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Techno-Economic Analysis of a PV-BESS-Diesel Hybrid System for Ndoriwoy Isolated Microgrid in Ende Island, Indonesia

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Abstract. Isolated power system in remote islands of Indonesia still rely heavily on diesel generators, resulting in high fuel costs, low operational efficiency, and vulnerability to fuel supply disruptions. Ende Island, located in Flores, East Nusa Tenggara, Indonesia, operates an isolated diesel-based microgrid that faces increasing electricity demand and logistic constraints. This study evaluates the techno-economic assessment of integrating a photovoltaic (PV) system and battery energy storage system (BESS) with the existing diesel power plant. A simulation-based optimization approach using HOMER Pro was employed based on site-specific load solar resources data. Three scenarios were analyzed: diesel-only, PV-BESS, and an optimized PV-BESS-Diesel hybrid system. The result indicates that the hybrid system configuration significantly reduces diesel fuel consumption and levelized cost of energy while maintaining high supply reliability, as indicated by zero unmet load. On the other hand, the simulation of existing diesel power plants without any additional resources shows the highest cost compared to all evaluated scenarios. Overall, the findings demonstrate that combining photovoltaic, battery energy system, and diesel generators can effectively improve economic performance in isolated island microgrids.

1 Introduction

Remote and isolated islands in Indonesia still largely depend on diesel generators to supply electricity. Although diesel power plants are relatively easy to deploy, this leads to high fuel costs, inefficient partial-load operation, carbon emissions, and vulnerability to fuel supply disruptions. These challenges are particularly evident in isolated power systems that face increasing electricity demand and logistical challenges.

Ndoriwoy microgrid power system, located in Ende island, East Nusa Tenggara Province, Indonesia, operates an isolated diesel-based power system to serve residential and public loads. Increasing electricity demand, coupled with high fuel transportation cost, has resulted in elevated generation costs. Meanwhile, the region has abundant solar power energy potential that remains underutilized. As illustrated in Fig. 1, the study area is located in a remote island system with no interconnection to the main grid, leading to a high dependence on diesel generation and emphasizing the importance of integrating renewable energy sources.

The integration of renewable energy systems with diesel generators in hybrid system are considered a strategic solution for minimize diesel dependence while maintaining system reliability in remote and isolated regions [1-3].

On the other hand, the government of the Republic of Indonesia is actively promoting a diesel phase-out program [4, 5]. This initiative aims to reduce the reliance of isolated and remote areas on diesel-based power generation systems. Many of these regions currently depend heavily on diesel generators, which are associated with high operational costs, logistical challenges in fuel supply, and significant environmental impacts.

Through the phase-out program, the government encourages the transition toward utilizing locally available renewable energy resources including solar. By harnessing these local resources, isolated power systems can achieve greater energy security, lower generation costs, and improved sustainability. In addition, this transition supports national targets for reducing greenhouse gas emissions and advancing the development of new and renewable energy across Indonesia [6, 7].

Fig. 1. Location of the Ende island (Ndoriwoy) isolated microgrid, East Nusa Tenggara, Indonesia.

The objective of this study is to evaluate and optimize the setup and operation of hybrid power system made up of diesel generators, PV system, and BESS. Additionally, by optimizing the use of renewable energy

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resources, the study aims to minimize the levelized cost of energy (LCOE) and lower diesel fuel usage. This strategy is anticipated to increase system efficiency and lessen reliance on fossil fuels.

This study's primary contribution is the use of actual operational data from the national electricity company PT. Perusahaan Listrik Negara (PLN), ensuring that the analysis accurately reflects real field conditions.

2 Load Profile Analysis and Assessment of Existing Power Plant and Renewable Resources

2.1 Load Profile Analysis

The load profile is a fundamental parameter in the design of hybrid energy systems, as it determines the required capacity of generation units, energy storage, and operational strategies. In this study, the load data were obtained from real operational measurements of an isolated power system and analyzed on an hourly basis. The observed load profile exhibits typical characteristics of remote microgrids, with significant variation between daytime and nighttime demand. As shown in Fig. 2, the typical daily load profile exhibits a peak demand during the evening period.

