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Research Article

Analysis of Battery Energy Storage System (BESS) Technology in Diesel Phase-Out: A Case Study of Off-Grid Areas

Wayan Ksamawati[1]; Alief Kurniawan[1]; Diah Wimantika[1]; Disa Zaini[1]; Bambang Priyono[1*]
[1] Teknik Sistem Energi, Fakultas Teknik, Universitas Indonesia
Corresponding author:** ***Disa Zaini, amaliyadisa@gmail.com

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Abstract: A This research aims to identify renewable energy solutions for the off-grid power system in Mentawai Regency, which currently relies heavily on diesel power plants (PLTD). As a world-renowned tourist destination with significant renewable energy potential, Mentawai Regency requires an adequate and sustainable electricity supply to support regional development and the tourism sector. This study analyzes several energy system configurations using combinations of solar photovoltaic (PV), wind power (PLTB), and Battery Energy Storage Systems (BESS) featuring NCA, NCM, and LFP battery technologies. Simulation results indicate that a PV-Wind configuration with NCA batteries achieves the lowest Cost of Energy (COE) at 1.291 USD/kWh, with renewable energy penetration reaching 94.8%. Several tested configurations also demonstrate competitiveness against the Mentawai's electricity generation cost (BPP) of 0.468 USD/kWh. Implementing these renewable energy systems could not only enhance energy resilience and reduce dependence on fossil fuels but also support infrastructure development and the tourism sector. Therefore, transitioning to renewable energy with phased BESS implementation is highly recommended to achieve energy efficiency and sustainability in the Mentawai Islands.

Keywords: Mentawai, Renewable Energy, BESS, Cost of Energy (COE)

1. Introduction

The Mentawai Islands are an archipelago located off the west coast of Sumatra in the Indian Ocean. Administratively, the Mentawai Islands are part of West Sumatra Province. The archipelago consists of four main islands: Siberut, Sipora, North Pagai, and South Pagai, along with numerous smaller islands. The Mentawai region is renowned as one of the world's best surfing destinations, with challenging waves attracting surfers to its famous spots. Besides surfing, eco-tourism activities such as jungle trekking, interacting with local communities, and enjoying pristine beaches also draw many visitors. This region has significant potential to boost national revenue through tourism if infrastructure, promotion, and tourism management are further improved.

According to the "Electrification Ratio and Energy Usage Report in the Mentawai Islands" and the "West Sumatra Electricity Statistics" by PT PLN (Persero) in 2020, the electrification ratio in the Mentawai Islands stands at around 70%. Currently, Diesel Power Plants (PLTD) serve as the primary source of electricity for the Mentawai Islands, especially on the main islands such as Siberut, Sipora, and Pagai. These PLTDs operate using fuel oil, which must be imported, leading to high operational costs. This results in limited electricity supply, both in terms of duration and coverage, leaving many areas without a 24-hour electricity supply [1].

The Indonesian government, through the "Bright Indonesia" program, focuses on providing electricity access by building power infrastructure and implementing renewable energy in areas not yet connected to the PLN grid. Given the significant solar energy potential in Mentawai, several renewable energy initiatives have been implemented in some areas. Solar Power Plants (PLTS) have been established in certain villages to provide more stable and environmentally friendly electricity. However, the development and expansion of PLTS remain limited and do not yet cover the entire Mentawai region [2].

To further the adoption of renewable energy, additional studies are needed to identify more efficient and sustainable energy solutions for the Mentawai region. Research [3] indicates that a configuration with 50 kW and 40 kW of PV arrays yields a lower CoE compared to the base cost of energy provision by PT PLN (Persero) for the Mentawai Islands. The lowest CoE obtained was IDR 2,087/kWh, with a renewable energy fraction of 69.6%. Integrating the PV system with pumped hydro storage also reduced diesel fuel consumption from 31,424 liters/year to 9,141 liters/year, resulting in lower operational costs and CO_2 emissions.

