Optimization of Nusa Penida Electrical System: A Simulation Approach for Cost and Emission Reduction

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Abstract. Nusa Penida is one of Indonesia's outer islands, territorially part of Bali Province. The electrical system in this area is separate from Bali's electrical grid and is supplied by a 20 kV interconnection from a hybrid solar-wind-diesel power station, which connects Nusa Penida, Nusa Lembongan, and Nusa Ceningan islands. This system is referred to as the "Three Nusa System." The average solar radiation is 5.34 kWh/m²/day with an average wind speed of 4.4 m/s. These conditions can be utilized to develop renewable energy generation in the region. However, environmental conditions greatly affect the system's performance in meeting electricity supply demands. This paper discusses the feasibility of the hybrid power plant established under the natural conditions and the equipment specifications used in the hybrid system in Nusa Penida, taking into account economic factors and the emissions produced. The expected outcome is to determine how the lowest LCOE can be achieved, as well as emission reduction factors, to create the most optimal electrical system structure.

Keywords: *LCOE, Economic, Renewable Energy, Diesel Power Plant, Emission*

1 Introduction

The increasing demand for energy and the need to reduce greenhouse gas emissions have driven the development of more efficient and environmentally friendly power generation technologies. Hybrid systems that combine various renewable and conventional energy sources have emerged as a cutting-edge solution to address these issues. These generation systems not only reduce reliance on fossil fuels but also enhance the reliability and efficiency of electricity supply. In principle, a hybrid power generation system integrates multiple energy sources to leverage the advantages of each while minimizing their drawbacks. Common combinations include diesel generators, solar power, and wind power. This thesis discusses the optimization of the operation of these three types of power plants in a specific area.

As the world's largest archipelago with over 17,000 islands, Indonesia faces significant challenges in meeting its growing energy demands. The nation's energy sector is still heavily reliant on fossil fuels such as coal, oil, and natural gas. One of the strategic steps to address this dependency is to increase the share

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of renewable energy (RE) in the national energy mix. The Indonesian government has set a target of generating 23% of its energy from renewable sources by 2025. Indonesia is endowed with abundant renewable energy resources, including solar, wind, hydro, bioenergy, and geothermal energy. Solar energy potential is particularly high due to the country's equatorial location, while geothermal potential is significant given Indonesia's numerous active volcanoes. Additionally, wind energy and bioenergy derived from agricultural residues present opportunities for diversifying energy sources.

In recent years, various projects and initiatives have been launched to harness these resources. These include the development of solar power plants, wind farms, and small-scale hydropower plants across different regions. These efforts aim to optimize Indonesia's renewable energy potential while addressing the growing energy needs of its people.Based on their sources, electricity can be divided into two types: renewable energy and non-renewable energy. Renewable energy is energy obtained directly from the environment in a natural and sustainable way. This type of energy, also known as green energy or sustainable energy, is naturally present in the environment, regardless of whether there are devices to harness or block it. On the other hand, non-renewable energy is obtained through human intervention. This energy remains statically stored in the earth without human involvement. It is also commonly referred to as finite energy due to its limited quantity and the lengthy process required for its formation, or as brown energy.

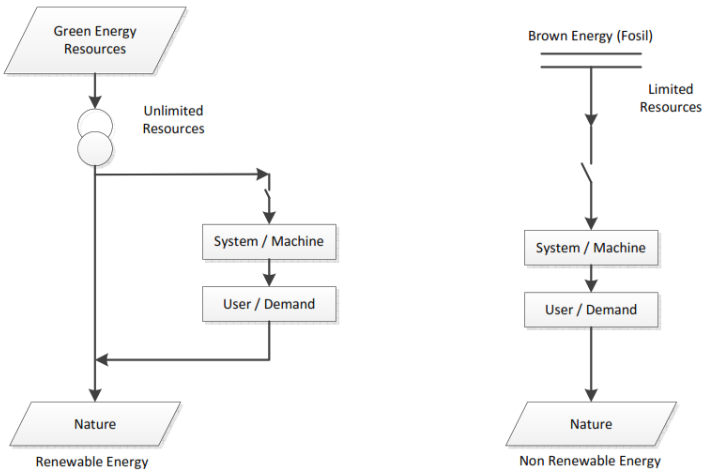

Figure 1 Difference in Energy Flow: (a) Renewable Energy vs. (b) Non-Renewable Energy

The optimization simulation of Economic Dispatch and Unit Commitment in Nusa Penida, with the addition of several new renewable energy sources, will be modeled using a software which is not only to determine the economic value of the given configuration scheme or power sources but also to achieve optimal optimization of the generation system in Nusa Penida based on the existing peak load history.

