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Research Article

Decarbonization of Isolated Power Systems through the Use of PV, BESS, and Hydrogen

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Abstract

The isolated electrical system on Gili Ketapang Island, East Java, which is entirely dependent on a diesel power plant (Installed Capacity: 2x525 kW), faces four pressing issues: (1) High Production Cost (BPP) due to 100% dependence on imported fuel oil (BBM), (2) Risk of power deficit and N-1 failure after adding 144 kVA customers, (3) Significant CO_2 emissions, and (4) Extreme fuel supply logistics risk, involving five manual stages and prone to marine pollution. This case study aims to design a phased dedieselization strategy to transform the Gili Ketapang PLTD into a 100% green, reliable, and zero-emission energy system. The proposed solution is the implementation of a PV-BESS -Hydrogen hybrid system through three stages: Stage 1: 170 kW/800 kWh Battery Energy Storage System (BESS) for peak shaving and efficiency optimization; Stage 2: Integration of Hydrogen Fuel Cells to substitute fuel and verify safe H_2 logistics; and Stage 3: Full integration of PV-BESS-Hydrogen to completely eliminate fuel. The urgent recommendation is to accelerate the installation of BESS to immediately address the potential power deficit of 88 kW (night peak load of 558 kW) and optimize the operation of existing engines, making it a green mini-grid model that is ready for replication.

Keywords: Decarbonization, Isolated System, PLTD, PV BESS, Hydrogen, Net Zero Emission.

INTRODUCTION

PT PLN (Persero) has committed to achieving Net Zero Emissions (NZE) by 2060

(PLN, 2021). This scenario includes thirteen key initiatives, with the conversion of Diesel Power Plants (PLTD) to Renewable Energy (RE) being a primary short-term focus, as PLTDs still contribute 28.82% of Indonesia's total power generation mix (PLN, 2021). In addition, PLN is actively developing a Green Hydrogen (H_2) ecosystem as a zero-emission solution for the future.

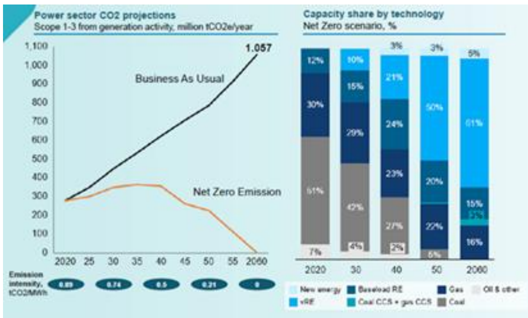

Figure 1. Scenario for PLN to achieve NZE 2060

The Gili Ketapang Diesel Power Plant (PLTD) under UP3 Pasuruan is an isolated power system serving 1,898 customers with continuous 24-hour operation. The plant has an installed capacity of 2 × 525 kW and an available supply of 2 × 470 kW. This system faces four critical challenges that require immediate resolution:

1. Risk of Power Deficit and N-1 Failure: The current nighttime peak load reaches 464 kW (October 2024), with a waiting list of customers demanding approximately 144 kVA. After connection, the projected peak load will increase to 558 kW. Following the N-1 reliability principle, sufficient reserve capacity must be available in case one unit fails or undergoes maintenance. If one generator goes offline, the system will face an 88 kW power deficit (558 kW – 470 kW), threatening reliability and potentially causing rolling blackouts.
2. High Financial Burden of Generation Costs (BPP): Total dependence on imported diesel fuel results in significantly higher production costs compared to grid-connected systems. Additionally, operating engines at partial loads—well below their optimal efficiency point (around 80–90% of full load)—increases Specific Fuel Consumption (SFC) and worsens financial losses.
3. Environmental Impact: Continuous fossil fuel combustion generates CO_2 emissions, contradicting the Net Zero Emission (NZE) target and directly degrading local air quality.

4. Severe Logistical Risks: The diesel fuel supply chain involves five complex and manual transfer stages—from depot to warehouse, to drums, to boats, and finally to carts. This process carries high risks of fuel loss, leakage, and uncontrolled environmental incidents, especially when fuel drums must be dropped into the sea during low tide.

This case study aims to design a phased and sustainable decarbonization model using Photovoltaic (PV), Battery Energy Storage Systems (BESS), and Hydrogen technologies to permanently resolve these challenges.

METHOD

This study employs a case study methodology using a combined qualitative and quantitative staged approach to formulate an optimal decarbonization model for isolated power systems. The research was conducted on Gili Ketapang Island, East Java, during the period of October to November 2025.