Furthermore, research [4] using HOMER software determined the optimal configuration to meet a community load demand of 165.44 kWh/day with a peak load of 20.46 kW. Simulation results showed that the optimal configuration consists of photovoltaic (PV) panels, diesel generators (DG), and pumped hydro storage (PHS), achieving the lowest net present cost (NPC). The optimal configuration includes 15 kWp PV modules, one PHS unit, and a 25 kW solar inverter.

Another study [5] focused on developing an optimal hybrid energy system consisting of solar PV, micro wind turbines, and battery energy storage systems (BESS) to complement existing diesel generators. The study also aimed to determine the renewable energy penetration ratio with a lower CoE compared to current energy costs while meeting the maximum allowable capacity shortage. Simulations using Homer Pro revealed that this system achieved a renewable energy penetration ratio of 57.1% and a CoE of IDR 3,510/kWh, which is lower than the current CoE of IDR 4,031/kWh.

Implementing energy storage systems (BESS) as part of the diesel phase-out program in the Mentawai Islands requires significant initial investment for the procurement of energy storage units and supporting technological equipment. Moreover, infrastructure limitations in the Mentawai Islands, particularly in transportation, pose challenges that may delay the delivery and maintenance of BESS equipment. Despite these challenges, the adoption of BESS offers several benefits, including the provision of renewable energy that supports government policies on green energy use, reducing dependence on fossil fuels, and increasing electricity availability to foster infrastructure development and tourism sector growth in the region.

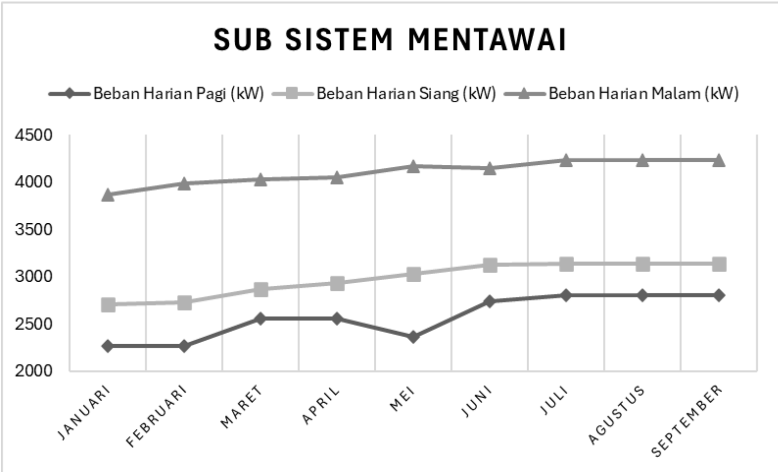
2. Materials and methods

2.1. Mentawai Islands

The Mentawai Islands are part of the West Sumatra Province, comprising several islands with a total area of 6,011.35 km² and a coastline length of 1,402.66 km. The land area can be divided into five land-use zones: protected forests, conservation and nature preservation areas, permanent production forests, convertible production forests, and other land uses. Approximately 81.89% (492,294.38 hectares) is dominated by forested areas, while 18.11% (108,840.62 hectares) consists of other land uses [6]. This highlights the potential for optimizing land use to support the transition from fossil energy to renewable energy, particularly through the use of solar power plants (PLTS) and wind power plants (PLTB) in isolated systems.

In terms of demographics, the Mentawai Regency has 21,568 households, with each household consisting of an average of four members [7]. Electricity consumption in the regency is primarily for household purposes, lighting, and public facilities. The daily load profile from January to September 2024 is shown in Figure 1.

Figure 1. Daily Load of the Mentawai Sub-System [8]



The morning load (kW) is represented by the blue line. Morning electricity usage shows a consistent increase from February to June, with a slight dip in May, before stabilizing again through September, averaging 2,574 kW. The midday load (kW) is depicted by the green line, where it consistently exceeds the morning load. From January to June, the graph displays a slight but steady increase, with stability returning from July to September. The evening load (kW), represented by the purple line, indicates the highest load throughout the day. From January to September, the evening load remains relatively stable, showing that most energy consumption occurs during nighttime. The load pattern in the Mentawai Islands is similar to that of other regions in Indonesia, where peak electricity usage occurs at night. This pattern highlights the need for appropriate energy storage planning when implementing green energy systems such as solar photovoltaics.