This journal also highlights the optimization of configuration to reduce carbon emissions, a highly relevant topic today. Carbon emissions have become a critical factor in evaluating company performance and a potential source of additional revenue to support operational performance. Improvements in emission values are significantly supported by the presence of renewable energy sources. However, practical implementation requires not only technical approaches but also considerations beyond the technical aspects. These include land availability and alignment with local government development plans. Addressing these factors is essential to ensure the successful integration of renewable energy and achieve the desired environmental benefits.

2 Analysis Methods

2.1 Research Location

Nusa Penida, a small island southeast of Bali, Indonesia, has unique and rapidly evolving energy needs driven by the growth of its tourism sector and the demands of the local population. In recent years, electricity demand in Nusa Penida has surged, with its load profile heavily influenced by tourism activities. Currently, the island's power system is dominated by Diesel Power Plants (PLTD) along with several renewable energy installations, including Solar Power Plants (PLTS). This combination of fossil and renewable energy sources provides operational flexibility but also presents economic and environmental challenges. Efforts to optimize Nusa Penida's power system are focused on improving efficiency, reducing operational costs, and minimizing environmental impacts, aligning with the island's sustainable energy development goals.

Figure 2 Research Location

2.2 Data Source

Based on data from software and sourced from the internet via the Solar GHI Resource feature, the average annual solar radiation in Nusa Penida is 5.34 kWh/m²/day.

Table 1 Solar Source from NASA

Month	**Daily Radiation** (kWh/m²/day)	**Month**	**Daily Radiation** (kWh/m²/day)
January	4.93	August	5.33
February	5.04	September	5.95
March	5.43	October	6.19
April	5.39	November	5.67
May	5.19	December	5.28
June	4.84	**Average**	**5.34**
July	4.79		

According to Table 1, the highest average solar radiation occurs in October at 6.19 kWh/m²/day, while the lowest occurs in July at 4.79 kWh/m²/day.

In addition to the renewable energy potential from the sun, Nusa Penida also has other potential sources from wind. Using the same software, sourced from the internet, the average annual wind speed is 4.25 m/s, with the following average monthly data:

Table 2 Wind Resource Source from NASA

Month	**Daily Radiation** (kWh/m²/day)	**Month**	**Daily Radiation** (kWh/m²/day)
January	3.78	August	5.32
February	3.75	September	4.88
March	3.23	October	4.31
April	3.61	November	3.67
May	4.49	December	3.60
June	4.97	**Average**	**4.25**
July	5.35		

According to Table 2, the highest average wind speed occurs in July at 5.35 m/s, while the lowest occurs in March at 3.23 m/s.

2.3 Data Profile

Nusa Penida has experienced a significant increase in energy demand following the declared end of the COVID-19 pandemic. The rapid growth of tourism has directly correlated with the surge in electricity demand on the island. Based on the cut-off data used in this journal for August 2024, the load data analyzed corresponds to the highest recorded load, which occurred on August 3, 2024, at 19:00 WITA, reaching 13,802.4 kW. This rising demand poses a critical concern as the electrical system struggles to meet the N-1 reliability criterion. Under these circumstances, the system operates in a precarious state on a daily basis, especially when equipment failure could potentially result in a Major Load Shedding (MLS) event. The load data, recorded at 30-minute intervals over a 24-hour period, is as follows:

