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Techno-economic and Environmental Analysis of Hybrid Energy System (HES) in an Isolated Area

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Abstract

This study aims to identify the most efficient hybrid energy system configuration from a techno-economic and environmental perspective in an isolated area. The existing system of electrification in remote areas that still rely on diesel power plants incurs high operational costs and produces significant carbon emissions. As a solution, a Hybrid Energy System (HES) integrating solar power plants, diesel power plants, and battery energy storage systems (BESS). The study analyzes the HES configuration on Kodingareng Island using HOMER Pro software. The parameter configuration includes 2024 electricity demand, technical specifications from power plant nameplates, diesel power plant-related data, and market-based estimates for other components. Simulation results show that the optimized system achieves a Net Present Cost (NPC) that is IDR 6.76 billion lower than the existing system, with the difference increasing to IDR 8.5 billion when emission penalties are considered. The Levelized Cost of Energy (LCOE) for the optimized system is IDR 322.23/kWh lower than the existing configuration, and with emission penalties, the savings increase to IDR 405.77/kWh. These findings highlight the potential of HES to reduce costs and emissions in the electrification of remote islands.

1. Introduction

Access to electricity is one of the key factors in improving the quality of life in communities. According to Indonesia's Ministry of Energy and Mineral Resources, the national electrification ratio in the first quarter of 2024 reached 99.81% and is projected to increase to 99.83% by 2025 [1]. This achievement shows the government's success in providing all Indonesians with access to electricity. However, providing affordable, environmentally friendly electricity remains a challenge. Indonesia is one of the world's largest archipelagos, and some remote areas still rely on diesel-powered plants (PLTD), intensifying the country's dependence on fossil fuels. Dependence on these plants often results in challenges related to high operational costs, particularly due to the transportation of fuel to hard-to-reach locations and logistical disruptions that cause instability in the electricity supply.

Indonesia's Golden Vision 2045 aims to achieve a developed and sustainable nation status, with the energy transition from fossil fuels to renewable energy sources (RES), such as solar and wind, serving as a core pillar. National targets stipulate a 23% share of RES in the energy mix by 2025 and 31% by 2050; however, as of September 2024, the share stood at only 13.93%, with fossil fuels comprising over 80%, primarily coal [2].

Despite an estimated RES potential of 443 GW, with 208 GW from solar alone, only about 0.04% of solar potential has been exploited [3].

Integrating renewable energy into the power system poses challenges due to the intermittent nature of sources such as solar and wind. For instance, electricity generation from solar power plants is highly dependent on sunlight intensity and weather conditions, with production peaking on clear days and declining at night or under cloudy skies. These fluctuations can threaten power supply stability if not supported by adequate energy storage systems or complementary energy sources.

One of the most effective solutions to address greenhouse gas emissions and integrate renewable energy is to implement a Hybrid Energy System (HES). An example of HES in an isolated area can be found on Kodingareng Island, South Sulawesi, Indonesia, where it primarily utilizes diesel generators and solar panels for its electrical generation, as well as a Battery Energy Storage System (BESS).

Previous research has explored the techno-economic analysis of hybrid energy systems in isolated areas. Khalil et al. [4] Designed a hybrid system for a coastal area in Baluchistan using HOMER Pro, integrating a diesel generator, wind turbine, PV array, and converter to minimize costs, with results covering power generation, emissions, NPC, and average electricity cost. Riayatsyah et al. [5] evaluated hybrid renewable–diesel systems for remote islands electrified after the 2004 tsunami, highlighting Indonesia's underutilized solar potential and showing that solar integration can significantly reduce fuel consumption despite high initial investment costs. Idris et al. [6] compared two hybrid system scenarios for a residential area to assess energy production and cost per kWh. Azman and Sulistiawan [7] Proposed a solar–diesel–battery hybrid system for Legundi Island, achieving nearly 80% renewable fraction and significant diesel savings. These studies underscore the importance of hybrid systems and inform the present work's focus on optimizing hybrid solutions for isolated regions.

Based on the background and recent studies, the existing HES configuration on Kodingareng Island is analyzed using HOMER Pro to evaluate economic and environmental aspects. The economic analysis focuses on NPC and COE, while the environmental analysis measures reductions in carbon emissions through the REF. The results aim to determine the optimal operating pattern for the HES configuration, ultimately providing practical solutions for similar systems in other remote areas of Indonesia.

