Design and Optimization of Hybrid Power Plants (Solar PV and Diesel Generators) for Remote Areas in the UID Kalselteng Region: A Case Study of Kerasian Island

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Abstract. This study investigates the operational performance and economic feasibility of a hybrid renewable energy system implemented on Kerasian Island, located in Kotabaru Regency, a remote off-grid area. The system integrates photovoltaic (PV) panels, a battery energy storage system (BESS), and a diesel generator (DG). Using HOMER Pro software, six different scenarios were analyzed to optimize the PV panel size and battery storage capacity, with the objective of minimizing the levelized cost of electricity (LCOE) while ensuring the system meets the required energy demand. The results demonstrate that the hybrid system, with PV panels accounting for 90,6% of the daily energy consumption, yields the lowest LCOE of Rp 3.522,21 per kWh. Compared to a diesel-only system, the hybrid configuration significantly reduces CO_2 emissions, thereby decreasing dependency on fossil fuels. While the initial investment in battery storage is relatively high, the hybrid system proves to be cost-effective in the long term, providing reductions in operational costs and diesel consumption. The PV-BESS-DG system represents a sustainable and economically viable energy solution for off-grid regions, with the potential for considerable reductions in CO_2 emissions.

Keywords: *hybrid energy system, off-grid areas, levelized cost of energy (lcoe), co_2 emissions, renewable energy, homer pro.*

1 Introduction

Indonesia, as the largest archipelagic nation in the world with more than 17.000 islands, faces considerable challenges in ensuring equitable and sustainable access to electricity, especially in its remote areas. Numerous regions, particularly those categorized as frontier, outermost, and underdeveloped, continue to experience inconsistent and unreliable electricity supply. The deployment of renewable energy technologies, such as Solar Photovoltaic (PV) systems, wind energy, micro-hydro power, and wave energy, offers significant potential for addressing the energy needs of these regions, taking into account the unique geographical conditions and natural resources present in each area.

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South and Central Kalimantan, in particular, exhibit substantial potential for renewable energy, especially solar power, due to the region's abundant sunlight. Hybrid power generation systems, which combine Solar PV with diesel power plants, offer a promising solution to ensure a reliable 24 hour electricity supply in remote areas. These hybrid systems can provide a stable energy flow while enhancing both economic and operational efficiency, particularly in regions with limited access to the electrical grid.

In line with Indonesia's National Energy Policy [1] and National Energy Plan [2], the country aims to achieve a 23% share of renewable energy in the national energy mix by 2025 and 31% by 2050. One key strategy to achieve these goals is the Green Booster program [3], implemented by PT Perusahaan Listrik Negara (PLN), which focuses on replacing isolated diesel power plants with solar energy systems. [3] in South Kalimantan has been identified as a promising candidate for this transition, given its significant solar energy potential. The integration of Solar PV to replace the existing diesel power plant is expected to reduce electricity costs, lower greenhouse gas emissions, and improve the reliability of the electricity supply.

Currently, Kerasian Island relies on a diesel-powered electricity system with an installed capacity of 448 kW and an available capacity of 325 kW, which operates only 12 hours per day [4]. The transition to Solar PV is expected to provide continuous 24 hour electricity service, contributing to both environmental sustainability and a reduction in carbon emissions. This study aims to design a hybrid power generation system for Kerasian Island that optimizes solar energy production while utilizing the diesel power plant as a backup during periods when solar energy generation is insufficient.

The integration of hybrid systems presents an effective solution for remote islands facing challenges in energy access. Previous studies have highlighted the benefits of hybrid systems in reducing operational costs and minimizing environmental impact. However, the application of this technology in regions with unique conditions requires a thorough understanding of local geography, energy demand, and existing infrastructure. Therefore, this research seeks to design a hybrid energy system tailored to the specific characteristics of Kerasian Island, with an emphasis on sustainability, cost-effectiveness, and environmental impact. Through this case study, the research will assess how the combination of Solar PV and diesel power plants can ensure a stable and sustainable energy supply, while supporting Indonesia's energy development goals in remote and underserved regions.

2 Methodology

This section outlines the methodology employed in selecting the study area, assessing the availability of renewable energy resources, and estimating the energy demand based on the minimum required load for the region. These aspects are elaborated upon in the following subsections.

