



Review of Hybrid Diesel–Solar Power System from Technical and Economic Perspectives at Power Plants in Lombok

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Abstract: Diesel Power Plants remain the main electricity source in Indonesia's archipelagic country and they are served as isolated power systems, that characterized by high fuel consumption, high operating costs, and significant greenhouse gas emissions. This study evaluates the technical, economic, reliability, environmental, and diesel reduction performance of a hybrid Diesel Power Plants system integrated with solar power and battery energy storage. A quantitative simulation-based approach using HOMER software compares three configurations: conventional Diesel Power Plants, Diesel–Solar PV, and Diesel–Solar PV–BESS. The analysis focuses on energy performance, fuel efficiency, economic indicators, system reliability, and carbon dioxide (CO₂) emissions.

Results show that integrating a 1 MWp PV system and a 1 MWh BESS into a 6 MW Diesel Power Plant in Lombok significantly improves system performance, reducing Specific Fuel Consumption by 4.70% and CO₂ emissions by 4.41%. Economically, the hybrid system lowers Net Present Cost by 3.31%, Operating Cost by 4.78%, and Levelized Cost of Energy by 3.58% to 0.2234 USD/kWh, with a payback period of 2.91 years, while also improving system reliability through reduced unmet load and capacity shortage. These findings confirm that the Diesel Power Plant–Solar PV–BESS configuration is a reliable, cost-effective, and environmentally sustainable diesel reduction solution for island-based power systems in Indonesia.

Keyword: Hybrid System, SFC, Operating Cost, Reliability, CO₂ Emissions

INTRODUCTION

The availability of reliable, efficient, and environmentally friendly electricity is a fundamental requirement for regional and national economic development. In Indonesia, electricity demand continues to increase in line with population growth, industrialization, and the expansion of the tourism sector, with an average annual growth rate of approximately 7.9% during the period 2020–2024. Through the National Electricity General Plan (RUKN), the government targets a renewable energy share of 23% by 2025 and the achievement of Net Zero Emissions by 2060, supported by a diesel reduction program aimed at decreasing reliance on

diesel power plants. Although Indonesia has abundant and evenly distributed solar energy potential, the utilization of solar power remains limited due to its intermittent nature, which requires support from dispatchable generation or energy storage systems. Numerous studies have shown that integrating solar power with diesel generators and battery energy storage systems can improve system reliability, reduce electricity generation costs, and significantly lower carbon emissions. (Kementerian ESDM, 2025)

In West Nusa Tenggara Province, particularly on Lombok Island, the power system still relies heavily on diesel- and gas-fired power plants, making it vulnerable to supply disruptions and fuel price fluctuations. The Lombok 6 MW diesel power plant, one of the main electricity suppliers in the region, has high fuel consumption, leading to elevated operating costs and substantial carbon dioxide emissions. Integrating solar power and battery energy storage offers a strategic solution to reduce fuel consumption, extend diesel engine lifetime, and enhance system reliability (Pratama, 2025). Based on these conditions, this study focuses on a techno-economic analysis of a hybrid diesel-solar-battery system at the Lombok 6 MW power plant in Lombok using an off-grid simulation approach with HOMER, covering technical, economic, reliability, and environmental aspects.

METHOD

This study employs a comparative quantitative research method with a multidisciplinary approach and energy system simulation using the HOMER software. The quantitative method is selected because all analyzed variables consist of numerical data that can be measured objectively, including electrical energy production, diesel fuel consumption, generation efficiency, economic indicators (Net Present Cost, Operating Cost, Levelized Cost of Energy, and payback period), system reliability, and carbon dioxide emissions. The analysis is conducted mathematically through modeling and simulation, ensuring that the results are measurable, systematic, and scientifically accountable.

This research is comparative performance, comparison of three scenarios power generation system configurations namely: conventional Diesel Power Plant as Scenarios 1, Diesel Power Plant-PV as Scenarios 2, and Diesel Power Plant-PV-BESS as Scenarios 3. All scenarios are analyzed using identical technical and economic parameters to ensure fair and consistent comparisons. The simulation approach is applied to model system behavior under various operating conditions and to comprehensively evaluate technical, economic, and environmental performance.

The research begins with a literature review and data collection, including technical and operational data of the Diesel Power Plant, electrical load data, solar energy potential data, and economic parameters required as simulation inputs. The collected data then undergo processing and formatting adjustments to ensure compatibility with the HOMER software.