2.2. Potential for Solar and Wind Energy

The Mentawai Islands, with their unique geographical characteristics as remote small islands, have the potential to utilize renewable energy sources such as solar and wind to meet local electricity needs. In tropical regions like Indonesia, specifically the Mentawai Islands near the equator, the average annual solar irradiation reaches 2,021 kWh/m². This abundant solar energy can be optimally harnessed through the development of local solar power plants.

Additionally, the relatively high average wind speed in the island region provides an opportunity to use wind energy as a source of electricity generation [9]. According to NASA's 2022 meteorological data for the Mentawai Islands, the average daily solar radiation is 4.8 kWh/m²/day, and the annual average wind speed is 13.46 m/s.

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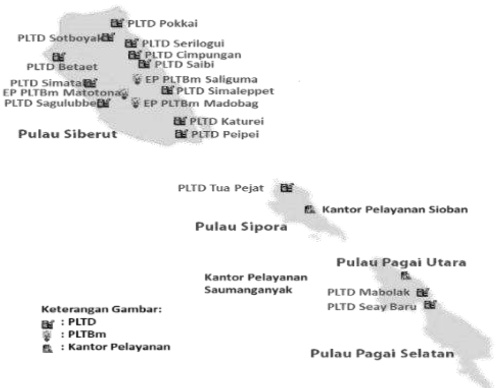
Table 1. Solar Radiation and Wind Speed Data for the Mentawai Islands [10]

Month	Brightness Index	Radiation (kWh/m^2/hari)	Win Velocity (m/s)
January	0.469	4.790	3.910
February	0.504	5.280	3.880
March	0.480	5.050	3.820
April	0.491	4.970	3.430
May	0.530	5.040	3.170
June	0.529	4.840	3.400
July	0.499	4.640	3.650
August	0.466	4.590	4.110
September	0.438	4.520	4.230
October	0.440	4.590	4.130
November	0.415	4.240	4.260
December	0.447	4.500	4.150

2.3. Electrical Condition of the Mentawai Islands

Currently, the Mentawai Islands are supplied by 17 diesel power plants (PLTD) spread across several islands such as Siberut, Sipora, and Pagai, as well as 2 solar power plants (PLTS), although the solar plants are not operating optimally. The diesel power plants in this region have varying operating hours, ranging from 6 hours, 12 hours, to 24 hours per day, depending on the location and capacity of the plants. The installed capacity of the PLTD units also varies, ranging from 0.05 MW to over 1 MW, such as the Tuapejat PLTD, which has a capacity of 4.85 MW and operates 24 hours a day.



Details	Number of Plants
Total Diesel Power Plants (PLTD)	17
Total Solar Power Plants (PLTS)	2
Plants Operating 24 Hours	5
Plants Operating 12 Hours	8
Plants Operating 6 Hours	6

Figure 2. Power Plant Locations in the Mentawai Islands [8]

The Net Capable Power (NCP) of the Tuapejat power plant is 10.26 MW, and the Peak Capable Power (PCP) is 6.12 MW with a reserve power of 1.69 MW. The local peak load is 4.43

MW. According to data obtained from PT PLN (Persero), most of the power plants have reserve power above 40%, such as the Saliguma PLTD with a reserve power of 63.64%, while others have smaller reserve powers, such as the Saibi PLTD with only 37.76% reserve power [8]. Based on this data, the electrical system of the Mentawai Islands is still highly dependent on diesel generators. The use of renewable energy with energy storage technology could be an alternative to meet the electricity demand in the Mentawai Islands.