2. Research Methodology

2. 1. Location Specification

Kodingareng Lompo, commonly known as Kodingareng Island, is in the waters of the Makassar Strait. Administratively, the island falls under Kodingareng Subdistrict, Sangkarrang Islands District, Makassar City, South Sulawesi, Indonesia. The island is situated at coordinates 5°8′54.000″S, 19°15′53.000″E.



FIGURE 1. Satellite image of Kodingareng Island

2. 2. Simulation Method

Simulations are carried out using HOMER Pro software, using both primary and secondary data on electricity generation on Kodingareng Island. The primary data includes the total load demand in 2024, specifications of the island's power plants obtained from PLN UP3 South Makassar and PLN Nusantara Power, and climatology data from NASA [8]. The secondary data were derived from literature reviews and previous studies.

The simulation process for Kodingareng Island begins by gathering load profile data, which serves as the basis for modeling. Two scenarios are evaluated: the existing and optimized configurations, both of which include a Solar Power Plant (PLTS), a Diesel Power Plant (PLTD), and a Battery Energy Storage System (BESS). Each scenario is characterized by its chosen components and input parameters, such as solar irradiance and diesel fuel consumption. Using HOMER Pro software, simulations are run to analyze system performance. The results are then compared using key indicators such as Net Present Cost (NPC), Levelized Cost of Energy (LCOE), Renewable Energy Fraction (REF), and greenhouse gas emissions, to identify the most efficient hybrid energy system configuration for the island.

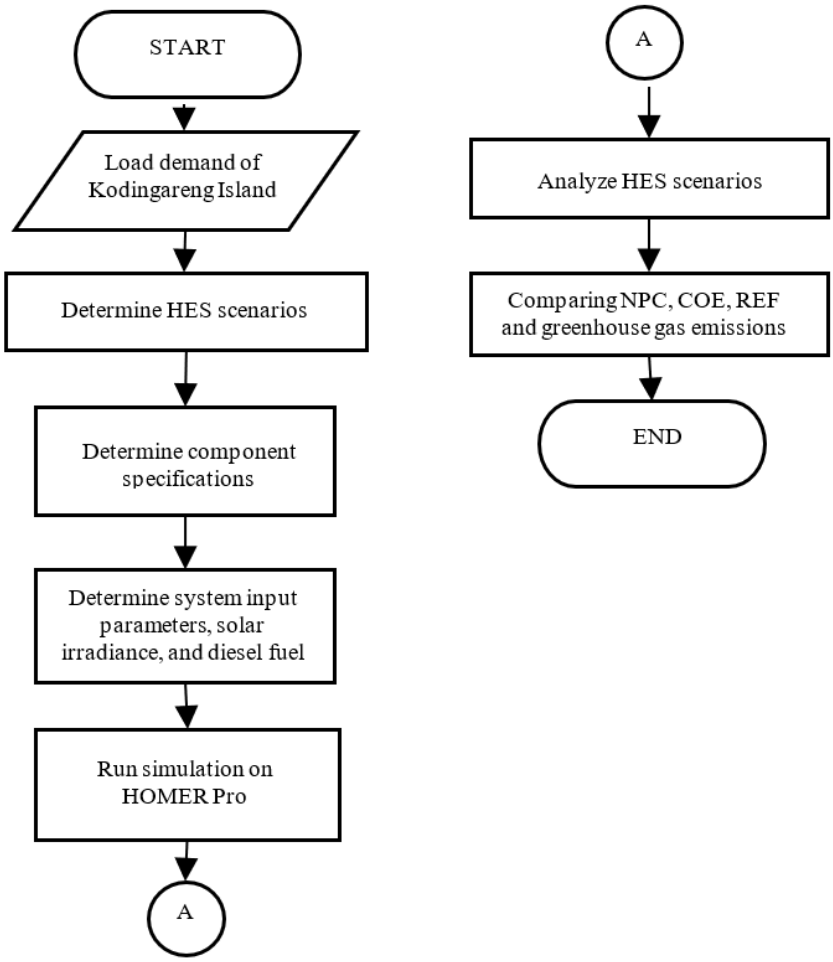


FIGURE 2. Methodology flowchart

2. 3. Hybrid Energy System Design

All simulation scenarios will follow the same design, as shown in Figure 3.