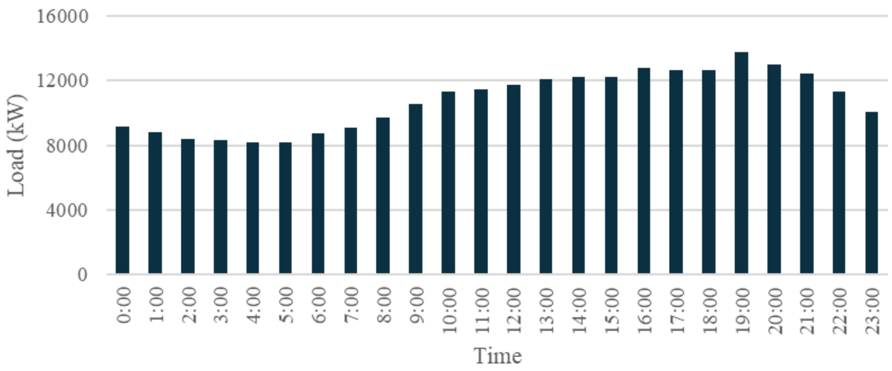

Figure 3 Nusa Penida Load Profile as August 3, 2024

The highest peak load in 2024, which also represents the record peak load for Nusa Penida, was 13,802 kW, occurring on August 3, 2024, at 19:00 WITA. The load profile in Nusa Penida, which is predominantly influenced by the tourism sector, typically starts to rise from 08:00 AM, peaks at 19:00 PM, and then tends to decrease afterward. The monthly load profile data entered into software is as follows:

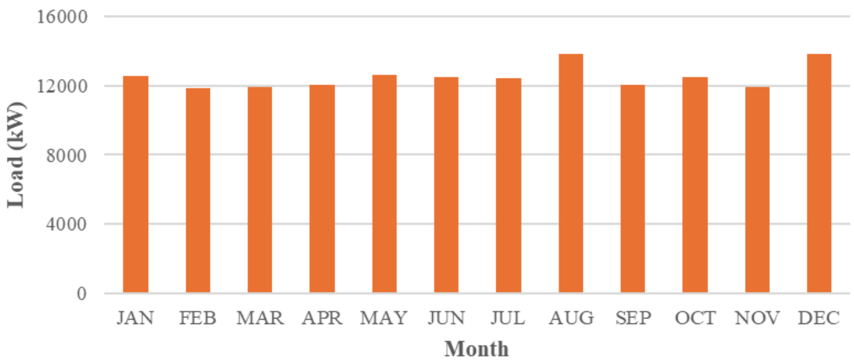

Figure 4 Monthly Load Profile

Considering the load growth in Nusa Penida over the past 5 years, the annual peak load data is as follows:

Table 3 Load Profile History 2019 – 2024

Year	Peak Load (kW)	%
2019	9,890	
2020	9,050	-8.5%
2021	5,930	-34.5%
2022	7,022	18.4%
2023	12,313	75.3%
2024	13,802	12.1%

Looking at the peak load trend in Nusa Penida from 2019 to 2024, there is an anomaly in 2020 and 2021 due to the COVID-19 pandemic. Considering the trend since the onset of the endemic phase (from 2022), an average annual growth rate of 35.29% can be observed. However, using this 35.29% as a benchmark for annual growth may be anomalous because the substantial growth is likely a result of the transition from pandemic to endemic. An alternative approach is to take the average growth over the past 5 years without considering specific conditions, which results in an average growth rate of 12.6%. This gives a predicted peak load for the next 5 years as follows:

Table 4 Load Profile Prediction 2025 – 2029

Year	Load Profile (kW)	%
2025	15,541	12.6%
2026	17,499	12.6%
2027	19,704	12.6%
2028	22,186	12.6%
2029	24,982	12.6%

3 Equiment Method

In this journal, since the optimization was performed on the existing network configuration in Nusa Penida, a comparison with the same application is necessary.

3.1 Existing Configuration

The existing configuration of the electrical system in Nusa Penida consists of Diesel Power Plants and Solar Power Plants (PV). The schematic is as follows:

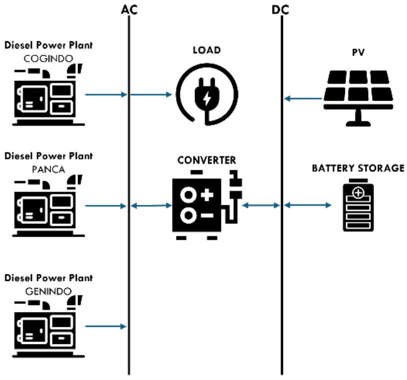

Figure 5 Existing Schematic

This existing configuration is an electrical system consisting of 3 Diesel Power Plants (PLTD), namely PLTD COGINDO (Capacity 7,700 kW), PLTD PANCA (Capacity 5,000 kW), and PLTD GENINDO (Capacity 2,500 kW), with an additional existing Renewable Energy Source in the form of Photovoltaic (PV) with a capacity of 3,500 MW, which is equipped with a Battery Energy Storage System (BESS) to meet the system's needs.