The next stage involves modeling and validation of the conventional Diesel Power Plant system as the baseline scenario. Validation is performed by comparing simulation results with actual operational data of the power plant. The model is considered valid when the deviation between simulation results and actual data falls below the predefined tolerance limit. The validated Diesel Power Plant model is subsequently used as the basis for developing hybrid system scenarios.

Based on Table 1 three system modeling scenarios are developed. The first scenario represents the conventional Diesel Power Plant, consisting of six diesel generator units each rated at 1 MW and no renewable energy contribution. The second scenario is the hybrid Diesel Power Plant-Solar PV system, where the Diesel Power Plant is integrated with a 1 MWp solar photovoltaic (PV) system, equivalent to approximately 16.6% of the peak load. The third scenario is the hybrid Diesel Power Plant-Solar PV-BESS system, which extends the previous

configuration by adding a Battery Energy Storage System (BESS) with a capacity of 1 MWh to enhance operational flexibility, energy utilization efficiency, and system reliability.

Table 1. System modeling scenarios of the HOMER simulation

Component	Scenario 1: Conventional Diesel Power Plant	Scenario 2: Hybrid Diesel Power Plant – Solar PV	Scenario 3: Hybrid Diesel Power Plant–Solar PV–BESS
Diesel Power Plant Capacity	6 × 1 MW (contracted capacity 5 MW)	6 × 1 MW (contracted capacity 5 MW)	6 × 1 MW (contracted capacity 5 MW)
PV Capacity	–	1 MWp (16.6% of peak load)	–
BESS Capacity	–	–	1 MWh
Main Energy Source	Diesel	Diesel + PV	Diesel + PV + BESS

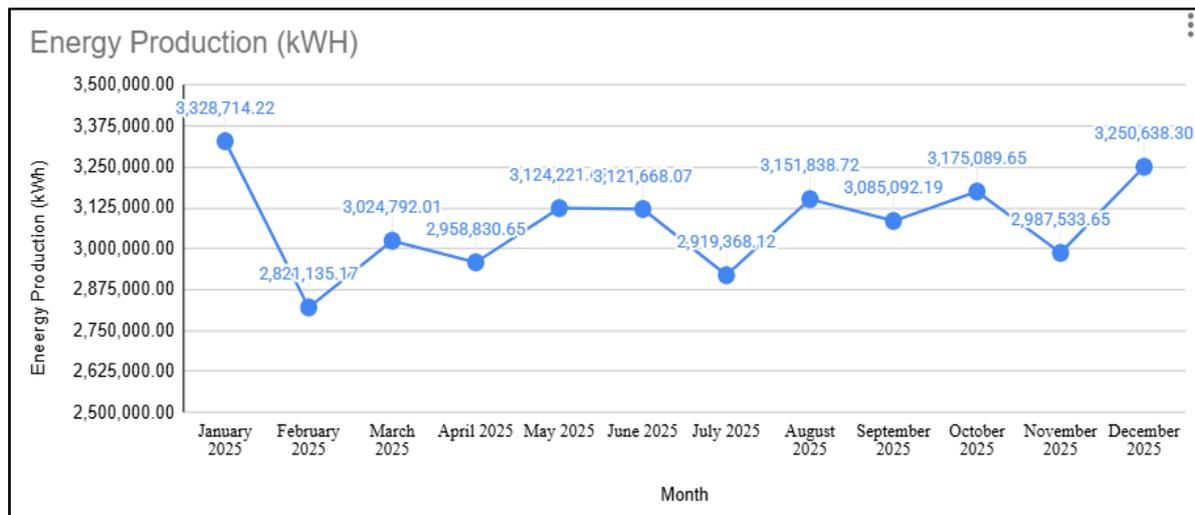
Source: Data by researcher

All scenarios are then simulated and evaluated through comparative analysis, covering energy performance and efficiency, fuel consumption, economic performance, system reliability, and environmental impact. In addition, a policy analysis is conducted to assess the alignment of the research findings with national energy policy directions. The final stage of the study involves drawing conclusions and formulating recommendations, summarizing the key findings and providing technical and policy recommendations regarding the implementation of hybrid Diesel Power Plant–Solar PV–BESS systems.

RESULT AND DISCUSSION

Energy Performance Diesel Power Plant and Solar Energy Potential

Based on Figure. 1 The Energy Production of the Lombok Diesel Power Plant (Diesel Power Plant) from January to December 2025, the plant continues to play a crucial role in meeting electricity demand in the Lombok power system.