2.1 Area Selection

Kerasian Island, located in Kotabaru Regency, is classified as a remote area with electricity supplied only for 12 hours a day, typically from 6:00 PM to 6:00 AM. The majority of the population in this village resides in coastal areas. Supplying energy to these regions is challenging, making the expansion of the electricity grid an infeasible solution. The availability of renewable energy sources, such as solar, wind, and wave energy, is abundant in this study area, and all of these sources are utilized in an off-grid mode.

2.2 Energy Demand estimation

The energy demand in the study area is projected to grow by 1% annually, indicating a consistent increase in energy consumption over time. To account for this potential growth, an estimation of the electrical energy required to support this rise has been conducted.

Primary data was collected through field surveys, which tracked a 24 hour power generation operational pattern. The surveys covered various load categories, including those from the local community. The primary energy demand is largely driven by lighting needs for essential facilities such as health centers, schools, retail establishments, street lighting, water pumping systems, and small industrial activities.

The results of the analysis estimate the total daily energy demand for the area at 2.750 kWh, with a peak load of 138 kW. This estimation is based on observed energy consumption patterns, which include lighting, clean water supply, and commercial and small-scale industrial operations. The findings provide a comprehensive understanding of the area’s energy requirements, essential for ensuring a reliable electricity supply moving forward.

2.3 Source Estimation

The daily solar radiation data for the study area is presented in **Figure 1** [5]. The peak solar radiation was observed in September, reaching 6,480 kWh/m²/day, while the minimum was recorded in January at 4,710 kWh/m²/day. After calculating the monthly averages over the course of the study period, the annual mean solar radiation was determined to be 5,43 kWh/m²/day.

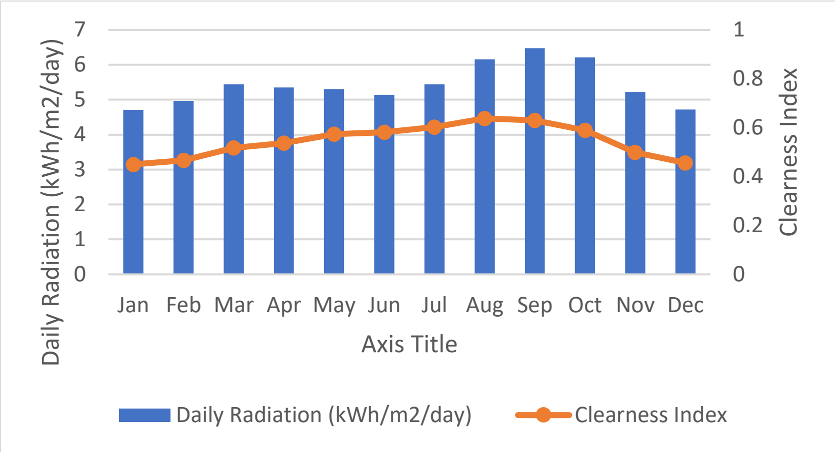

Figure 1 Monthly solar radiation available

3 System Construction and Modeling of System Components

The proposed Hybrid Renewable Energy System (HRES) integrates several key components: Photovoltaic (PV) panels, a Diesel Generator (DG), a battery bank, and a bidirectional inverter. These components work together to ensure a continuous and reliable energy supply, effectively meeting the energy demands of the remote area. The system optimizes the interaction between solar energy, stored energy, and backup power, ensuring efficient operation to meet fluctuating energy demands while maintaining a stable power supply, as illustrated in **Figure 2**.

Having outlined the overall system architecture, the next crucial step is to model the behavior of each individual component. This process is essential for understanding how each component contributes to the overall system's performance. Such modeling plays a vital role in optimizing both the design and operation of the system. The following sections present the mathematical models for each component of the Hybrid Renewable Energy System, including the necessary formulations and their practical applications.

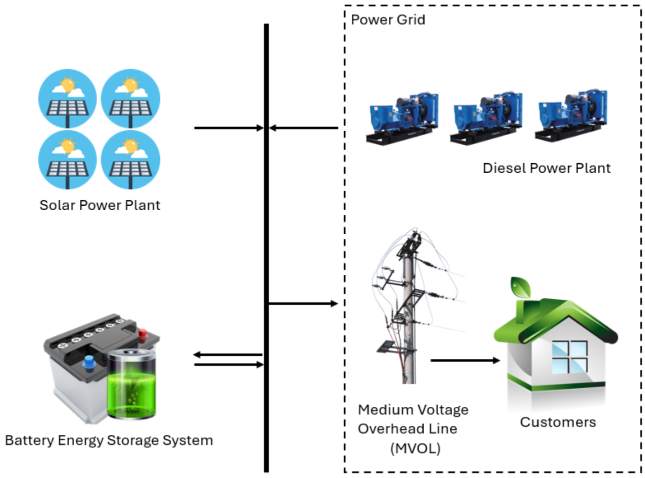

Figure 2 Configuration of the Hybrid Power Generation System (Diesel Power Plant and Photovoltaic Solar Power System)