3.2 Optimized Configuration

Based on the existing configuration and several planned electrical system developments under the real conditions of PT PLN (Persero) Unit Induk Distribusi Bali, the configuration has changed. The schematic is as follows:

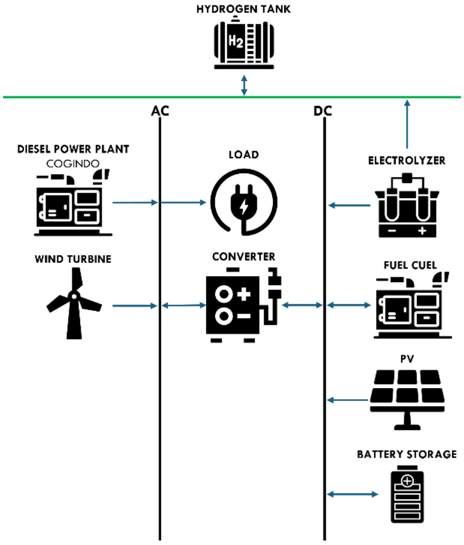

Figure 6 Optimized Schematic

The optimization system for Nusa Penida continues to rely on Diesel Power Plants as the base load generator, with a more optimized capacity of 10,000 kW. The existing solar PV installations remain operational, with an additional capacity of 8,000 kW contributed as a grant from USAID and KEPCO for integration into Nusa Penida's power system. A critical point regarding this grant is that the additional PV capacity has no capital cost element, significantly influencing the overall cost factor or Levelized Cost of Energy (LCOE) for the system. In addition to the PV upgrade, the system includes the introduction of a 10,000 kW Wind Power Plant and a 250 kW Hydrogen Power Plant, which comprises a hydrogen tank and an electrolyzer system. While hydrogen is still a relatively new energy source in Indonesia's power sector, it is associated with high costs in terms of procurement, operation, and maintenance. However, one of hydrogen's main advantages is its non-intermittent nature, making it an excellent complement to the intermittent characteristics of solar PV and wind power, despite the incorporation of Battery Energy Storage Systems (BESS) to manage intermittency.

3.3 Methodology

This journal essentially represents an ongoing project within the electrical system of PT PLN (Persero) Unit Induk Distribusi Bali. With the progress of the research in this journal, it is expected to provide input for decision-making to obtain the best electrical configuration with the most optimal LCOE value using the software application. The research methodology for this journal is as shown in the following figure:

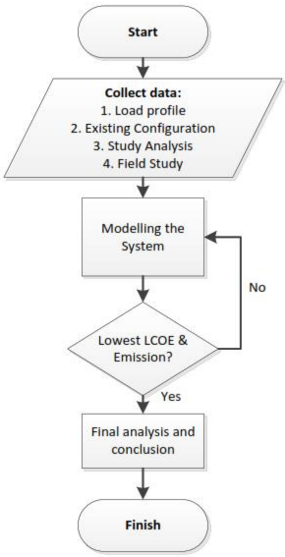

Figure 7 Methodology Optimization

Based on the existing network configuration, the following component prices [4] are included in the Schematic:

Table 5 Existing Price Component

No	Component	Capital (IDR)	Replacement (IDR)	O&M (IDR)
1	Diesel	0*)	4,000,000	4,000
2	PV	0*)	13,000,000	600,000
3	Storage	0*)	3,000,000,000	50,000,000
4	Inverter	0*)	3,200,000	100,000

The data represents a conversion from US Dollars with an exchange rate of US$1 = IDR 16,000.00. Note that the Capital value is zero because the system is existing, and only Replacement and O&M costs are considered. Additionally, the price of Diesel is calculated at IDR 15,000/liter.