Source: Research Results Data

Figure 1. Energy Production 6 MW Diesel Power Plant

Total annual energy production reached 36,948,922.42 kWh, with relatively stable monthly generation in the range of 2.8 -- 3.3 GWh. The lowest production occurred in February due to maintenance activities and reduced load demand, while the highest production was recorded in January when the Diesel Power Plant operated as a primary backup generator. This

pattern indicates that the Lombok Diesel Power Plant operates intensively as a load-following and peaking plant, particularly during supply imbalances or outages at larger power plants. In terms of fuel consumption, total annual diesel usage reached approximately 10 million liters, reflecting the high operational intensity of the diesel generators, especially during peak load periods and when power supply from non-diesel generation sources declined. Fuel consumption peaked in January in line with higher energy production and reached its lowest level in February.

The Specific Fuel Consumption (SFC) analysis shows that the Lombok Diesel Power Plant operated under relatively stable and efficient conditions, with an annual SFC value of 0.271 liters/kWh. This value falls within the optimal range for medium-speed diesel power plants, indicating good combustion quality and relatively consistent load distribution among generator units. However, increases in SFC under low-load operating conditions suggest potential opportunities for efficiency improvement through operational optimization.

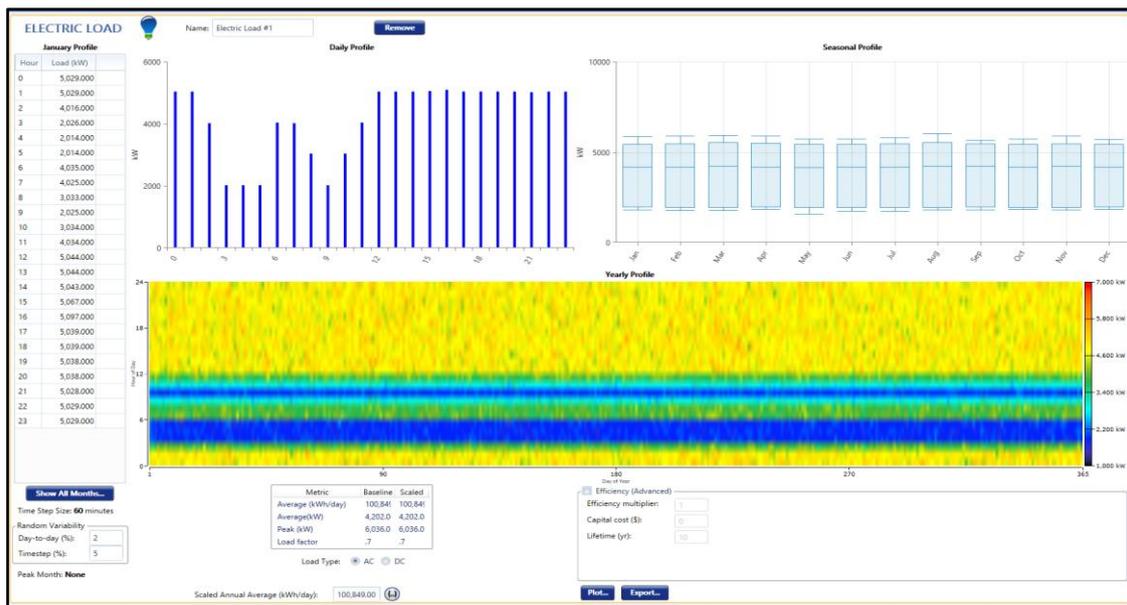
From the renewable energy perspective, data from the Global Solar Atlas (2025), the research location has very good solar energy potential for the development of a solar power system. The Global Horizontal Irradiation (GHI) is recorded at 5.276 kWh/m²/day, equivalent to approximately 1,925.6 kWh/m²/year, indicating sufficient and stable solar energy availability throughout the year. In addition, the Direct Normal Irradiation (DNI) reaches 4.312 kWh/m²/day; however, this parameter is not directly applied in the HOMER Pro simulation because the modeled system is a fixed-tilt photovoltaic system without solar tracking or concentrators. Consequently, GHI is used as the primary input parameter in the simulation.

Overall, the Global Solar Atlas data confirm that the study area has high solar energy potential and is technically suitable for integrating a solar power plant into the existing diesel-based power system, providing a strong basis for modeling and analysis of the hybrid PLTD–PLTS system using HOMER.