3.1 PV System

Accurate system design requires hourly solar radiation data, which was obtained for a horizontal surface, while the photovoltaic (PV) panels are inclined to optimize sun exposure. The power generated by the PV panels is calculated using Eq. (1) [6] :

$$P_{PV} = Y_{PV} \times f_{PV} \times \left(\frac{\bar{G}_T}{\bar{G}_{T,STC}}\right)\left[1 + \alpha_P\left(T_C - T_{C,STC}\right)\right] \tag{1}$$

Where P_{PV} represents the power output from the PV panel, Y_{PV} is the rated power under standard conditions, f_{PV} is the derating factor of the PV system, $\bar{G}_T$ is the solar radiation incident on the PV panels, $\bar{G}_{T,STC}$ is the reference solar radiation, which equals 1000 W/m². Additionally, $\alpha_P$is the temperature coefficient of PV Panels, T_C denotes the actual temperature of the PV cells, and $T_{C,STC}$ cell temperature at reference conditions and it equals to 25 ^{0}C.

The rated power of the photovoltaic (PV) system can be calculated using the following Eq. (2) [6] :

$$P_{PV} = \frac{E_L \times SF}{\eta_{system} \times PSH} \tag{2}$$

Where E_L represents the daily load energy, SF is the stacking factor used to account for resistive losses and temperature effects on the photovoltaic (PV) system, η_{system} refers to the efficiencies of the charge regulator and the bidirectional inverter, and PSH stands for the peak sunshine hours, which is numerically equivalent to the daily average solar radiation at the specified location [7].

3.2 Battery Energy Storage System

The capacity of the battery is primarily determined by the energy required to meet the load during the day and the duration for which the battery must supply this load in the absence of solar radiation. The number of days the battery bank is designed to supply the load is referred to as the autonomy period, and this factor is incorporated into the design process. The storage capacity of the battery is calculated using Eq. (3) and Eq. (4) [6] :

$$E_{total} = N_{batt} \times V_{nom} \times Q_{nom} \tag{3}$$

$$A_{batt} = \frac{N_{batt} \times V_{nom} \times Q_{nom} \times \left(1 - \frac{q_{min}}{100}\right) \times \eta_{system} \times 24}{L_{prim,ave} \times 1000} \tag{4}$$

Where E_{total} denotes the total energy provided by the battery, N_{batt} represents the number of batteries, V_{nom} is the nominal voltage of each battery, Q_{nom} refers to the nominal capacity of the battery, A_{batt} indicates the battery storage capacity in hours. Additionally, q_{min} represents the minimum depth of discharge for the battery, η_{system} refers to the efficiency of the energy storage system, and, $L_{prim,ave}$ is the average daily primary load demand.

3.3 Converter

In the calculation of converter capacity, which includes both the inverter and rectifier, the capacity is calculated using the following mathematical Eq (5) [6] :

$$P_{inverter} = \frac{P_{load}}{\eta_{inverter}} \tag{5}$$

Where $P_{inverter}$ represents the power required by the inverter, P_{load} refers to the power needed by the load, and $\eta_{inverter}$ denotes the efficiency of the inverter.

3.4 Economical modelling

Various financial indices can be utilized to provide financial metrics for comparing different projects[8]. In this study, the economic evaluation is carried out using life-cycle costing, which takes into account several factors, including the costs of components, installation, fuel and operating expenses, maintenance, replacement, the time value of money, economic variables, and the salvage value of components that will be replaced. The primary comparison indicator is the cost of energy production, specifically the levelized cost of electricity (LCOE), which represents the cost of generating one kilowatt-hour (kWh) of energy.

For any project undergoing economic analysis, a life-cycle period is determined based on the component with the longest expected lifetime. In this case, the lifespan of the photovoltaic (PV) panels is considered to be 20 years. The operational hours of the diesel generator dictate its lifetime, which is dependent on the manufacturer's specifications. For the battery, the life-cycle duration is influenced by the number of charge/discharge cycles and the depth of discharge.

