	-	-	2-4-5
751.58	11,076	38.38	117.84	-	1,570	4,108	3-4-5
1,497.93	22,075	81.88	145.72	-	3,546	9,275	1-2-3-5
1,510.65	22,262	84.21	120.00	-	3,701	9,681	2-3
1,535.58	22,630	88.96	66.45	-	4,063	10,626	1-3-5
1,571.30	23,156	93.34	30.00	-	4,332	11,330	3

Architecture: 1. PV, 2: WT, 3: GenSet, 4: BESS, 5: Inverter

The primary objective of developing an energy system to meet the electricity demands of Reni Island was successfully achieved. Simulation results indicate that the optimal configuration can supply 4,315 kWh/year, with a total generation of 4,816 kWh/year from 5 kWp PV modules. This not only meets the island's energy demand but also produces excess power that can be utilized for additional activities. Furthermore, the system consistently matches the load profile across various time intervals with minimal reliance on non-renewable energy sources, ensuring energy reliability and resilience for the local community (Syafii *et al.*, 2021).

The configuration 1-4-5 (PV, BESS, and Inverter) is conclusively selected as the optimal microgrid for Reni Island. This selection is based on a trade-off analysis between economic cost, represented by the Net Present Cost (NPC), and environmental impact, measured by CO_2 emissions. This architecture is the clear economic winner, with the lowest NPC (IDR 204.14 million) and Cost of Energy (CoE at IDR 3,008/kWh). It also has the lowest operating cost (IDR 5.80 million/yr). Environmentally, it is the most viable option, achieving a 100% Renewable Fraction. This means all energy is sourced from solar PV, resulting in zero fuel consumption and zero CO_2 emissions.

A comparison with the second-ranked configuration, 1-3-4-5 (which includes a diesel generator, GenSet), reinforces this decision. Although the GenSet-inclusive system has a marginally lower operating cost, its significantly higher capital cost results in a higher overall NPC (IDR 226.82 million) and CoE (IDR 3,343/kWh). Furthermore, while its renewable fraction is 99.94%, it still burns a trivial amount of fuel (1 L/yr) and produces minimal emissions (2 kg CO_2/yr). This indicates that the small generator use adds cost and emissions without providing a substantial economic or reliability benefit.

The Renewable Energy Fraction (Ren Frac) is the percentage of total energy demand met by renewable sources; on Reni Island, these are PV and Wind. The last five configurations in the table lack a reported renewable fraction because these architectures either lack energy storage (BESS) or have insufficient BESS. In a renewable-heavy microgrid, the BESS is critical for storing excess energy generated during peak production and dispatching it when renewables are unavailable. Without adequate storage, the system cannot effectively utilize intermittent renewable power. Architectures without BESS, such as 3 (GenSet only) or 1-3-5 (PV/GenSet/Inverter), must rely primarily on the diesel generator to provide stable power. This results in high fuel consumption and CO_2 emissions, leading to a renewable fraction that is effectively zero or too low for the software to report meaningfully.

In the chosen optimal configuration (1-4-5), the phenomenon of Excess Electricity is present. This is surplus energy generated by the PV system that is not used to serve the immediate load and cannot be stored because the batteries are full. The presence of excess power is a positive indicator, confirming that the PV system is correctly oversized to ensure reliability during periods of low solar irradiance. This surplus clean energy presents a valuable opportunity for Load Growth. Instead of being wasted, it can be utilized to power additional devices that improve quality of life and economic activity, such as water purification systems, street lighting, community cooling centers, and small-scale electric tools for workshops.

Some of the final configurations do not include renewable generation components, and therefore a Renewable Fraction cannot be calculated. Specifically, two of the last five configurations (e.g., 3 and 2–3) consist solely of diesel generator–based systems without PV or wind generation; consequently, these architectures rely entirely on fossil fuel energy and their renewable contribution is effectively zero. Additionally, although configuration 3–4–5 includes a Battery Energy Storage System (BESS), the battery itself does not generate electricity but only stores energy produced by other sources. Since this configuration lacks PV and WT generation, the stored energy originates from the diesel generator, meaning that no renewable energy contribution exists despite the presence of storage. Therefore, the Renewable Fraction field remains blank for the last five configurations listed in Table 2.