Input Data for HOMER Simulation

The system simulation was conducted using HOMER software with the study location set in Mataram, West Nusa Tenggara (8°12'48" S, UTC+8), representing the operational conditions of diesel power plants in eastern Indonesia with high solar energy potential. Referring to Figure. 2, the data electrical load profile was developed based on actual Diesel Power Plant operational data, with an average daily energy consumption of 100,849 kWh, an average load of 4,202 kW, and a peak load of 6,036 kW. A load factor of 0.7 indicates relatively stable load variations throughout the year, with lower demand during early morning hours and higher demand from daytime to nighttime, suggesting strong potential for solar PV contribution during daylight hours. The economic parameters applied in the simulation include a discount rate of 9.66%, an inflation rate of 1.61%, a project lifetime of 20 years, and an initial annual capacity shortage allowance of 10% for sensitivity analysis, which was reduced during the final evaluation stage.

The Diesel Power Plant system was modeled using six Mitsubishi S16R-PTAS diesel generator units, each with a continuous rated capacity of 1,050 kW and a nominal capacity of 1,250 kW, connected to an AC bus. The biodiesel fuel price was set at 0.773 USD/L, with a minimum load ratio of 50% and a generator lifetime of 25,000 operating hours. The capital cost of each generator was 352,336 USD, the replacement cost 126,421 USD, and the operation and maintenance cost 6.94 USD per operating hour. Routine maintenance was scheduled every 400 hours, while top overhaul was performed every 6,000 operating hours.



Source: Research Results Data
Figure 2. Input Data Electrical Load for HOMER

The solar PV system was modeled with a fixed capacity of 1 MW_p using *flat-plate* photovoltaic modules. The capital cost was set at 598,184 USD/MW_p, annual operation and maintenance cost at 5,982 USD, and a derating factor of 80%, resulting in an effective PV capacity of approximately 800 kW. Solar resource data were based on a Global Horizontal Irradiation (GHI) annual average of 5.28 kWh/m²/day, with monthly values ranging from 4.80 to 6.13 kWh/m²/day, indicating excellent solar potential at the study site.

The inverter system was modeled with a capacity of 1,000 kW, a capital cost of 187,465 USD, an annual O&M cost of 1,875 USD, and a 10-year lifetime. DC–AC conversion efficiencies were set at 95%, and the rectifier capacity was set at 100% of inverter capacity to allow battery charging from the AC side when required.

The Battery Energy Storage System (BESS) was modeled using an *idealized battery model* with an energy capacity of 1 MWh (1,000 kWh). The BESS has a round-trip efficiency of 90%, a nominal voltage of 600 V, a minimum state of charge (SOC) of 20%, and an initial SOC of 100%. The capital and replacement costs were each set at 392,825 USD, with an annual O&M cost of 3,928 USD. The battery lifetime was estimated at 10 years or until a throughput of 3,000,000 kWh.

Conventional Diesel Power Plant Simulation and Model Validation

The simulation results of the conventional Diesel Power Plant/Scenario 1 using HOMER in Figure. 3 indicate that the entire electricity demand of the system is supplied solely by six diesel generator units, with no contribution from renewable energy sources. Total annual electricity production delivered to the load reaches approximately 36.59 GWh, all of which is allocated to the AC primary load. The energy contribution among the generator units is relatively evenly distributed, reflecting a *diesel-only* operating strategy aimed at maintaining supply continuity and avoiding overload on individual units. The zero values of renewable fraction and maximum renewable penetration confirm the system’s full dependence on fossil fuel.



Source: Research Results Data
Figure 3. Electrical Summary Conventional Diesel Power Plant

In terms of fuel consumption, the Scenario 1 Plant exhibits very high diesel usage, totaling approximately 9.96 million liters per year, with a relatively stable consumption pattern throughout the year. Based on the total energy production and fuel consumption, the calculated Specific Fuel Consumption (SFC) is 0.2723 L/kWh, representing the thermal performance of the diesel generators under actual operating conditions.

The economic performance analysis shows that Scenario 1 has a Net Present Cost (NPC) of approximately USD 83.72 million over the project lifetime, with fuel costs accounting for more than 90% of the total NPC. The annual operating cost is about USD 8.30 million, largely dominated by fuel expenses. Based on a Total Annualized Cost of approximately USD 8.48 million per year and the annual energy supplied to the load, the Levelized Cost of Energy (LCOE) is calculated at USD 0.2317/kWh. This value serves as the baseline for economic comparison with the Diesel Power Plant–PV and Diesel Power Plant–PV–BESS scenarios.