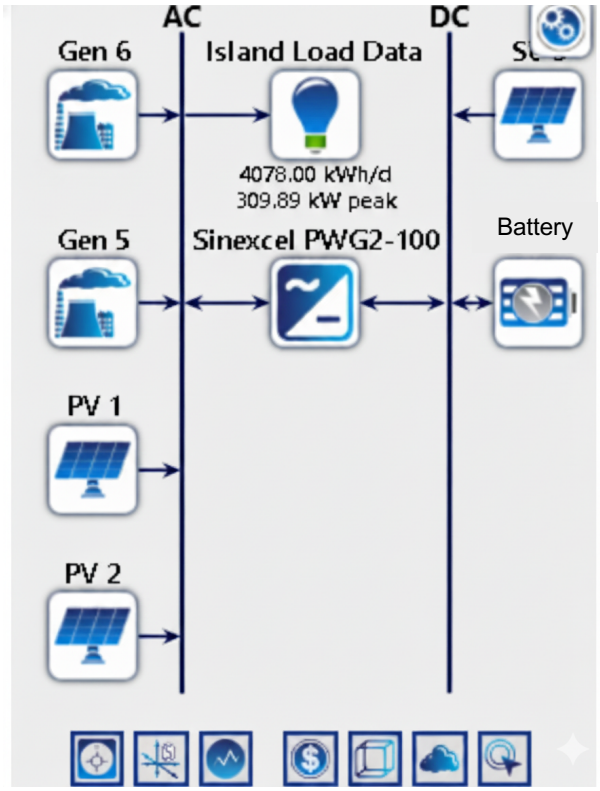


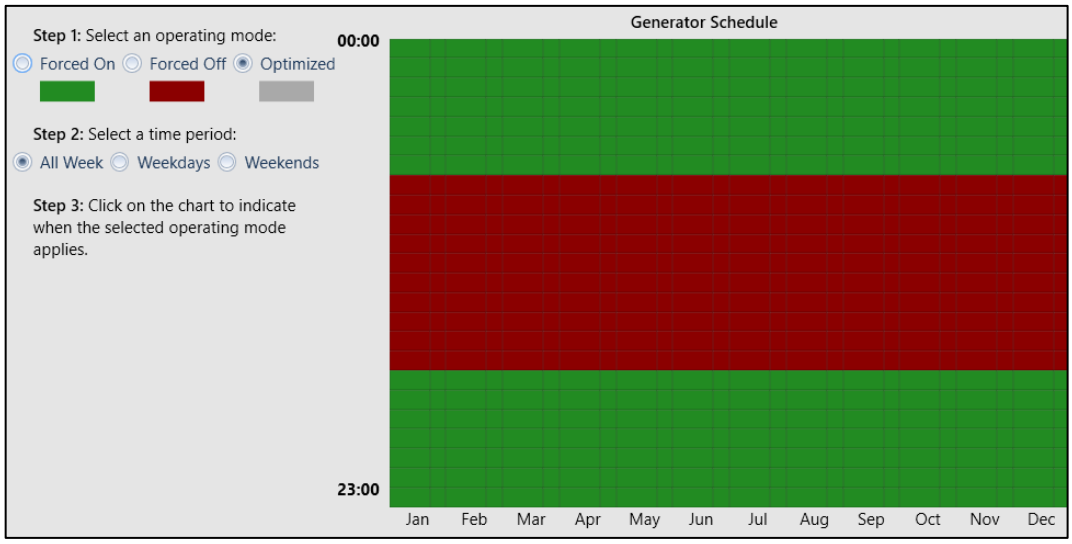
FIGURE 3. Simulation Diagram for Hybrid Energy System

In HOMER Pro, the simulation consists of PLTD, PLTS, and BESS based on Kodingareng Island's load profile. The PLTD comprises two generators, namely Generator 5 (Stamford) and Generator 6 (AGG). The PLTS and BESS include three PV arrays (PV 1, PV 2, PV 3), a Sinexcel PWG2-100K-EX bidirectional inverter, and Shoto GFX 2250 batteries. PV 1 and PV 2 are equipped with 100 kW and 60 kW on-grid inverters each, supplying power directly to the AC grid and loads, represented in HOMER Pro through dedicated PV converters. PV 3 connects to the AC grid via the bidirectional inverter. The PV arrays use iSolar panels for PV 1 (12 strings, 216 modules) and PV 2 (21 strings, 378 modules), while PV 3 uses Sankelux panels (66 modules).