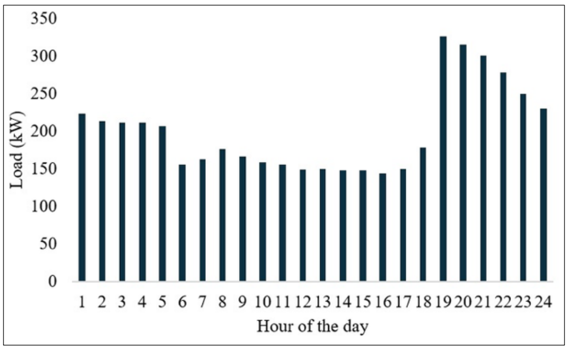

Fig. 2. Typical daily load profile of the Ndoriwoy isolated microgrid.

The daily load pattern indicates that electricity consumption can be divided into three main periods. During the off-peak hours (00:00–06:00), the electricity demand ranges from 156 kW to 224 kW, with an average load of approximately 198 kW. The demand gradually decreases from 224 kW at 00.00 to its minimum of 156 kW at 05.00, before slightly increasing again to 163 kW at 06.00. This relatively low and primarily consists of basic household consumption.

During the daytime period (06.00-17.00), the load demand between 144 kW and 178 kW, with an average of approximately 157 kW. This pattern suggests that daytime electricity consumption relatively moderate and influenced by mix of household and limited economic and social activities.

However, the highest demand occurs during the evening peak period (18:00–23:00), where the load ranges from 230 kW to 327 kW, with an average of approximately 284 kW. This peak is primarily driven by increased residential activities, including lighting and intensive appliance usage.

This condition highlights a mismatch between energy demand and solar energy availability, as photovoltaic (PV) generation is only available during daylight hours.

To better understand the load characteristics, key parameters such as peak load, average load, daily energy consumption, and load factor are evaluated. A relatively low load factor indicates high variability in demand, which can lead to inefficient operation of conventional generators. In particular, diesel generators tend to operate under partial loading conditions, reducing their efficiency and increasing fuel consumption.

Furthermore, the load profile demonstrates significant fluctuations, especially during the transition from daytime to nighttime. These rapid changes in demand require a flexible and responsive system. In this context, battery energy storage systems (BESS) play a crucial role in maintaining system stability by balancing supply and demand and reducing the need for frequent start-stop operations of diesel generators [8, 9].

The average electricity demand on Ende Island in January 2026 is approximately 5,094 kWh per day, serving a total of 2,006 customers (house and public service facilities). Based on customer growth records, the number of customers has increased at an average rate of 14.37% per year from 2021 to 2025. The livelihood composition of the population on Ende Island is predominantly fishermen. They require electrical energy to support cooling systems used to preserve fish and other marine catches before being sold to buyers in nearby cities.

Overall, the load profile analysis reveals that peak demand occurs during night time hours, while solar energy is available during the day, creating a temporal mismatch. This condition emphasizes the importance of integrating both photovoltaic generation and battery storage into the system.

2.2 Existing Diesel Generator Assessment

The Ndoriwoy isolated microgrid in Ende island operates independently without interconnection to the main grid. The existing is supplied by multiple diesel generators (7 units) with varying capacities to serve residential and community loads as illustrated in

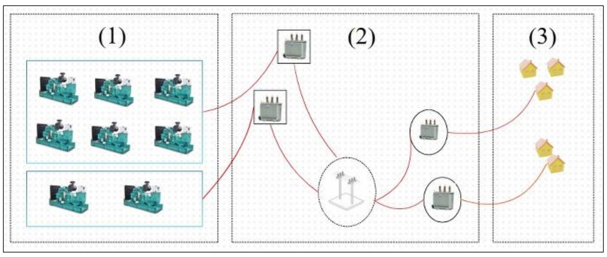

Fig. 3. Single line diagram of the model representing the existing diesel-based isolated power system in Ende island (Ndoriwoy microgrid). Numbered components: (1) Diesel generators; (2) 20 kV distribution line; (3) Rural load.