From a reliability perspective, the Scenario 1 produces no excess electricity, indicating that all generated energy is directly utilized by the load. However, the system still experiences unmet load and capacity shortage, particularly during peak load conditions or when some generator units are not operating optimally, highlighting limitations in installed capacity.

From an environmental standpoint, the Scenario 1 generates very high CO₂ emissions, reaching approximately 26.47 million kg/year, due to its full reliance on diesel fuel combustion. This high carbon intensity underscores the environmental impact of diesel-based generation and provides a benchmark for evaluating emission reductions in hybrid system scenarios.

Tabel 2. Model Validation

Parameter	HOMER Simulation	Actual Data	Difference	Deviation (%)
Energy Production (kWh/year)	36,593,148	36,948,922	-355,774	0.96
Fuel Consumption (L/year)	9,964,132	10,013,880	-49,748	0.5
Specific Fuel Consumption (L/kWh)	0.2723	0.271	0.0013	0.48

Source: Data by researcher

To ensure the reliability of the simulation results, based on Table. 2 model validation was conducted by comparing HOMER simulation outputs with actual operational data of the Lombok Diesel Power Plant. The validation results show that deviations in annual energy production, fuel consumption, and SFC are below 1%, well within the commonly accepted tolerance limit ($\leq 5\%$) for power system modeling. Therefore, the conventional Diesel Power Plant model is considered valid and representative, and it can be reliably used as the basis for further analysis of Diesel Power Plant–Solar PV and Diesel Power Plant–Solar PV–BESS hybrid system configurations.

Summary of the Diesel Power Plant–Solar PV Simulation

The simulation results of the Diesel Power Plant – PV (1 MW) system as Scenario 2 in Figure 4, indicate that integrating solar photovoltaic generation provides technical, economic, and environmental improvements compared to the conventional diesel-only configuration. The total annual electricity production reaches approximately 36.76 GWh, with the PV system contributing about 1.56 GWh per year, equivalent to 4.23% of total energy generation. Although diesel generators remain the primary energy source, the PV integration effectively reduces diesel loading, particularly during daytime hours, without compromising the supply of the AC primary load.



Source: Research Results Data
Figure 4. Electrical Summary Diesel Power Plant–Solar PV

In terms of fuel consumption, the Scenario 2 PV system reduces annual diesel usage to approximately 9.61 million liters, resulting in a Specific Fuel Consumption (SFC) of 0.2620 L/kWh, which is lower than that of the conventional Diesel Power Plant. This improvement reflects enhanced operational efficiency due to partial substitution of diesel-generated electricity with solar energy.

From an economic perspective, the Scenario 2 achieves a Net Present Cost (NPC) of approximately USD 81.80 million over the project lifetime. Although fuel costs remain the dominant component, the integration of PV helps mitigate long-term operational cost escalation. The annual operating cost is approximately USD 8.03 million, while the Levelized Cost of Energy (LCOE) decreases to USD 0.2259/kWh. The PV investment demonstrates economic feasibility, with a simple payback period of approximately 2.71 years and a discounted payback period of about 3.13 years.

Regarding system reliability, the Scenario 2 configuration shows improvement compared to the diesel-only system, as indicated by reduced unmet load and capacity shortage. However, a small amount of excess electricity remains, reflecting limited operational flexibility due to the absence of energy storage.

From an environmental standpoint, integrating a 1 MW PV system reduces annual CO₂ emissions to approximately 25.52 million kg, corresponding to a reduction of about 0.95 million kg CO₂ per year (approximately 3.6%) relative to the conventional Power Plant. This confirms the role of PV integration in reducing fossil fuel consumption and carbon emissions.

Summary of the Diesel Power Plant–Solar PV–BESS Simulation

The simulation results of the Scenario 3 in Figure 5, demonstrate that integrating a 1 MWp photovoltaic (PV) system and a 1 MWh Battery Energy Storage System (BESS) into the Lombok Diesel Power Plant (Diesel Power Plant) delivers the most optimal performance compared to the Scenario 1 and the Scenario 2 configurations. Total annual electricity production reaches approximately 36.79 GWh, with 36.70 GWh supplied to the load, all serving the AC primary load. The PV contribution remains at 1.56 GWh per year (4.23%), with a renewable fraction of 4.00% and maximum renewable penetration of 36.1%, confirming that the primary role of BESS is not to increase renewable capacity, but to enhance the utilization of existing solar energy through controlled energy storage and dispatch.