2.4. Battery Technology

Lithium-ion battery technology has become one of the components in efforts to meet reliable electricity needs, especially in areas not covered by conventional electricity grids [11]. This technology has advantages in its high specific energy, as well as high energy density and power compared to other battery technologies, making it the technology of choice for various applications such as portable electronic devices, power tools, and hybrid and full-electric vehicles [12][13]. Additionally, the high energy efficiency, relatively long service life, and low self-discharge rate of lithium-ion batteries also make them suitable for various grid applications, including improving the quality of energy produced from renewable sources such as wind, solar, and geothermal [11]. Lithium-ion batteries have combinations of anode and cathode materials that affect their technical and economic characteristics, including Lithium Nickel Manganese Cobalt Oxide (NMC), Lithium Nickel Cobalt Aluminum (NCA), Lithium Iron Phosphate (LFP), and Lithium Titanate (LTO), as shown in Table 2.

Table 2. Comparison of Technical Parameters Based on Li-Ion Battery Type [14]

Parameter	**Battery Type of Li-ion**			
	NMC	**NCA**	**LFP**	**LTO**
Efficiency AC-to-AC (%)	92	92	86	96
DoD (%)	90	90	90	95
Max Operating Temp (^{o}C)	55	55	65	65
Charge/Discharge Cycle (kali)	3500	1500	3500	10000
Energy Throughput (kWh/qty)	0.47	0.41	0.41	0.41

Batteries with NMC, LFP, and LTO cells have better thermal stability compared to NCA, allowing them to operate at higher temperatures, while NCA experiences a reduction in capacity at temperatures between 40-70°C. The best energy density is found in batteries with NMC cells, which can also operate at higher voltages compared to other battery cells. Batteries with LTO cells have the longest lifespan compared to other cells, but the high cost of titanium material makes LTO one of the most expensive technologies among other lithium-ion batteries [15].

2.5. System Model

2.5.1. HOMER Application

HOMER (Hybrid Optimization of Multiple Electric Renewables) is software developed by the National Renewable Energy Laboratory (NREL) to help design and evaluate technical and financial solutions for power systems, both grid-connected (on-grid) and off-grid. HOMER processes mathematical data to generate various possible system configurations and then ranks them based on Net Present Cost (NPC). This helps compare design options based on operational efficiency and economic cost. Additionally, the software uses optimization and sensitivity analysis to evaluate the feasibility of each configuration. Overall, HOMER focuses on three main tasks: simulation, optimization, and sensitivity analysis, which are used to determine the most optimal energy system design [16].

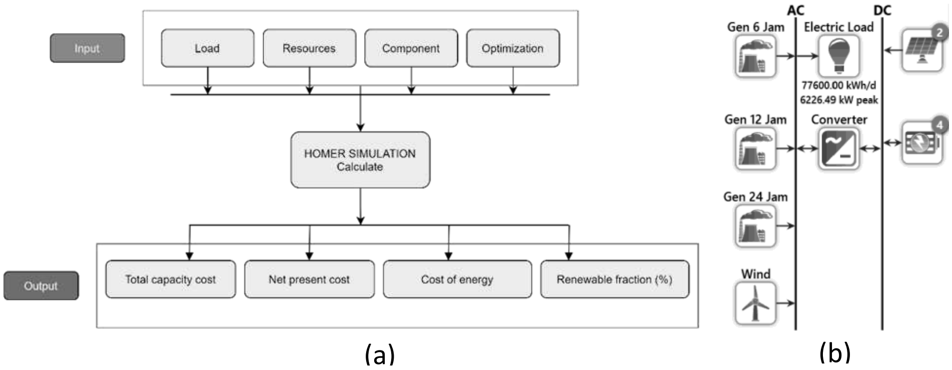


Figure 3. (a) Concept of HOMER Application [17], (b) Microgrid Modeling

Economic modeling is crucial in the simulations performed by HOMER to ensure the system operates at the most efficient cost and to determine the optimal configuration. The average cost per kWh of electricity, known as the Cost of Energy (COE), serves as the basis for assessing the system's efficiency, calculated using the following equation:

$$COE = \frac{C_{ann,tot}}{E_{ann,tot}} \tag{1}$$

In this equation, $C_{ann,tot}$ represents the total annual cost incurred, while $E_{ann,tot}$indicates the total energy generated over one year, measured in kWh.