The load profile exhibits low daytime demand and sharp evening peaks, leading to inefficient diesel operation at partial loads. This can be observed from the average specific fuel consumption (SFC) value of 0.314 liters per kWh. An increase in specific fuel consumption is associated with a decrease in brake thermal efficiency, indicating that higher SFC values correspond to lower engine efficiency [10].

This isolated system microgrid is not interconnected with the mainland transmission system on Flores Island. This is due to the need to cross approximately 29 km of sea, making interconnection economically unfeasible.

Fuel supply is transported from the nearest supplier, specifically from the storage facilities of national oil company (PT. Pertamina) in the town of Ende. The transportation of fuel to Ndoriwoy relies in traditional sea transport. To maintain supply reliability, the fuel storage is managed to ensure a minimum reserve of at least five days of operation. However, during certain periods of the year, high waves and strong wind occur, creating vulnerabilities on fuel availability.

2.3 Renewable Resource Assessment

The assessment of solar energy potential is essential for evaluating the feasibility of integrating photovoltaic (PV) systems into isolated power systems. In this study, the solar resource is characterized using the Global Horizontal Irradiance (GHI), with an average value of approximately 5.8 kWh/m²/day. The relatively high irradiance level suggests that solar energy can significantly contribute to reducing reliance on diesel-based generation.

As illustrated in Table 1, the study area indicates a strong solar energy potential, making it suitable for PV deployment.

Table 1. Parameter of Irradiation.

Map Data	Value	Unit
Direct Normal Irradiation (DNI)	5.220	kWh/m2 per day
Global Horizontal Irradiation (GHI)	5.767	kWh/m2 per day
Diffusion Horizontal Irradiation (DIF)	2.021	kWh/m2 per day
Global Tilted Irradiation at Optimum angle (GHIinput)	5.869	kWh/m2 per day
Optimum Tilt of PV Modules (OPTA)	12.0	°
Air Temperature (Temp)	26.4	°C
Terrain Elevation (ELE)	13	meter

Based on the available solar resource, the potential energy generation from the photovoltaic (PV) system is estimated in terms of daily energy production (kWh/day), considering installed capacity, solar irradiance, and system efficiency. Under the given solar conditions, the PV system is expected to significantly contribute to meeting daytime electricity demand [11].

3 Methodology

Three system scenarios are defined to represent the existing condition and different levels of renewable energy integration, namely diesel-only, PV–BESS, and an optimized PV–BESS–diesel hybrid system. The evaluation focuses on key indicators such as levelized cost of energy (LCOE), net present cost (NPC), fuel consumption, and system reliability to identify the most optimal and feasible configuration.

3.1 System Scenario Configuration

3.1.1 Scenario A – Diesel Generators Only System

This scenario models diesel generators (DGs) as the sole electricity-generating source. It represents the existing operating condition of power system in Ende island (Ndoriwoy), where diesel generators are commonly operated by the national electricity company, PT. Perusahaan Listrik Negara (PLN) to supply electricity in remote and isolated areas of Indonesia.

The diesel only configuration serves as the baseline scenario for evaluating current system performance and for comparing the techno-economic impacts of integrating photovoltaic (PV) generation and battery energy storage systems (BESS) in subsequent scenarios. Multi-year inputs are applied in this study to account for the dynamic variation of key parameters over the project lifetime of 5 years. The system fixed operation and maintenance (O&M) cost is assumed to increase by 3% annually, reflecting operational cost escalation. Similarly, the diesel fuel price is projected to rise by 2% per year, representing fuel price uncertainty. In addition, the electric load is assumed to grow at an annual rate of 3%, capturing demand growth over time. The projected cost escalation assumption in scenario A follows the historical operating trend of the PLN isolated power system, ensuring that comparative economic analysis remains representative of actual utility operation conditions.

3.1.2 Scenario B – PV and BESS Only

In this scenario, the full-fledged supply is covered by PV with storage. The storage supplies the night-time load, while the PV provides for daytime load. The total system fixed capital cost of approximately IDR 1,317,103,700 and an annual fixed operation and maintenance (O&M) cost of IDR 240,000,000. The capacity shortage penalty is set to IDR 0/kWh, and all economic calculations are conducted using Indonesian Rupiah (IDR) as the base currency.