Table 6 Optimation Price Component

No	Component	Capital (Rp)	Replacement (Rp)	O&M (Rp)
1	Diesel	0*)	4,000,000	4,000
2	PV1	0*)	13,000,000	600,000
3	PV2	0*)	13,000,000	600,000
4	PV3	0*)	13,000,000	600,000
5	Storage	0*)	3,000,000,000	50,000,000
6	Inverter	3,000,000	3,200,000	100,000
7	Wind	20,000,000,000	12,000,000,000	500,000,000
8	H. Tank	6,000,000	5,000,000	50,000
9	Electrolyzer	7,500,000	6,000,000	300,000
10	Fuel Cell	15,000,000	12,000,000	300,000

The upper data represents the component prices [4] which is a conversion from US Dollars with an exchange rate of US$1 = IDR 16,000.00. Note that the Capital value is zero for some components because they are existing, and costs are only considered for Replacement and O&M. Specifically, for PV2 and PV3, the Capital value is zero because they are grant assets, whereas additional components compared to the existing configuration have costs associated with Capital, Replacement, and O&M. Additionally, the price of Diesel is calculated at IDR 15,000/liter, and the price of Fuel is IDR 48,000/kg.

4 Simulation Result

Based on all the data entered as the basis for the calculation, the results for both cost and electrical aspects under the two conditions are as follows:

Table 7 Result Comparison

No	Component	Existing	Optimized
1	LCOE (IDR/kWh)	7,771	3,981
2	NPC (IDR Billion)	7,373	3,790
3	Op. Cost (IDR Billion)	691	335
4	Renewable Frac. (%)	5.12	55.4

The results of the simulation (best LCOE) were obtained with the following comparison of power plant sizes:

Table 8 Power Plant Composition

No	Component	Existing	Optimized
1	Diesel (kW)	11,700	10,000
2	PV1 (kW)	3,500	11,500
3	PV2 (kW)	-	
4	PV3 (kW)	-	
5	Wind (kW)	-	10,000
6	Hidrogen (kW)	-	250
7	Electrolyzer (kW)	-	417
8	Hydrogen Tank (kg)	-	2,000

From Tables 7 and 8, several key points warrant special attention. The Levelized Cost of Energy (LCOE) represents the average cost of producing electricity within a system or power generation over the system's operational lifetime. The improved LCOE in this optimization configuration is influenced by several factors. One significant contributor to the reduction in LCOE is the decrease in Diesel power generation, as the addition of renewable energy sources has lowered reliance on diesel-based generation. The 8,000 kW of PV capacity, which is a grant, further improves the LCOE since it does not include capital cost components, which has a substantial impact on the overall cost. Moreover, the optimization system continues to rely on Diesel due to Nusa Penida being an isolated island system with high electricity demand. This reliance on diesel ensures system reliability, especially since relying solely on renewable energy would make the system vulnerable. From a technical standpoint, fully operating with only renewable energy sources would require large land areas, which is often impractical for implementation in Nusa Penida. This land requirement, combined with the intermittency issues of renewable energy, reinforces the need for a balanced energy mix that includes both renewable sources and reliable backup from Diesel.

From the simulation results for the optimized configuration with the best LCOE, the Power Output and energy production in kWh for PV generation are as follows:

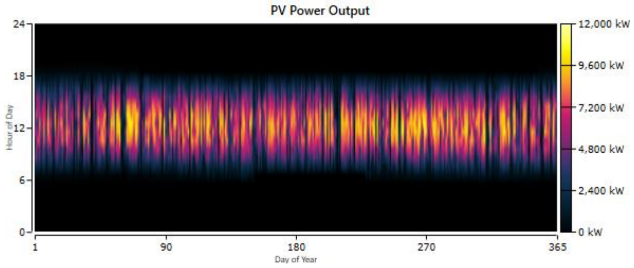

Figure 8 PV Output (kW)

Based on Figure 8 with the best optimization scheme, the kWh production over a one-year period (Y-axis) occurs between 7 AM and 5 PM (X-axis on the left), with the kWh production Heat Map corresponding to the color scale explained on the right X-axis. The highest production is typically observed between around 10 AM and 2 PM, with some days showing no kWh generation due to suboptimal sunlight intensity (indicated by black gaps in certain parts). For the optimized PV results, a Rated Capacity of 11,500 kW was achieved, with total kWh production of 18,103,064 kWh/year. The operating hours totaled 4,388 hours/year, with an LCOE of 137 IDR/kWh.