As evidenced in Table 2, configurations reliant on GenSets (e.g., 3, and 2-3) have the highest CO_2 emissions, ranging from 4,108 kg/yr to over 11,330 kg/yr, which significantly impacts the local environment and contradicts sustainability goals. Economically, these GenSet-based systems also have the highest NPC and CoE, often 5-7 times higher than the optimal renewable system, due to the ongoing, high cost of diesel fuel and maintenance. Therefore, based on the results, there is no justification for including a GenSet in the recommended configuration for Reni Island. The data conclusively demonstrates that a 100% renewable system with solar PV and battery storage is technically feasible, economically superior, and environmentally essential. A GenSet would add unnecessary cost, operational complexity, and environmental harm.

3.3 Electrical Aspect

The proposed microgrid system is designed to reliably serve an electrical load that requires approximately 11 kWh of energy per day, with a peak power demand of 2.97 kW. To meet this demand, the system integrates a combination of complementary generation sources. It is important to note, however, that the Reni Microgrid is fundamentally anchored by a 5.12 kWp solar photovoltaic plant, which serves as the primary power backbone of the system. This solar array forms the core of the generation mix, substantially covering daily energy needs and peak power requirements. Additional sources, such as battery storage for nighttime and cloudy periods, and potentially a backup diesel generator for extended contingencies, are orchestrated to supplement the solar power, ensuring a stable and uninterrupted electricity supply to the community.

The solar production data reveals a unique pattern aligned with the island's two-season cycle. Contrary to typical solar profiles, generation is higher during the cool season, peaking at 0.425 MWh in October, and slightly lower during the hot season, dipping to 0.360 MWh in June as given in Figure 3. This inverted trend suggests the primary factor affecting output is not daylight hours, but likely seasonal weather patterns—such as persistent cloud cover, monsoons, or dust during the hot season that reduce panel efficiency, and clearer skies during the cool season. Consequently, while the 5 kWp solar plant provides a stable baseload, its predictable seasonal dip during the hot season must be planned for, requiring the microgrid's energy storage or backup generation to be sized to cover this period of relative under-production.

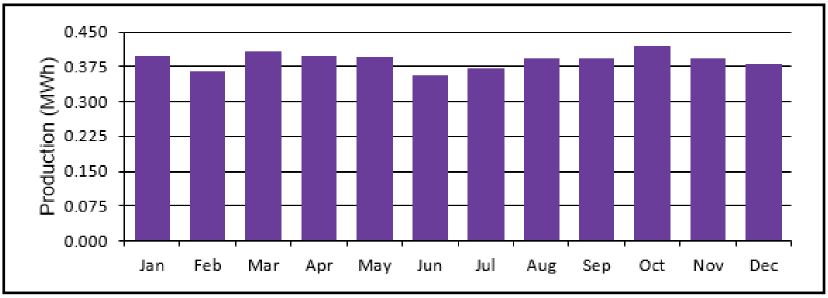

Figure 3. Power output of solar power plant

Figure 4 illustrates the 7-day operational profile of the optimal system configuration. A dominant feature of this period is the frequent occurrence of excess power generation, visually indicated by the brown line (PV output) diverging from and moving above the green line (battery input). This divergence occurs when the battery is fully charged and can no longer accept more energy, forcing the PV system to generate power that exceeds the combined storage and demand capacity—a phenomenon known as energy curtailment, which is common in renewable-heavy systems during peak solar hours (Hernández-Mayoral *et al*., 2023; Mohseni *et al*., 2021).