2.5.2. Microgrid Modeling

The microgrid system modeling in this study was carried out using the HOMER software, which includes five main components: Diesel Generator, Solar Panels (PV), Wind Turbine, Converter, and Battery. To create scenarios that reflect real-world conditions in energy provision, the Diesel Generator is operated in three different modes: 6 hours, 12 hours, and 24 hours. The Diesel Generators are operated with different schedules and capacities to meet the daily load requirement of 77,600 kWh, with a peak load reaching 6,226.49 kW. The first Diesel Generator, with a capacity of 200 kW, operates for 6 hours a day to meet energy needs during certain times, such as during low load periods in the morning or evening. The second Diesel Generator, with a capacity of 680 kW, operates 12 hours a day to support medium load, while the third Diesel Generator, with a capacity of 5,050 kW, operates 24 hours a day as the primary system support. Additionally, a 5 kW solar panel (PV) is used as an additional energy source during the day to help reduce the load on the Diesel Generators and save fuel. Furthermore, for sustainable system development, increasing the capacity of the PV and batteries could be considered to reduce dependence on Diesel Generators, especially during the daytime when solar energy is available.

Table 3. Economic Parameters of Technology in HOMER Modeling [14], [18]

Component	CAPEX (USD)	OPEX (USD)	Raplacement Cost (USD)	Life Time
PLTD 6 Jam	0	0.13	200	150000 hour
PLTD 12 Jam	0	0.18	200	150000 hour
PLTD 24 Jam	0	1.08	200	150000 hour
Solar PV	670	6.8	335	30 years
Wind Turbine	1200	36	600	30 years
Converter	410	0	270	12 years
Li-ion Battery				
Nickel Mangan Cobalt Oxide (NCM)	339	8	339	15 years
Nickel Cobalt Aluminum (NCA)	284	8	284	15 years
Lithium Iron Phosphate (LFP)	466	8	466	15 years
Lithium Titanate (LTO)	880	6	880	25 years
Fuel and Transport Cost (USD/L)		0.892		

In this study, two configurations were used: a hybrid configuration combining existing diesel power generation technology with renewable power generation technologies, namely Solar PV and Wind Turbine (PLTS and PLTB), and a configuration using 100% renewable energy technology to simulate the de-dieselization program. Additionally, the competition of battery storage technology with four types of Li-Ion batteries in the microgrid system will also influence the optimization results of the renewable power generation capacity that will be selected for use in the system. The 8 scenario options are described in Table 4.

Table 4. Scenario Options in the Microgrid System Study

No	Configuration	PLTD	Scenario	Battery
1	Hybrid	Yes	Optimation PLTS-PLTB	NCM
2	Hybrid	Yes	Optimation PLTS-PLTB	NCA
3	Hybrid	Yes	Optimation PLTS-PLTB	LFP
4	Hybrid	Yes	Optimation PLTS-PLTB	LTO
5	Full RE	No	Optimation PLTS-PLTB	NCM
6	Full RE	No	Optimation PLTS-PLTB	NCA
7	Full RE	No	Optimation PLTS-PLTB	LFP
8	Full RE	No	Optimation PLTS-PLTB	LTO

3. Results and discussion

The simulation in this study uses a 1-hour time step setting based on the system load data for the year 2023. The electrical system for each island in the Mentawai Regency is considered as a single unit (island). The capacities of solar PV, wind turbines, batteries, and converters are optimized by HOMER, with no additional diesel power plants introduced during the simulation period, which is set at 5,930 kW. The project lifespan is approximately 25 years, assuming a discount rate of 10%. The average annual electrical load for the Mentawai system is 77,600 kWh/day, with a peak load of 6,230 kW. Table 5 presents a comparison of HOMER simulation results, showing hybrid configurations with renewable technology utilization in the isolated system of the Mentawai islands.