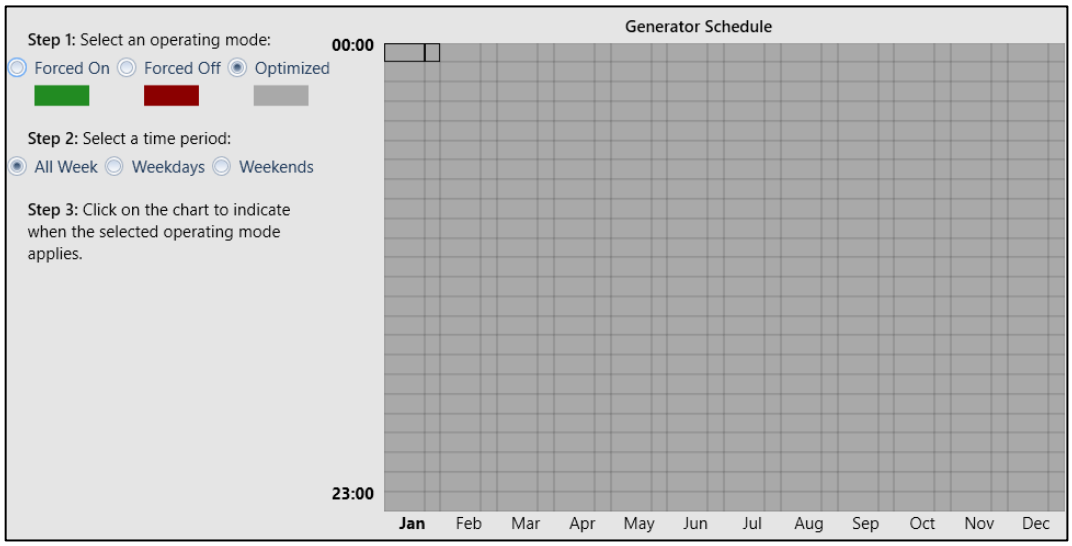
2. 4. Simulation Scenarios

The existing scenario refers to the current schedule on Kodingareng Island, where the PLTD operates from 5:00 PM to 6:00 AM. Meanwhile, in the optimized scenario, HOMER Pro will assign the system's operation schedule to achieve the best results.

The operational schedule for each scenario can be seen in Figure 4



(a)



(b)

FIGURE 4. Operational Schedule of Diesel Power Plant (a) Existing Scenario and (b) Optimized Scenario

2. 5. Component Specification

Technical and economic specifications were used as input parameters in the HOMER Pro software for each power generation component. The technical specifications were the nameplate data of each element, while the economic specifications were categorized into capital cost, replacement cost, and operation and maintenance (O&M) cost. For PLTD, fuel prices (IDR/L) were also included.

In calculating O&M costs for PLTD, the O&M value per hour was derived from the local BPP (Basic Cost of Electricity Supply) of IDR 4,263/kWh, which includes fuel and O&M costs. First, the generator's average Specific Fuel Consumption (SFC) (L/kWh) was multiplied by the fuel price per liter to obtain the fuel cost per kWh. This value was then subtracted from the BPP to estimate the O&M cost per kWh, which was multiplied by the generator's hourly energy production to obtain the O&M cost in IDR/hour. For the solar PV system,

O&M costs were assumed at 2% of CAPEX for PV modules and 1% of CAPEX for the inverter and batteries, each calculated in IDR/year.

The components' specifications are presented in Table 1, where the economic data are given on a per-module basis rather than for the total quantity used.

TABLE 1. Component Specifications

Components	**Specifications**	
	Solar Panel	
iSOLAR 190 W	Capital Cost	IDR 4,000,000
	Replacement Cost	IDR 4,000,000
	O&M Cost	IDR 80,000/year
SANKELUX 390 W	Capital Cost	IDR 3,300,000
	Replacement Cost	IDR 3,300,000
	O&M Cost	IDR 66,000/year
	Inverter	
Huawei SUN2000 60KTL-M0 60 kW	Capital Cost	IDR 103,971,000
	Replacement Cost	IDR 77,978,250
	O&M Cost	IDR 1,039,710/year
Huawei SUN2000 100KTL-M1 100 kW	Capital Cost	IDR 170,809,500
	Replacement Cost	IDR 128,107,125
	O&M Cost	IDR 1,708,095/year
Sinexcel PWG2 100K-EX 100 kW	Capital Cost	IDR 720,000,000
	Replacement Cost	IDR 540,000,000
	O&M Cost	IDR 7,200,000/year
	Diesel Generator	
Stamford (Generator 5) 200 kW/250 kVA	Capital Cost	IDR 281,541,177
	Replacement Cost	IDR 281,541,177
	O&M Cost	IDR 101,799/hour
	Fuel Price	IDR 10,600/L
	Lifetime	20,000 hours
AGG (Generator 6) 112 kW/140 kVA	Capital Cost	IDR 150,756,980
	Replacement Cost	IDR 150,756,980
	O&M Cost	IDR 112,010/hour
	Fuel Price	IDR 10,600/L
	Lifetime	15,000 hours