3.1.3 Scenario C - Hybrid of Diesel Generators, PV and BESS

In this scenario, diesel generators are integrated with PV and BESS to form a hybrid energy system. The DGs can cover the load that is not catered for the PV and storage and during the days when there is no PV production and storage supply. In this configuration, PV serves as the primary energy source, while the battery system manages energy fluctuations and peak demand, and diesel generators act as back up to ensure system stability as illustrated in Fig. 4.

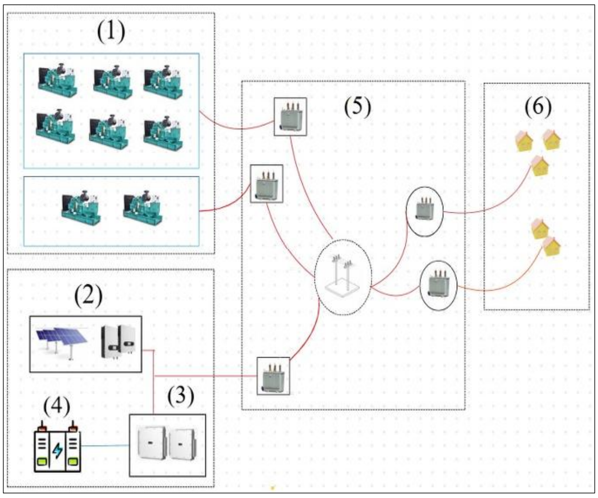

Fig. 4. Schematic configuration of the hybrid system. Numbered components: (1) Diesel generators; (2) PV and grid inverters; (3) Power conversion system (PCS); (4) Battery energy storage system (BESS); (5) 20 kV distribution line; (6) Rural load.

The PV system has a capacity of 2300 kWp, while the BESS is sized 6000 kWh and equipped with power conversion system (PCS) rated at 700 kW. During daytime, PV supplies the load and excess energy is stored in the BESS. Conversely, when PV output is insufficient, the system prioritizes battery discharge before activating diesel generators as back up. During evening peak hours, the BESS discharges to support the load. The battery operates with an initial state of charge (SOC) of 100% and minimum SOC limit of 20%. Diesel generators operate when stored energy in the BESS are insufficient or when operating reserve requirements are not met. The energy management strategy prioritizes renewable energy utilization while ensuring system reliability.

The cost inputs for PV and BESS were assumed to be identical to those applied in scenario B, whereas the economic parameters of the diesel generators where adopted from scenario A. This assumption was made to ensure a consistent and fair comparison between scenarios. All data were derived from actual PLN operational data and market research.

3.2 Economic Parameter

In this study, a project lifetime of 5 years is assumed, although the economic lifetime of the equipment exceeds this duration. The currency used in this study is Indonesian Rupiah (IDR) for all input parameters. The economic analysis is conducted using a discount rate of 8% and an inflation rate of 2%. The discount rate reflects the time value of money by converting future costs and revenues into their present value, while the inflation rate accounts for the variation of costs over the project lifetime and significantly influences the economic performance of energy system [12]. These parameters are applied within the simulation to ensure a realistic representation of the long-term economic performance of the hybrid energy system.

Meanwhile, the fuel used in this study is B40 biodiesel, with a price of IDR 12,086 per liter. The relatively higher fuel cost reflects the inclusion of transportation expenses required to deliver the fuel to the remote study location. The capital cost of the diesel generator is assumed to be zero, as the system utilizes existing diesel units that have already been installed. Therefore, the initial investment cost is not considered in the economic analysis, and only operational and maintenance costs are included. Table 2 presents all cost components.

Table 2. Cost of Component.