Table 5. HOMER Simulation Results

No	Konfig	Optimasi	Jenis BESS	COE (USD/kWh)	PLTD (kW)	PLTB (kW)	PLTS (kWp)	BESS (kWh)	RE Fraction (%)
1	Hybrid	PV-Wind	NCM	0,349	3.380	14	43.642	79.565	94.8
2		PV-Wind	NCA	0,329	3.380	85	44.386	80.734	95.1
3		PV-Wind	LFP	0,389	3.380	3.651	40.247	74.719	95.1
4		PV-Wind	LTO	0,534	3.380	6.755	38.515	68.892	94.8
5	Full	PV-Wind	NCM	0,314		64	49.314	80.071	100
6	RE	PV-Wind	NCA	0,291		2.210	44.940	78.644	100
7		PV-Wind	LFP	0,352		2.644	44.621	77.578	100
8		PV-Wind	LTO	0,505		5.834	41.217	73.788	100

The table above compares eight configuration scenarios with various combinations of battery technology (BESS) and PV-Wind power generation. In the hybrid configurations (scenarios 1-4), the system still involves the use of diesel power plants (PLTD) to maintain supply reliability, although renewable energy already contributes significantly. In the Full RE scenarios (scenarios 5-8), PLTD usage is completely eliminated, and the system relies on the combination of PV-Wind and batteries to meet the entire energy demand.

Scenario 2 shows a COE of 0.329 USD/kWh, slightly lower than the Mentawai Islands' 2024 BPP. This configuration uses NCA batteries with a capacity of 80,734 kWh and a wind turbine contribution of 85 kW. With an RE fraction of 95.1%, this scenario demonstrates high efficiency while maintaining PLTD capacity as a backup. Meanwhile, scenario 4 has the highest COE in the hybrid category at 0.534 USD/kWh, exceeding the regional BPP value, even though it has the largest wind turbine contribution (6,755 kW). This indicates that excessive wind turbine capacity may not always be economically effective without further optimization.

In the Full RE category, scenario 8 has the highest COE among all scenarios, at 0.505 USD/kWh. This suggests that while LTO battery technology is reliable for long-term use, it comes with higher investment costs. On the other hand, scenario 6, which uses NCA-type Li-ion batteries, has the lowest COE at 0.291 USD/kWh, making it the most economical choice among all scenarios. With a battery capacity of 78,644 kWh and a solar PV capacity of 44,940 kWp, this configuration achieves an optimal balance between wind and solar power in the isolated system.

The Basic Production Cost (BPP) of electricity in Mentawai Regency in 2024 is recorded at 0.468 USD/kWh (exchange rate: 1 USD = IDR 15,490) [19]. The simulation results show that six out of the eight scenarios have a Cost of Energy (COE) lower than the existing BPP. The full RE configuration with NCA-type Li-ion battery technology achieves the lowest LCOE among all configurations, at 0.291 USD/kWh.

4. Conclusion

The analysis results indicate that the implementation of renewable energy in Mentawai Regency has significant potential to reduce dependence on diesel power plants (PLTD). The PV-Wind configuration with NCA batteries yields the lowest COE (1.291 USD/kWh) and a renewable energy proportion of 94.8%, making it the optimal solution both technically and economically.

Meanwhile, the Full Renewable Energy (RE) scenario offers long-term sustainability with 100% renewable energy, albeit requiring high investment. The Hybrid System can serve as a transitional solution by gradually reducing the use of PLTD. With a BPP (Basic Production Cost) of 0.468 USD/kWh, several renewable energy configurations can compete economically. Battery technologies, such as NCA and LFP, play a key role in the stability and efficiency of the energy system. A phased implementation is highly recommended to ensure energy sustainability and resilience in Mentawai.

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