4 Simulation and power management

For a multi-source energy system, an effective energy management strategy is crucial for the efficient operation of power generation units. In this study, two main energy management strategies are employed: load-following and cycle-charging. In the load-following scenario, the diesel generator operates to match the primary load demand, while in the cycle-charging scenario, the diesel generator runs at full capacity each time it is activated. The hybrid system performs energy balance calculations on an hourly basis throughout the entire year. The simulation assumes uninterrupted power supply, ensuring that the system's reliability remains at 100%. This simulation software allows for the modification of various variables and parameters within the hybrid system, with the primary goal of identifying the optimal configuration that meets load demands efficiently while minimizing operational costs.

4.1 Energy Management Strategy

In this study, the energy management strategy prioritizes meeting the load demand with renewable energy generated by the Photovoltaic (PV) panels and the battery bank. When the energy provided by these two sources is insufficient, the diesel generator will be activated to supplement the required power supply. The decision to operate the diesel generator, as well as to charge or discharge the battery bank, is made on an hourly basis, based on the energy balance calculated for each period. The energy management strategy employed in this study involves several scenarios with varying proportions of renewable energy, namely 25%, 50%, 75%, 90%, and 100% of the total daily electricity demand.

4.2 Data and Simulation Program Inputs

The daily average solar irradiation in South Kalimantan, measured on a horizontal surface, varies between 4,710 kWh/m²/day to 6,480 kWh/m²/day. The study focuses on Kerasian Island, situated at a latitude of -4,027° N and longitude of 116,203° E. Hourly data over the course of a year were utilized for this analysis.

The inputs for the simulation model include solar radiation data, load profiles, component efficiencies, costs for various system components, and other relevant economic parameters. The data utilized in this research are summarized in Table 1. The prices for most of these components, including PV modules, battery bank, charge controller, and bidirectional inverter, were sourced from IRENA [9] and the operational data reports of PT PLN (Persero) UP3 Kotabaru [4].

Table 1 Input Data for Simulation in HOMER PRO Software

System Parameters	Input Data	Value	Unit
Generator Diesel 1 & 2	Capital Cost	0	IDR/100 kW
	Replacement Cost	900.000.000,00	IDR/100 kW
	O&M cost	95.000	IDR/Day
	Fuel Type	Diesel Oil/B30	
	Fuel Curve Slope	0,3440 and 0,3420	L/day/kW
	Fuel Price	11.195	IDR/L
	Minimum Load Ratio	50	%
	Minimun Runtime	0	minutes
	Lifetime	15.000	hours
PV	Capital Cost	8.910.000,00	Rp/kW
	Replacement Cost	8.910.000,00	Rp/kW
	O&M cost	145.000	Rp/year
	Panel Type	Longi Solar Technology	
	Lifetime	20	Years
	Derating Factor	80	%
Baterai 6 V 167 Ah	Capital Cost	3.250.000,00	IDR/kW
	Replacement Cost	3.250.000,00	IDR/kW
	O&M cost	327	IDR/year
	String Size	8	
	Initial SoC	100	%
	Minimum SoC	20	%
	Lifetime	5	Years
Inverter	Capital Cost	Rp136,283,400.00	IDR/200 kW
	Replacement Cost	Rp136,283,400.00	IDR/200 kW
	O&M cost	Rp13,080,000.00	IDR/year
	Lifetime	10	Years
	Efiiciency	97,6	%
	Discount Rate	6,25	%
	Inflation Rate	2,84	%
Economics	Project Lifetime	20	Years
	System Fixed Capital Cost	4.500.000.000,00	IDR
Electric Load	Total Load	2.750	kWh/Day

Constraints	Maximum Annual Capacity Shortage Annual Peak Load	5 1	% %

5 Result and Discussion

The simulation was conducted to analyze the performance of the hybrid power generation system under various scenarios, aiming to optimize two key parameters: the size of the photovoltaic (PV) panels and battery capacity, in order to minimize the Levelized Cost Of Energy Generation (LCOE) while ensuring load demand fulfillment. Six scenarios were tested, involving the operation of the Diesel Power Plant (DPP) with an optimized daily schedule, maintaining a minimum load ratio of 50% for both DPP 1 and DPP 2. In subsequent scenarios, the system was supplemented with PV and battery storage, providing 25%, 50%, 75%, and 90% of the total annual energy demand, respectively. In the final scenario (System 6), the PV and battery systems were designed to cover 100% of the total annual energy demand.