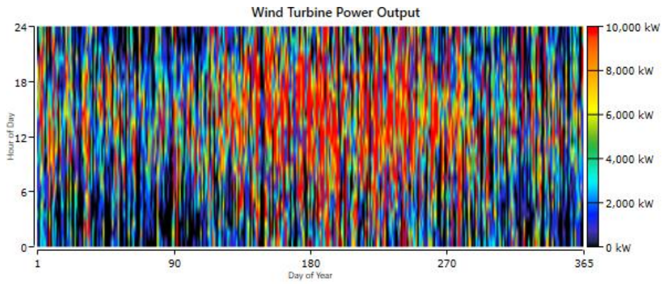

Figure 9 Wind Turbine Output (kW)

From Figure 9, the kW production over one year (Y-axis) occurs almost throughout the entire day with varying intensities, illustrated by the kWh production Heat Map corresponding to the color scale explained on the right X-axis. Observing the increasing redness (indicating higher production), kWh production from the Wind Turbine reaches its peak between May and September, consistent with the data in Table 2. For the optimized Wind Turbine results, a Rated Capacity of 10,000 kW was achieved, with a total kWh production of 34,783,571 kWh/year. The operating hours totaled 7,064 hours/year, with an LCOE of 683 IDR/kWh.

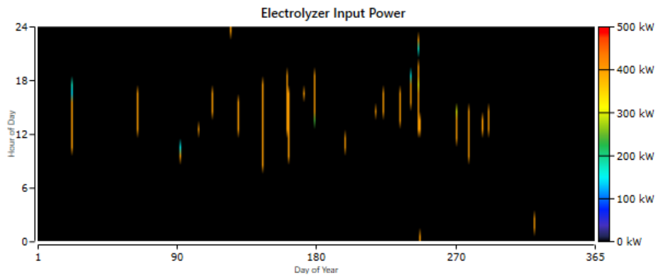

Figure 10 Electrolyzer Input (kW)

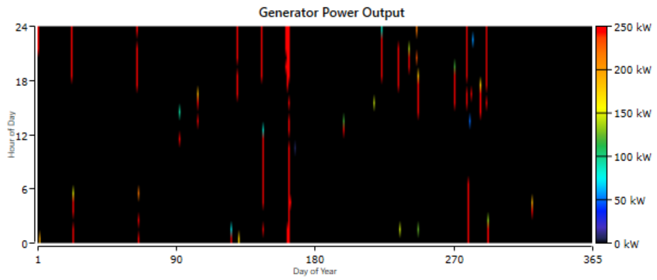

Figure 11 Fuel Cell Output (kW)

Figures 10 and 11 show the output of the Hydrogen generation system with the best optimization. The Fuel Cell in the Hydrogen generation system can produce 5,060 kWh/year, with a generation cost of IDR 300,300/hour. The energy generated from this 250 kW Fuel Cell comes from the Hydrogen generation system, which consists of a Hydrogen Tank and an Electrolyzer. The Hydrogen Tank has a capacity of 2,000 kg with an energy storage capacity of 66,667 kWh, while the Electrolyzer has a capacity of 417 kWh, an operating time of 1,980 hours/year, and a total energy production of 442 kg/year.

Several analyses can be drawn from why, despite its relatively low output capacity, the optimized results still include Hydrogen generation. This is because, during certain periods, other renewable energy sources are unable to produce energy, so the energy generated by the Electrolyzer and stored in the Hydrogen Tank is integrated into the system to meet demand. Another analysis regarding this Hydrogen generation is that it requires high costs because, in the generation process, the Electrolyzer also requires a power source, and only about 40% of the initial energy can be converted into kWh from this Hydrogen generation process.