TABLE 1. Continued

Components	Specifications	
	Battery	
Shoto GFX-2250 2 V 2250 Ah	Capital Cost	IDR 11,000,000
	Replacement Cost	IDR 9,000,000
	O&M Cost	IDR 220,000/year
	Cell Quantity	180
	Nominal Voltage	2 V
	Maximum Charging Current	337.5 A
	Min. State of Charge (SoC)	40%
	Initial SoC	80%
	Lifetime	10 years

In the HOMER Pro simulation, 2022 was chosen as the baseline year because significant components, such as the new Huawei inverters and Sankelux PV panels, were installed during that year, representing the most recent operational configuration. A 20-year project horizon was adopted in accordance with standard techno-economic assessment practices for renewable–diesel hybrid systems to encompass complete component replacement cycles and facilitate cost comparability.

This choice ensures that technical and economic calculations reflect the most recent system configuration. Capital costs of pre-existing components were set to zero, with adjusted lifetimes based on their installation dates.

TABLE 2. Remaining Lifetime of Components

Component	Year	Remaining Lifetime
iSolar 190 W	2013	16
Sankelux 390 W	2022	25
Inverter Huawei	2022	15
Battery	2019	7
Bidirectional Inverter	2019	12

TABLE 3. Emission Penalties

Emission	Penalty
Carbon Dioxide (CO_2)	IDR 1,369,200/t (ton)
Carbon Monoxide (CO)	IDR 4,890,000/t
Sulfur Dioxide (SO_2)	IDR 42,380/t
Nitrogen Oxide (NO_x)	IDR 3,260,000/t
Particulate Matter (PM)	IDR 1,500,000,000/t
Unburned Hydrocarbon (HC)	IDR 4,890,000/t

The project lifetime was defined as 20 years, with nominal discount and inflation rates of 9.22% and 5.51% [10-11], resulting in a real discount rate of 3.52% that will be used to calculate economic parameters. Following [12-15]The emission penalties are presented in Table 3.

3. Results and Discussion

3. 1. Existing Scenario

Based on the simulation results for the existing scenario, the total electricity production is 1,520,049 kWh/year, with an REF of 10,4%.

Production	kWh/yr	%
iSOLAR 190 W	99,617	6.55
iSOLAR 190 W (1)	54,078	3.56
SANKELUX 390 W	33,864	2.23
PLTD 6	572,320	37.6
PLTD 5	761,170	50.0
Total	1,521,049	100

Consumption	kWh/yr	%
AC Primary Load	1,487,549	100
DC Primary Load	0	0
Deferrable Load	0	0
Total	1,487,549	100

Quantity	kWh/yr	%
Excess Electricity	7,553	0.497
Unmet Electric Load	921	0.0619
Capacity Shortage	1,117	0.0750

Quantity	Value	Units
Renewable Fraction	10.4	%
Max. Renew. Penetration	178	%

FIGURE 5. Electrical Simulation Results (Existing Scenario)

Total NPC:	IDR 82,050,010,000.00
Levelized COE:	IDR 3,886.68
Operating Cost:	IDR 5,746,935,000.00

(a)

Total NPC:	IDR 107,213,800,000.00
Levelized COE:	IDR 5,078.67
Operating Cost:	IDR 7,520,091,000.00

(b)

FIGURE 6. Economic Simulation Results (Existing Scenario), (a) Without Emission Penalty and (b) With Emission Penalty

Quantity	Value	Units
Carbon Dioxide	1,072,078	kg/yr
Carbon Monoxide	2,742	kg/yr
Unburned Hydrocarbons	81.4	kg/yr
Particulate Matter	194	kg/yr
Sulfur Dioxide	2,374	kg/yr
Nitrogen Oxides	145	kg/yr

FIGURE 7. Emission Simulation Results (Existing Scenario)