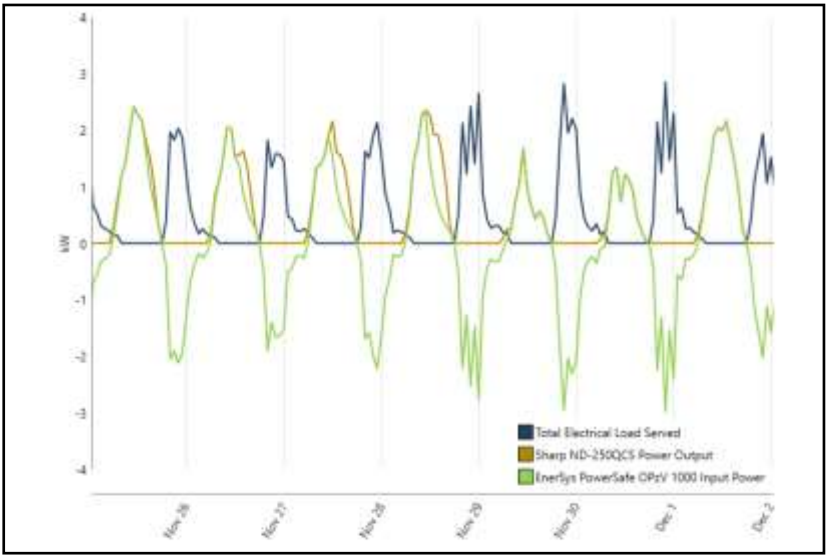

Figure 4. A 7-day operational profile

A critical point of operation is that the electrical demand (blue line) is consistently met by the battery's discharge. The PV output (brown line) does not directly power the load but is instead channeled almost exclusively to charging the battery. This indicates a control strategy where the battery acts as a single, stable buffer between the intermittent solar source and the load, ensuring a consistent and reliable power supply.

This operational pattern suggests that the system is designed for full energy autonomy, prioritizing reliability over the immediate utilization of all generated solar power. The battery energy storage system is sized to store sufficient energy to cover the load demand, as evidenced by its ability to consistently serve the blue line. Meanwhile, the PV array is likely sized to ensure the battery is fully recharged even on days with sub-optimal solar insolation, which naturally leads to excess generation on sunny days. Therefore, the figure confirms a well-sized system where the battery reliably meets the entire load demand, while the PV array provides abundant charging energy, often resulting in a surplus once the battery is full.

3.4 Economic Analysis

The Net Present Cost (NPC) of the proposed PV/BESS/Inverter hybrid system was calculated at IDR 204.14 million, reflecting the total lifecycle cost of the system over the 25-year project duration. This value represents the most cost-effective option among the evaluated configurations, as it incorporates capital, replacement, operation, and maintenance costs. Compared to the diesel-only base case, which had a lower initial capital cost of IDR 30 million but a substantially higher operating cost of IDR 93.34 million/year, the hybrid system offers a more economically viable solution in the long term. The substantial reduction in operating expenses validates the NPC outcome and supports the system’s economic feasibility for off-grid applications.

The payback period of the hybrid system was relatively short, recorded at just 12 years and 6 months (12.47 years), well within the 25-year project lifespan. This rapid return on investment demonstrates the economic attractiveness of the system, especially when considering the high cost of fuel and maintenance associated with conventional diesel systems in remote island settings. The quick payback period reflects the financial advantage of reduced operational expenditures and minimal fuel dependency, which cumulatively offset the higher initial capital investment within a relatively brief timeframe. This characteristic makes the system particularly suitable for deployment in isolated or archipelagic regions with limited access to conventional energy infrastructure.

The Cost of Energy (CoE) for the hybrid configuration was determined to be IDR 3,008/kWh. Although this may appear high in general terms, it remains competitive and acceptable in the context of remote island electrification, where logistical challenges and fuel transport costs typically drive energy prices upward. Importantly, this CoE is the lowest among the tested configurations when accounting for the sustainability and reliability benefits provided. Supported by HOMER Pro simulation outcomes, the system's low CoE, coupled with its 100% renewable energy fraction and minimal reliance on fossil fuels, reinforces its potential as a sustainable and economically justifiable energy solution for underserved and remote communities (Babatunde *et al.*, 2019; Muleta & Badar, 2023).