Component	Lifetime	Capital Cost	Replacement Cost	O&M Cost
Diesel generator	30,000 h	IDR 0/kW	IDR 4.659.185/kW	IDR 596.621/year
Solar PV	20 years	IDR 3.150.000/kW	IDR 2.500.000/kW	IDR 94.500/year
Converter	10 years	IDR 729.824/kW	IDR 700.000/kW	IDR 42.000/year
BESS @100 kWh	8 years	IDR 230.691.671/pcs	IDR 200.000.000/pcs	IDR 5.000.000/year
Controller	25 years	IDR 262.990.000/set	IDR 250.000.000/set	IDR 0/year

3.3 System Modelling and Optimization

HOMER is used to perform simulation and optimization of hybrid energy systems by evaluating different system configurations, component sizes, and operational strategies. The software ranks feasible solutions based on economic indicators such as net present cost (NPC) and levelized cost of energy (LCOE), enabling the identification of the optimal system design. In addition, HOMER provides detailed technical and economic analysis, including energy balance, fuel consumption, renewable energy penetration, and system reliability performance.

4 Results and Discussion

This scenario presents and discusses the simulation of the proposed energy system under different scenarios. The analysis focuses on techno-economic performance. The results are interpreted to evaluate the effectiveness of integrating PV and BESS in reducing diesel dependency and improving overall system performance.

Table 3 shows the capacity of the system components for each scenario.

Table 3. System configuration for each scenario

Component	Capacity for Each Scenario		
	Scenario A	Scenario B	Scenario C
DG 1	478 kW	0 kW	478 kW
DG 2	288 kW	0 kW	288 kW
DG 3	100 kW	0 kW	100 kW
DG 4	100 kW	0 kW	100 kW
DG 5	100 kW	0 kW	100 kW
DG 6	135 kW	0 kW	135 kW
DG 7	250 kW	0 kW	250 kW
PV	0 kWp	2300 kWp	2300 kW
INV	0 kW	700 kW	1100 kW
BESS	0 kWh	10500 kWh	6000 kWh

4.1 Scenario A – Diesel Only System

This scenario represents the existing baseline condition in which the entire load demand is supplied by diesel generators. The HOMER simulation shows that this configuration results in a total NPC of IDR 53.17 billion, an LCOE of IDR 5,885.98/kWh, and an operating cost of IDR 12.23 billion/year. The cost structure is dominated by fuel cost (IDR 35.71 billion) and operation and maintenance (O&M) cost (IDR 20.53 billion), indicating that the major economic burden of the system comes from long-term operation rather than initial investment. Table 4 displays the capacity, fuel consumption, and generating cost of the diesel generators.

Table 4. Fuel consumption and generating cost of DGs.

Component	Capacity (kW)	Hours of Operation (hours/year)	Electrical Production (kWh/year)	Capacity Factor (%)	Fuel Consumption (liter/year)	Fuel Cost (IDR/year)
DG 1	478	7	3,329	0.07	1,019	155,103,652.27
DG 2	288	383	110,148	4.37	33,710	2,494,151,638.42
DG 3	100	6,750	640,433	73.1	197,113	10,689,167,976.56
DG 4	100	2,205	191,903	21.9	59,666	3,686,542,420.17
DG 5	100	67	6,700	0,76	2,050	155,373,759.35
DG 6	135	8,216	712,076	60,2	230,999	12,640,232,948.75
DG 7	250	1,502	298,195	13,6	93,799	5,888,473,288.50

Among the generators, GEN 3 and GEN 6 are the most cost-dominant units, suggesting that these generators carry the main share of electricity production. Overall, this scenario confirms that while diesel-only operation is reliable, it is highly dependent on fuel and therefore less economical and less sustainable for isolated systems in remote areas.

4.2 Scenario B – PV with BESS to cover the total demand

In this scenario, the system is configured to operate entirely based on renewable energy, where photovoltaic (PV) generation and battery energy storage systems (BESS) are used to meet the total electricity demand without any diesel generator support.

Based on the simulation results, the system yields a Total Net Present Cost (NPC) of IDR 35.34 billion, with a Levelized Cost of Energy (LCOE) of IDR 4.761/kWh. Compared to the diesel-only scenario, this configuration eliminates fuel costs entirely, resulting in a significant reduction in operational expenditure.

The total electricity production is recorded at 3.303.483 kWh/year, which is fully supplied by PV generation.

The battery energy storage system plays a critical role in maintaining supply continuity, with a nominal capacity of 10.5 MWh and operating within a specified state-of-charge range.