5.1 Result of the main scenario

The primary scenario examined in this study involves a hybrid system combining photovoltaic (PV) panels, a battery bank, and a diesel generator. The simulation results indicate that the lowest Levelized Cost of Energy (LCOE) of Rp 3.522,21/kWh is achieved when the PV system contributes 90,6% of the total energy, with an autonomy of 0,82 days. Table 2 presents a comparative analysis of the HOMER simulation results for various PV-diesel hybrid configurations, showcasing the performance and economic feasibility of different system setups.

A similar study conducted by [10] which utilized HOMER software for a larger load, identified that the optimal scenario involved the use of a diesel generator. The hybrid system in that study, like in this research, consisted of PV panels, a battery bank, and a diesel generator. A significant difference in the results stemmed from the higher cost of PV panels used in the Malaysian study (5,6$/Wp), compared to the lower costs observed in the current study. Another study by [11] also using HOMER software for a case study in Jordan, produced findings similar to this research. In Hrayshat's study, the hybrid system comprised PV panels, a battery bank, and a diesel generator, with a comparable optimal scenario and an LCOE of 0,297$/kWh.

In the optimal scenario of this study, where PV contributes 90,6% of the total energy and autonomy is 0,82 days, **Figure 3** hows the distribution of initial costs across various components of the hybrid system. It is evident that the largest share of the total system cost is attributed to the initial investment and installation of

Table 2 Comparison of HOMER Simulation Results for Various PV-Diesel Hybrid Systems

Parameter	**System 1**	**System 2**	**System 3**	**System 4**	**System 5**	**System 6**
System Capacity						
PV (kW)	-	168	344	516	688	745
Diesel (kW)	200	200	100	100	100	(Diesel Off)
Inverter (kW)	-	200	200	200	200	200
Battery 6V/167Ah (units)	-	688	1.376	2.064	2.752	8280
Dispatch	LF	CC	CC	LF	LF	CC
Initial capital (IDR)	4.500.000.000	8.369.163.400	12.173.323.400	15.941.843.400	19.710.363.400	38.184.790.275
Operating cost (IDR)	6.735.900.000	4.760.193.000	3.828.809.000	2.992.940.000	2.132.057.000	4.197.636.000
NPC (IDR)	101.848.500.000	77.164.378.039	67.507.991.671	58.184.725.696	50.523.249.901	98.849.823.490
COE (IDR)	7.023,19	5.319,34	4.722,09	4.011,40	3.522,21	7.033,23
Annual Operational Analysis						
Diesel energy (kWh)	1.010.381	783.248	530.309	271.475	111.179	-
Diesel fuel (Liters)	390.427	290.258	197.796	105.932	42.218	-
Diesel fuel cost (IDR)	63.168.015.665	46.961.439.882	32.001.856.732	17.138.955.832	6.830.488.709	-
Diesel O&M cost (IDR)	21.643.308.440	11.298.729.615	8.972.929.574	7.623.167.083	3.700.481.475	-
CO_2 emission (kg)	1.021.193	759.192	517.352	277.073	110.424	0
PV energy (kWh)	-	261.301	564.855	802.567	1.070.090	1.158.843
RE fraction (%)	0	25	50,2	74,7	90.6	100
Baterai autonomy (Day)	-	4,8	9,61	14,4	19.2	57,8
Excess electricity (kWh)	6.952	290	28.437	14.330	117.814	108.020
Excess electricity (%)	0.688	0,0277	2,67	1,33	9,97	9,32
Economic Metric						
IRR (%)	-	53	40	36	32	-
ROI (%)	-	46	33	28	25	-
Simple Payback (Year)	-	1,7	2,2	2,4	2,7	-