3. 2. Optimized Scenario

Production	kWh/yr	%
iSOLAR 190 W	99,617	6.49
iSOLAR 190 W (1)	54,078	3.52
SANKELUX 390 W	33,864	2.20
PLTD 6	327,708	21.3
PLTD 5	1,020,688	66.5
Total	1,535,955	100

Consumption	kWh/yr	%
AC Primary Load	1,488,470	100
DC Primary Load	0	0
Deferrable Load	0	0
Total	1,488,470	100

Quantity	kWh/yr	%
Excess Electricity	231	0.0150
Unmet Electric Load	0	0
Capacity Shortage	0	0

Quantity	Value	Units
Renewable Fraction	9.40	%
Max. Renew. Penetration	178	%

FIGURE 8. Electrical Simulation Results (Optimized Scenario)

Total NPC:	IDR 75,294,270,000.00
Levelized COE:	IDR 3,564.45
Operating Cost:	IDR 5,270,895,000.00

(a)

Total NPC:	IDR 98,708,950,000.00
Levelized COE:	IDR 4,672.91
Operating Cost:	IDR 6,920,801,000.00

(b)

FIGURE 9. Economic Simulation Results (Optimized Scenario), (a) Without Emission Penalty and (b) With Emission Penalty

Quantity	Value	Units
Carbon Dioxide	995,551	kg/yr
Carbon Monoxide	2,542	kg/yr
Unburned Hydrocarbons	75.6	kg/yr
Particulate Matter	182	kg/yr
Sulfur Dioxide	2,201	kg/yr
Nitrogen Oxides	135	kg/yr

FIGURE 10. Emission Simulation Results (Optimized Scenario)

TABLE 4. Comparison of Economic Parameters of Each Scenario

Scenario	Economic Parameters	
Existing	NPC	IDR 82,050,020,000 IDR 107,213,800,000 (penalty)
	LCOE	IDR 3,886,68 IDR 5,078,68 (penalty)
	Operating Cost	IDR 5,746,936,000 IDR 7,520,092,000 (penalty)
Optimized	NPC	IDR 75,294,280,000 IDR 98,708,960,000 (penalty)
	LCOE	IDR 3,564,45 IDR 4,672,91 (penalty)
	Operating Cost	IDR 5,270,896,000 IDR 6,920,802,000 (penalty)

Based on the simulation results for the optimized scenario, the total electricity production is 1.535.955 kWh/year, with an REF of 9,4%. These results confirm that the optimized configuration achieves improved performance primarily through enhanced generator scheduling, which keeps the generator closer to its optimal load, reducing fuel consumption and O&M costs. Meanwhile, PV and BESS units are prioritized for daytime

and transition periods, thereby lowering diesel dependency. The renewable fraction decreases slightly due to load balancing.

The results indicate that the optimized system achieves an NPC reduction of IDR 6.76 billion compared to the existing system, increasing to IDR 8.5 billion when emission penalties are included. Similarly, the optimized scenario shows a lower LCOE of IDR 3,564.45/kWh, saving IDR 322.23/kWh over the existing system. With emission penalties, the cost advantage grows to IDR 405.77/kWh, confirming the optimized system's economic benefit. The system achieves higher overall efficiency, translating to lower NPC and LCOE values.

From the environmental perspective, Figures 7 and 10 show a significant reduction in greenhouse gas emissions in the optimization scenario compared to the existing system. This indicates that the optimized system is more cost-effective in the long term and environmentally friendly due to its lower emissions.

4. Conclusion

The economic and environmental aspects were analyzed by comparing two system scenarios: the existing and the optimization scenarios. The optimization scenario resulted in lower NPC (IDR 75.29 billion) and LCOE (IDR 3,564.45/kWh) than the existing system. Including emission penalties further increased the cost gap, with the optimized system saving IDR 8.5 billion in NPC and IDR 405.77/kWh in LCOE. These results confirm the economic advantage of the optimized HES system. The optimal operating pattern configuration was analyzed by focusing on the diesel power plant settings, given that this component has a dominant influence on operational costs and greenhouse gas emissions in the system. Generator 5 is prioritized at full capacity during nighttime loads, with Generator 6 used only for battery charging or peak demand support. The system maximizes battery utilization before engaging Generator 6, while PV and BESS adapt to the load profile. This strategy improves overall efficiency and reduces operational costs and emissions.

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Data Availability Statement

The data that support the findings of this study are available from the corresponding author upon reasonable request.

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