From an environmental perspective, the system achieves zero fuel consumption and zero emissions, resulting in a renewable fraction of 100%. This represents a major improvement compared to the diesel-only scenario, which produces significant greenhouse gas emissions.

Despite these environmental benefits, the economic performance of this scenario is highly influenced by the large capital investment required for PV and battery energy storage systems. Therefore, while technically feasible and environmentally sustainable, this configuration may not always be the most cost-effective option compared to hybrid systems that combine renewable energy with diesel generation.

4.3 Scenario C – Optimized hybrid PV with BESS and diesel generators

The simulation show that optimal configuration of the system consists of a hybrid combination of photovoltaic (PV), battery energy storage system (BESS), and multiple diesel generators. The PV system, with a capacity of approximately 2.3 MW, dominates the energy supply, while the battery functions as an energy buffer and the diesel generators act as backup units. This configuration reflects a transition from a diesel dependent system to a renewable-dominated system suitable for isolated areas.

From an economic perspective, the system demonstrates strong feasibility with a total Net Present Cost (NPC) of IDR 20.64 billion and a Levelized Cost of Energy (LCOE) of IDR 2,056.64/kWh.

The renewable contribution of the system is very high, with a renewable fraction of 94.4%. This confirms that the majority of the energy demand is supplied by renewable sources, while diesel generators are only utilized under specific conditions such as low solar generation or peak load periods. The diesel generators operate with very low capacity factors and minimal fuel consumption, highlighting their role as backup rather than primary energy sources.

The operational behavior of the system further supports this finding. During daytime, PV generation reaches its peak and supplies most of the load while charging the battery. At night, the battery discharges to meet demand, reducing the need for diesel operation. The time series analysis shows that diesel generators are rarely used, indicating that the system follows a renewable-priority dispatch strategy. Table 5 present a comparison of techno-economic and reliability indicators.

Table 5. Techno-economic comparison.

Indicator	Scenario A	Scenario B	Scenario C
NPC (IDR)	53.17 billion	35.34 billion	20.63 billion
LCOE (IDR/kWh)	5,885	4,761	2,056
Renewable fraction (%)	0	100	94.4
Excess electricity (%)	0	39.2	26.4

5 Conclusion

The comparison of the three scenarios reveals significant differences in technical performance, economic feasibility, and energy sustainability.

This study assumes that the diesel generators are existing assets; therefore, the capital cost of diesel generators were excluded from scenario A. Consequently, the results are specifically applicable to isolated power systems with existing diesel infrastructure and should not be directly generalized to greenfield projects where all generation assets must be newly installed.

In the diesel-only scenario, the system relies entirely on fuel-based generation to meet the load demand. This results in high operational costs due to continuous fuel consumption and transportation challenges, particularly in isolated areas. Although the system is simple and reliable, it is highly vulnerable to fuel price fluctuations and supply disruptions. In addition, the environmental impact is substantial due to high carbon emissions.

The PV–BESS scenario eliminates diesel generators and relies fully on renewable energy supported by battery storage. This configuration significantly reduces fuel costs and emissions, making it environmentally sustainable. However, the system requires a large battery capacity to maintain reliability, especially during nighttime and low solar irradiation periods. Without sufficient storage, the risk of unmet load increases. In some cases, oversizing of PV is required to ensure reliability, which may lead to high excess energy and increased capital costs.

The PV–BESS–Diesel hybrid scenario provides a balanced solution by combining renewable energy with diesel backup. The results show that this configuration achieves a high renewable fraction (above 90%) while maintaining system reliability with zero unmet load. Diesel generators operate only during critical conditions, significantly reducing fuel consumption compared to the diesel-only scenario. Economically, this scenario offers a lower LCOE and improved long-term cost efficiency due to reduced operational expenses.

The PV–BESS–Diesel hybrid system emerges as the most optimal configuration for isolated power systems. It achieves high renewable energy penetration, significantly reduces fuel consumption, and maintains system reliability. In addition, it provides better economic performance compared to the diesel-only system, as reflected by lower LCOE and operating costs.

In conclusion, the hybrid PV–BESS–Diesel system represents a practical and scalable solution for electrification in remote areas, supporting both energy transition goals and operational reliability.

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