3.5 Environmental Impact

The base case scenario in the simulation involves a system fully powered by a diesel generator. To meet the island's annual energy demand, this configuration requires approximately 4,332 liters of diesel fuel, resulting in carbon dioxide (CO_2) emissions of 11,330 kg per year. In addition to CO_2, the diesel-based system also contributes to the release of other harmful pollutants, including carbon monoxide (CO), particulate matter (PM), sulfur dioxide (SO_2), and nitrogen oxides (NO_x), all of which pose significant risks to environmental and public health. This underscores the environmental cost of relying solely on conventional fossil fuel-based energy sources for remote island electrification.

In contrast, the integration of renewable energy significantly transforms the environmental footprint of the energy system on Reni Island. By employing a 5 kWp photovoltaic (PV) array, the system is capable of supplying 100% of the island’s electricity demand without generating any CO_2 emissions. Furthermore, the complete replacement of diesel with solar energy leads to the elimination of associated pollutants such as CO, PM, SO_2, and NO_x. This clean energy transition not only aligns with Indonesia’s national decarbonization goals but also contributes to broader global efforts to reduce greenhouse gas emissions and mitigate climate change. The environmental advantages of the PV-based system reinforce its suitability as a sustainable solution for powering off-grid and ecologically sensitive regions (Babatunde *et al.*, 2019; Syafii *et al.*, 2021).

4. Conclusions and Recommendations

This study has comprehensively demonstrated the feasibility and efficacy of a hybrid renewable energy microgrid system tailored to the specific needs of Reni Island, a remote and previously unelectrified area in Indonesia. The key findings from the design and simulation confirm that the optimal configuration is the PV–BESS–Inverter system. Through detailed simulations using HOMER Pro software, this configuration was optimized to meet the island's daily load demand of 11.26 kWh and peak load of 2.97 kW. The proposed system achieved the lowest Net Present Cost (NPC) of IDR 204.14 million, an economically viable Cost of Energy (CoE) of IDR 3,008/kWh, and a payback period of 12 years and 6 months, all within the 25-year operational project horizon. These indicators affirm the economic sustainability of the system, especially when benchmarked against diesel-only configurations with significantly higher long-term operational costs.

In addition to financial viability, the proposed hybrid system yields considerable environmental benefits. The transition from a diesel-only base case—requiring 4,332 liters of fuel annually and emitting 11,330 kg of CO_2—to a 100% renewable PV-dominant system underscores a meaningful step toward decarbonization. The integration of renewable energy components enabled a full supply of electricity from PV modules without CO_2 emissions, while also eliminating associated air pollutants such as carbon monoxide, sulfur dioxide, particulate matter, and nitrogen oxides. These outcomes align with national and global commitments to reduce greenhouse gas emissions and promote environmental stewardship. The research thus provides a validated, replicable model for electrifying off-grid communities in island and archipelagic settings using hybrid renewable technologies, offering both economic justification and environmental imperatives for broader adoption.

Future work should focus on several key areas to further improve upon this study. In enhancing system adaptability and resilience, future research should consider incorporating dynamic load forecasting and real-time energy management algorithms. The integration of advanced storage technologies, such as lithium-ion batteries or hydrogen-based systems, should be evaluated for performance under fluctuating demand and renewable resource conditions. Furthermore, a detailed sensitivity analysis on component costs and fuel prices would strengthen the robustness of the economic findings. Moreover, incorporating socio-economic assessments and stakeholder engagement strategies would improve the practical implementation of such systems, ensuring that technological solutions align with local capacities and development goals. Finally, on-site validation through a pilot-scale implementation is recommended to corroborate the simulation results with real-world performance data. By addressing these dimensions, future initiatives can build on the findings of this study to deliver more robust, inclusive, and context-responsive energy systems for remote and underserved regions.

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