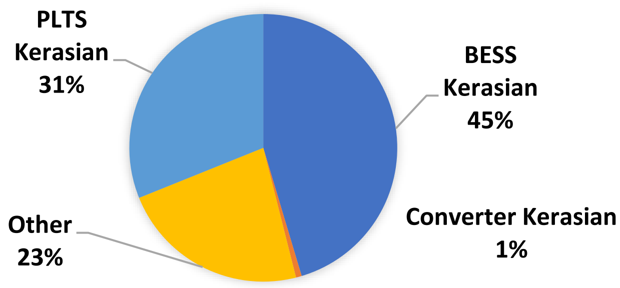

Figure 3 Percentage of initial cost of components of the hybrid system

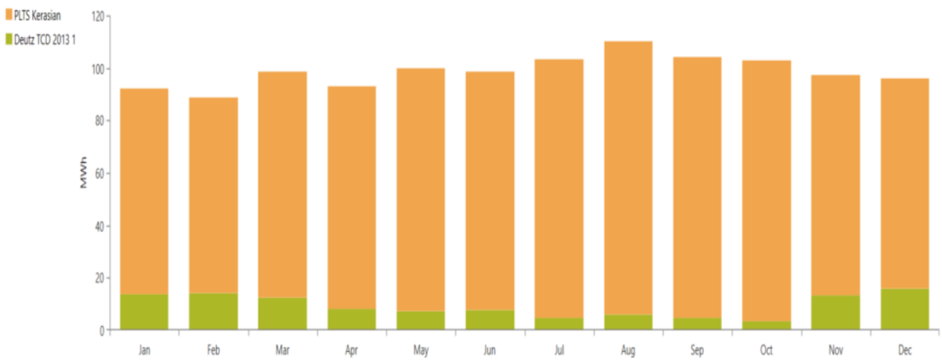

Figure 4 Energy contributions from the photovoltaic (PV) panels and diesel generator for each month of the year.

the battery energy storage system. **Figure 4** illustrates the monthly energy contributions from the PV panels and diesel generator in meeting the energy demand throughout the year. During months with higher PV energy generation, the diesel generator's contribution is notably reduced.

In the optimal scenario, the energy generation from the photovoltaic (PV) panels and the diesel generator, as well as the state of charge of the Battery Energy Storage System (BESS) and the energy discharged to the system, are depicted in **Figures 5, 6 , 7 and 8**. **Figure 6** shows that the diesel generator operates with the lowest energy supply in September. During this month, the energy generated by the PV system peaks (as shown in **Figure 4**), which is sufficient to meet the load demand and charge the BESS. Additionally, **Figure 1** demonstrates that the average daily solar radiation in September is at its highest, contributing to the optimal charge level of the BESS.

In contrast, **Figure 6** reveals that the diesel generator operates more frequently in December, providing a significantly higher total energy output. During this period, the energy produced by the PV system is at its lowest, resulting in a reduced rate of charging for the BESS. In both September and December, as well as in other months, some energy is discharged, primarily due to energy losses within the BESS and the overall electrical system.

A comprehensive summary of this optimal scenario is presented in Table 1, which details the CO_2 emissions generated. This estimation assumes that each liter of diesel fuel consumed by the internal combustion engine produces approximately 2,4 to 2,7 kg of CO_2 [12].