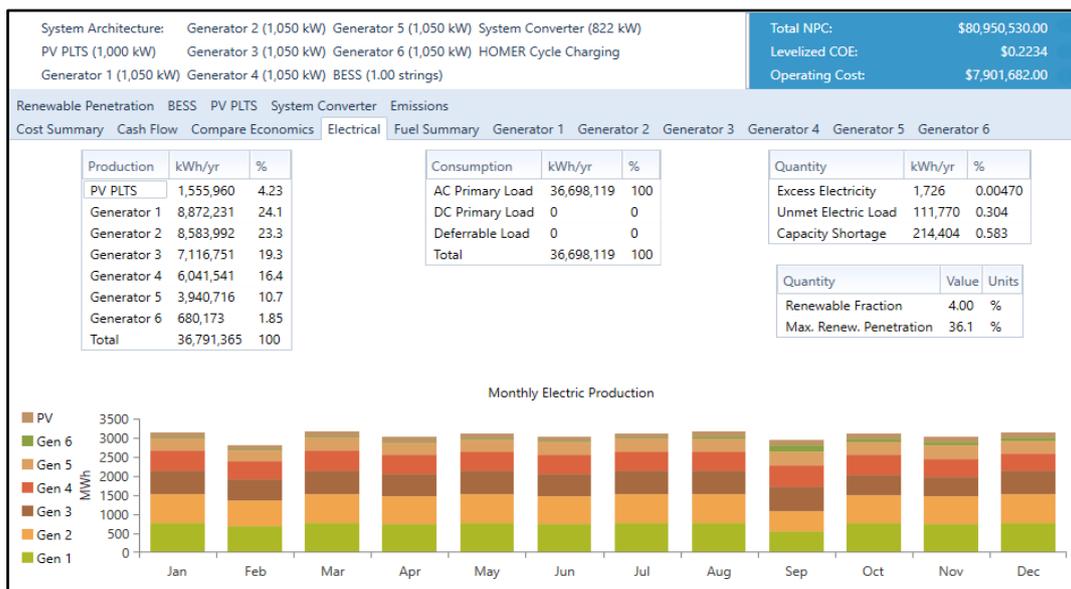


Figure 5. Electrical Summary HOMER Diesel Power Plant–Solar PV–BESS

In terms of fuel consumption, the Scenario 3 system records the lowest diesel usage, at approximately 9.52 million liters per year, with a Specific Fuel Consumption (SFC) of 0.2595 L/kWh. This indicates a significant improvement in generation efficiency compared to both the diesel-only and Diesel Power Plant–Solar PV systems, leading to reduced operating costs and lower emissions.

From an economic perspective, the Scenario 3 configuration achieves a Net Present Cost (NPC) of approximately USD 80.95 million, the lowest among all evaluated scenarios. The annual operating cost is about USD 7.90 million, while the Levelized Cost of Energy (LCOE) decreases to USD 0.2234/kWh, representing the most cost-efficient configuration. The investment is economically attractive, with a simple payback period of approximately 2.91

years and a discounted payback period of about 3.34 years, indicating a relatively fast return on investment.

Regarding system reliability, the Scenario 3 system shows a substantial improvement, with very low excess electricity and the lowest levels of unmet load and capacity shortage among all scenarios. This highlights the critical role of BESS in enhancing operational flexibility and system responsiveness to load fluctuations and solar variability.

From an environmental standpoint, annual CO₂ emissions are reduced to approximately 25.31 million kg, corresponding to a reduction of about 1.17 million kg CO₂ per year, or approximately 4.41%, compared to the conventional Diesel Power Plant. These results confirm that the integration of PV and BESS contributes meaningfully to reducing fossil fuel consumption and greenhouse gas emissions.

Summary of the Energy Performance and Fuel Efficiency Comparison

A comparative analysis based on Table 3 was conducted to evaluate the impact of integrating solar photovoltaic (PV) systems and Battery Energy Storage Systems (BESS) on the ability of the Lombok Diesel Power Plant to meet annual electricity demand. The simulations were performed using HOMER with consistent assumptions and parameters across three scenarios—conventional Diesel Power Plant (Scenario 1), Diesel Power Plant – Solar PV (Scenario 2), and Diesel Power Plant – Solar PV – BESS (Scenario 3) ensuring an objective comparison of results.