Comparing the results between the existing configuration and the optimization with the best LCOE, the reduction in emission values is as follows:

Table 9 Emission Comparison

No	Emission	Existing (kg/year)	Optimized (kg/year)
1	Carbon Dioxide	57,119,252	26,934,553
2	Carbon Monoxide	295,505	139,345
3	Unburned Hydrocarbons	15,684	7,396
4	Particulate Matter	2,527	1,192
5	Sulfur Dioxide	139,626	65,840
6	Nitrogen Oxides	56,635	26,706

The optimization results obtained required a fairly long simulation time due to the large number of sensitivities, with the following data:

Table 10 Sensitivity Variables in Software

No	Sensivity Variable	Value
1	Electrolyzer (Capital – Multiplier)	1; 0.75
2	Electrolyzer (Replacement – Multiplier)	1; 0.75
3	Electrolyzer (O&M – Multiplier)	1; 0.75
4	Electrolyzer (MW)	Lower 0; Upper 1,000
5	Hydro Tank (kg)	2,000; 4,000; 6,000; 8,000; 10,000; 12,000; 14,000; 16,000; 18,000; 20,000
6	PV (MW)	3.5; 7; 11.5
7	Diesel (Size - MW)	0; 5; 10
8	Wind Turbine (Quantity)	0; 10
9	Expected Inflation (%)	2.5; 1.84

The simulation results for the optimization configuration were based on the input of 64 sensitivity variables. This sensitivity approach can be likened to the iterative process in Particle Swarm Optimization, which increased the simulation time due to the varied input scenarios, ultimately resulting in significantly improved outcomes. For example, increasing the number of Electrolyzers or Hydrogen Tanks did not necessarily lead to better energy output, as economic factors played a crucial role in the system's operational efficiency. Similarly, sensitivity values for other renewable energy components, such as PV and Wind Turbine, were adjusted to find the most optimal configuration. The number of sensitivity variables proved to be a decisive factor in achieving the best results. When comparing simulations with the same inputs but different sensitivity values, the results varied in terms of LCOE. Without sensitivity analysis, the LCOE was Rp 4,015/kWh, while the simulation with 64 sensitivity variables yielded an LCOE of Rp 3,981/kWh, marking it as the best result for optimizing the electrical system in Nusa Penida as presented in this journal.

In other scenarios generated through software simulations, higher LCOE values were observed, particularly in configurations where the Fuel Cell component was removed, but additional Battery Energy Storage Systems (BESS) were integrated into the system. Among all the proposed scenarios, the Wind Turbine plays a significant role in determining the overall LCOE, due to its relatively consistent energy output on a daily average, as reflected in the output diagram. As additional context, the number of additional PV and Wind Turbine units considered in this journal has been determined based on the available land in Nusa Penida and the plans for their construction and integration in the near future.

5 Conclusion

The optimization results for the Nusa Penida electrical system showed improved economic and electrical performance with a system composition consisting of Diesel Power Plants (PLTD) with 10,000 kW, Photovoltaics (PV) with 11,500 kW, Wind Power Plants (PLTB) with 10,000 kW, and 250 kW Fuel Cell to support Hydrogen generation, along with an additional 417 kW Electrolyzer and a 2,000 kg Hydrogen Tank. When comparing the Levelized Cost of Energy (LCOE) results, the system's generation cost improved from IDR 7,771/kWh to IDR 3,981/kWh, a reduction of IDR 3,790/kWh (49%). This was accompanied by a 49% optimization in Net Present Cost (NPC) and a 52% reduction in Operational Cost. This optimized electrical configuration also achieved a significant reduction in emissions, with a 53% decrease per year in Carbon Dioxide, Carbon Monoxide, Unburned Hydrocarbons, Particulate Matter, Sulfur Dioxide, and Nitrogen Oxides.

Another important consideration is that this optimization configuration involves a significant amount of renewable energy (EBT), which introduces the challenge of intermittency. This issue must be addressed from the outset. The placement of renewable energy sources, their configuration, and the smoothing system through Battery Energy Storage Systems (BESS) must be properly managed to prevent power fluctuations that could lead to widespread disturbances in the system.

Both technical and non-technical factors must always be considered in optimization decisions, especially given the unique characteristics of Nusa Penida's electrical system. The island's electricity system and its demand are substantial for an isolated island that is not yet interconnected with the larger Bali grid, either via transmission or distribution networks. By addressing these factors, the optimization can lead to an even better LCOE, as it would reduce or eliminate the reliance on diesel power generation in both the existing system and the optimized configuration proposed in this journal. This would enhance the overall economic and environmental performance of the energy system on Nusa Penida.

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