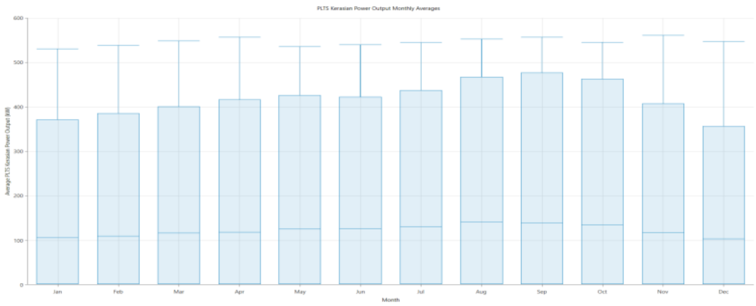

Figure 5 Monthly Average Energy Contributions from Photovoltaic (PV) Panels

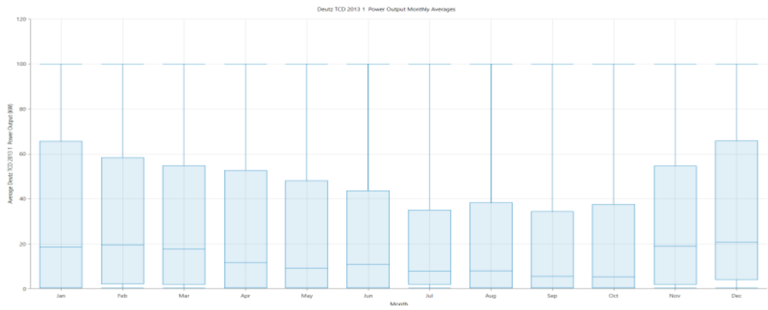

Figure 6 Monthly Average Energy Contributions from Diesel Generator

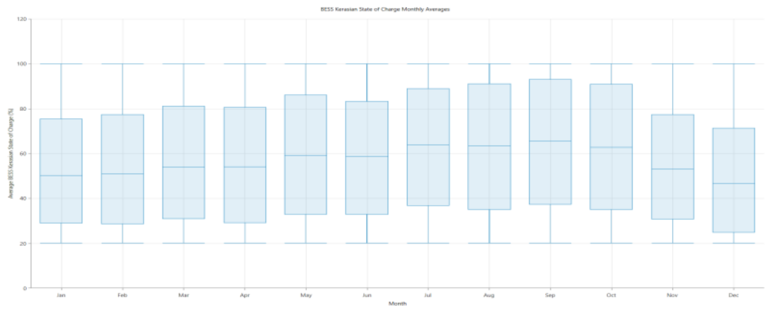

Figure 7 Monthly Average State of Charge of the BESS on Kerasian Island

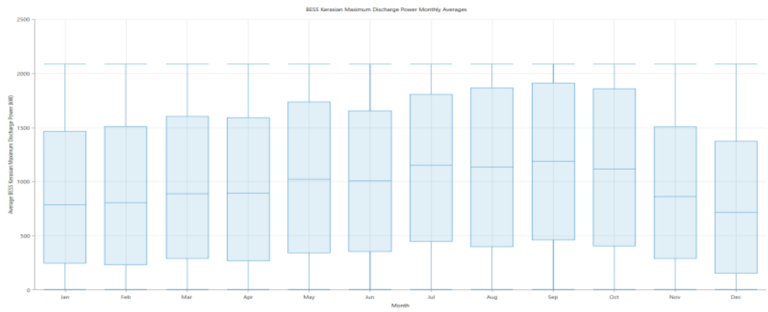

Figure 8 Monthly Average Maximum Discharge Power of the BESS

5.2 Result of the main scenario

In addition to the main scenario, several other scenarios were also analyzed. For the standalone PV system (without the diesel generator), the Levelized Cost of Energy (LCOE) was found to be Rp 7.033,13/kWh. In this scenario, the PV capacity is 745 kW, with an autonomy days of 2,41 days, and a battery capacity of 8.280 kWh. This configuration does not produce CO_2 emissions.

Another scenario considers only the diesel generator. In this case, the LCOE was found to be Rp 7.023,19/kWh, with two diesel generators operating 24 hours each. The annual CO_2 emissions from this scenario reach 1.021.193 kg/year.

The results indicate that the most economical scenario is the hybrid system consisting of PV panels, a battery bank, and a diesel generator.

5.3 Sensitivity analysis

In the sensitivity analysis, the impact of changes in several input parameters was examined to assess their effects on the overall system specifications. The simulation results indicate that the Levelized Cost of Energy (LCOE) is most sensitive to variations in capital costs, discount rate, and project lifespan. Further analysis reveals that LCOE is more significantly influenced by changes in the discount rate than by variations in diesel prices. A higher discount rate makes the renewable energy system less financially attractive. Regarding project lifespan, the analysis shows that a shorter project lifetime results in a higher and more sensitive LCOE, whereas a longer project lifespan leads to the LCOE being primarily influenced by the replacement costs of key components. Additionally, the configuration of the hybrid system—such as PV contribution, battery autonomy, and diesel generator operating hours—varies with the changes in these parameters [13].

6 Conclusions

This study analyzed six different scenarios, with the most cost-effective configuration being a hybrid system that integrates photovoltaic (PV) panels, a battery energy storage system (BESS), and a diesel generator. In this optimal scenario, the Levelized Cost of Energy (LCOE) is Rp 3.522,21 per kWh, with the PV panels meeting 90,6% of the total daily energy demand, and the BESS providing an autonomy of 0,82 days. The other two scenarios investigated resulted in higher LCOE values.

Regarding CO_2 emissions, the hybrid system consisting of PV panels, BESS, and a diesel generator was found to emit less CO_2 compared to the diesel-only scenario. This highlights the environmental benefit of integrating renewable energy sources. Furthermore, in remote areas that are far from the grid, as well as in situations where environmental concerns are a priority, the hybrid system proves to be a more feasible option. The optimal energy mix is achieved when the PV contribution reaches 90,`6% of the total daily energy demand.

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