Tabel 3. Energy Performance Comparison

Parameter	Scenario 1	Scenario 2	Scenario 3
Annual Energy Production (kWh/year)	36,593,148	36,762,288	36,791,365
Annual Energy Supplied to Load (kWh/year)	36,593,148	36,669,453	36,698,119
PV Energy (kWh/year)	–	1,555,960	1,555,960
PV Contribution (%)	–	4.23	4.23
Renewable Fraction (%)	–	4	4
Maximum Renewable Penetration (%)	–	36.1	36.1

Source: Data by researcher

The simulation results indicate that the Scenario 1 relies entirely on diesel generation, supplying approximately 36.59 GWh per year to the load, with no contribution from renewable energy sources. The integration of a 1 MWp PV system in the Scenario 2 increases total annual energy production to about 36.76 GWh, with the PV system contributing approximately 1.56 GWh per year or 4.23% of total generation. The resulting renewable fraction of 4.00% and maximum renewable penetration of 36.1% demonstrate that PV generation can significantly reduce diesel loading during periods of high solar irradiance.

In the Scenario 3, total energy production and energy supplied to the load further increase to approximately 36.79 GWh per year. Although the PV contribution, renewable fraction, and maximum renewable penetration remain unchanged, the addition of a 1 MWh BESS improves energy management by storing surplus solar energy and dispatching it when needed. This leads to a more stable energy supply and enhances system flexibility and operational reliability.

Table 4. Fuel Efficiency Comparison

Parameter	Scenario 1	Scenario 2	Scenario 3
Fuel Consumption (L/year)	9,964,132	9,605,950	9,525,741
Specific Fuel Consumption (L/kWh)	0.2723	0.262	0.2595
SFC Reduction vs. Diesel Power Plant (L/kWh)	–	0.0103	0.0128
SFC Reduction vs. Diesel Power Plant (%)	–	3.78	4.7

Source: Data by researcher

Based on Table 4, the Scenario 1 system shows the highest fuel consumption at 9,964,132 liters per year, with a Specific Fuel Consumption (SFC) of 0.2723 liters/kWh, reflecting full dependence on diesel fuel. Integrating solar power into the Scenario 2 system reduces fuel consumption to 9,605,950 liters per year and lowers the SFC to 0.2620 liters/kWh, representing a 3.78% reduction compared to the conventional system. The best performance is achieved by the Scenario 3 configuration, with fuel consumption further reduced to 9,525,741 liters per year and an SFC of 0.2595 liters/kWh, equivalent to a 4.70% reduction. These results indicate that the addition of battery energy storage improves diesel generator efficiency by optimizing solar energy utilization and reducing generator operation under partial-load conditions.

Summary of the Economic Performance Comparison

The economic analysis in Table 5, indicates that the Scenario 1 exhibits the lowest economic performance, with a Net Present Cost (NPC) of USD 83.72 million, an annual operating cost of USD 8.30 million, and an LCOE of USD 0.2317/kWh, primarily due to its full dependence on diesel fuel. The integration of solar PV (Solar PV) in the Scenario 2 configuration improves economic performance by reducing the NPC by 2.30%, operating cost by 3.25%, and LCOE by 2.50%, mainly as a result of decreased diesel fuel consumption.

Table 5. Economic Performance Comparison

Economic Parameter	Scenario 1	Scenario 2	Scenario 3	Unit
Net Present Cost (NPC)	83,724,682.65	81,797,265.00	80,950,526.93	USD
NPC Reduction vs. Diesel Power Plant	–	1,927,417.65	2,774,155.72	USD
NPC Reduction	–	2.3	3.31	%
Annual Operating Cost	8,298,566.07	8,028,572.97	7,901,682.45	USD/year
Operating Cost Savings	–	269,993.10	396,883.62	USD/year
Operating Cost Reduction	–	3.25	4.78	%
Levelized Cost of Energy (LCOE)	0.2317	0.2259	0.2234	USD/kWh
LCOE Reduction vs. Diesel Power Plant	–	0.0058	0.0083	USD/kWh
LCOE Reduction	–	2.5	3.58	%
Simple Payback Period	–	2.71	2.91	Years

Source: Data by researcher

The Scenario 3 system delivers the best economic performance, achieving reductions of 3.31% in NPC, 4.78% in operating cost, and 3.58% in LCOE compared to the Scenario 1. In

addition, this configuration offers a short payback period of approximately 2.9 years, indicating strong investment feasibility. Overall, while PV integration alone improves the economic performance of diesel-based generation, the addition of BESS provides the most significant economic benefits, making the Scenario 3 configuration the most cost-effective and sustainable option for long-term deployment in island-based power systems.

Summary of the Reliability Performance Comparison and Environmental Impact Analysis

The analysis Table 6, indicates a consistent improvement in system reliability from the Scenario 1 to the Scenario 2 and further to the Scenario 3 configuration.

Table 6. Reliability Performance Comparison

Reliability Parameter	Scenario 1	Scenario 2	Scenario 3
Excess Electricity (kWh/year)	0	15,828	1,726
Excess Electricity (%)	0	0.0431	0.0047
Unmet Electric Load (kWh/year)	216,737	140,436	111,770
Unmet Electric Load (%)	0.589	0.382	0.304
Capacity Shortage (kWh/year)	464,554	403,334	214,404
Capacity Shortage (%)	1.26	1.1	0.583

Source: Data by researcher

The Scenario 1 produces no excess electricity, but still experiences relatively high unmet load and capacity shortage, particularly during peak load conditions, indicating limitations in effective generation capacity. The integration of PV in the Scenario 2 reduces unmet load and capacity shortage; however, a small amount of excess electricity appears due to limited operational flexibility in the absence of energy storage. The Scenario 3 configuration delivers the best reliability performance, with the lowest levels of excess electricity, unmet load, and capacity shortage. This highlights the critical role of BESS in enhancing operational flexibility by storing surplus energy and supplying power when demand increases, resulting in a more reliable and stable system for long-term operation.

Table 7. Environmental Impact Analysis

Parameter	Scenario 1	Scenario 2	Scenario 3
CO ₂ Emissions (kg/year)	26,472,420	25,520,813	25,305,365
Emission Reduction vs. Diesel Power Plant (kg/year)	–	951,607	1,167,055
Emission Reduction (%)	–	3.59	4.41

Source: Data by researcher

The environmental impact analysis in Table. 7, shows that CO₂ emissions decrease progressively with the integration of PV and BESS into the diesel-based power system. The Scenario 1 records the highest CO₂ emissions due to its full reliance on diesel fuel. The integration of PV in the Scenario 2 significantly reduces CO₂ emissions by lowering fossil fuel consumption. The Scenario 3 system achieves the largest emission reduction, demonstrating that BESS optimizes solar energy utilization and reduces diesel generator operation under partial-load conditions. Overall, the Scenario 3 configuration is identified as the most

environmentally friendly option, aligning well with the transition toward a more sustainable and low-carbon power system.

CONCLUSION

From the perspective of energy efficiency, the conventional diesel power plant (Diesel Power Plant) exhibits the lowest performance, as all electrical energy demand is supplied solely by diesel generators. The integration of solar photovoltaic (PV) generation in the 6 MW Diesel Power Plant–Solar PV system improves energy efficiency, as indicated by a 3.78% reduction in Specific Fuel Consumption (SFC). Furthermore, the addition of a Battery Energy Storage System (BESS) in the Diesel Power Plant–Solar PV–BESS configuration enhances efficiency even further, achieving a 4.70% reduction in SFC compared to the conventional Diesel Power Plant system.

From an economic standpoint, the Diesel Power Plant–Solar PV system demonstrates improved performance, with a 2.30% reduction in Net Present Cost (NPC), a 3.25%

reduction in annual operating cost, and a 2.50% reduction in Levelized Cost of Energy (LCOE). The best economic performance is achieved by the Diesel Power Plant–Solar PV–BESS system, which records reductions of 3.31% in NPC, 4.78% in operating cost, and 3.58% in LCOE compared to the conventional Diesel Power Plant system. These results indicate that the combination of PV and BESS provides the most optimal cost efficiency over the long term.

In terms of reliability, the integration of PV generation reduces the occurrence of energy supply shortages compared to the conventional Diesel Power Plant system, although excess electricity still occurs due to limited operational flexibility. The addition of BESS provides the most significant improvement in system reliability, as indicated by a reduction in unmet load from 0.589% to 0.304% and a reduction in capacity shortage from 1.26% to 0.583%, resulting in a more stable and reliable power supply.

From an environmental perspective, the integration of PV reduces carbon dioxide (CO₂) emissions by 3.59%, while the combined PV–BESS system further increases emission reductions to 4.41% compared to the conventional Diesel Power Plant system.

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