Figure 2. Gili Ketapang Diesel Power Plant Electrical System

Literature Review and Data Collection

This stage establishes both the theoretical framework and empirical data foundations:

1. Literature Review: Covers PLN's NZE initiatives (PLN, 2021), the concept of Dedieselization (Burguillo-Cuesta et al., 2011; Winanti et al., 2024), and the integration of Battery Energy Storage Systems (BESS) for optimizing diesel power plant operations through peak shaving (Branco et al., 2018; Matragi, 2025; Sebastián, 2016).
2. Primary Operational Data: Involves collecting technical and operational data from PLTD Gili Ketapang, including engine capacity, available power supply of 940 kW,

current peak nighttime load of 464 kW, 3.2 km of medium-voltage distribution lines, and generation performance indicators (monthly production, fuel consumption, and Specific Fuel Consumption/SFC).

Benchmarking and Field Observation

1. Technology Benchmarking: Comparative studies were conducted on similar projects, focusing on the performance of Fuel Cell Generators and hydrogen distribution systems already tested at other PLN sites. This benchmarking is essential to design a safe and efficient hydrogen transport model for Gili Ketapang.
2. Critical Logistics Observation: Direct field observations were carried out to document in detail the five stages of the diesel fuel supply chain, which form the primary justification for transitioning to safer energy sources. The physical condition of the PLTD site and the available 1,920 m² of land were also assessed to determine suitable locations for the BESS installation and PV potential.

Figure 3. Hydrogen Distribution to Gili Ketapang Diesel Power Plant

Design of a Phased Decarbonization Model

The design of the proposed solution model is based on calculations aimed at addressing the projected nighttime peak load of 558 kW following the addition of 144 kVA of new customer demand.

Table 1. Stages of Implementation of Hybrid EBT Solutions for Gili Ketapang

Stage	Key Technologies	Key Capacity	Main Focus	Quantitative Targets
1	BESS	170 kW /	Operational	Overcoming power deficit

	(Storage)	800 kWh	Optimization and Short-Term Reliability	(88 kW); Increasing fuel efficiency (10-15% savings).
2	*Fuel Cell* H2	Partial	Energy Substitution & H2 Logistics Verification	Reduction of fuel consumption (30-40%); Elimination of solar logistics risks.
3	PV-BESS-Hydrogen	Full	Total Elimination & GREEN 100%	Zero Fuel; Zero Emissions; 24/7 Reliability.

RESULT AND DISCUSSION

Power Demand and N-1 Risk Analysis (Stage 1 Justification)

Existing Condition (Night Peak Load ≈ 464 kW):

Although the total available supply capacity is 940 kW, both generators often need to operate simultaneously to handle load fluctuations and maintain reliability. However, this results in low-load operation (around 53%), which is highly inefficient and increases Specific Fuel Consumption (SFC).

Estimated Condition (After Adding 144 kVA of New Customers):

1. Estimated Night Peak Load: 558 kW
2. Required BESS Capacity (N-1 Deficit): The deficit between the estimated peak load and the supply capacity of one generator unit:
3. Required BESS Power = 558 kW – 470 kW = 88 kW

This 88 kW deficit represents a critical point that must be addressed. A conventional solution, such as adding another diesel generator, would contradict PLN's Net Zero Emission (NZE) goals. Therefore, the installation of a 170 kW / 800 kWh BESS is proposed as a non-fossil alternative to cover the N-1 reserve requirement and eliminate the need for new diesel capacity investment.

Stage 1: Implementation of BESS for Peak Shaving and Efficiency

The integration of a 170 kW BESS serves as a strategic peak shaving solution:

1. Improving PLTD Efficiency:

   The BESS will supply the portion of the load exceeding 470 kW, allowing a single diesel generator to operate steadily at full efficiency. Operating near full load optimizes the engine's heat rate, potentially reducing fuel consumption by 10–15% (Chua et al., 2016; Martins et al., 2018; Sebastián et al., 2013).

2. Accommodating New Customers:

   The BESS effectively provides the additional 88 kW needed, enabling all pending customer connections (144 kVA) to be served without risking N-1 outages.

3. Risk Mitigation:

   The BESS ensures sufficient buffer time to plan and implement Stages 2 and 3, while enhancing system resilience against single-unit failures.

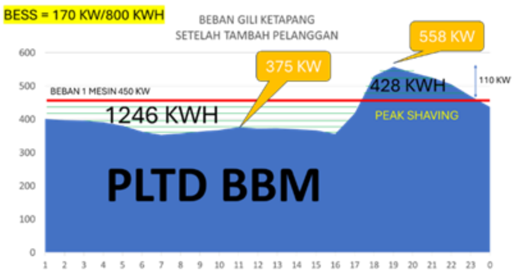

Figure 4. Estimated Load Curve of Gili Ketapang after adding customers

Figure 5. BESS at the Gili Ketapang PLTD

Stage 2: Partial Dedieselization Using Hydrogen

Stage 2 focuses on energy substitution through the installation of a Hydrogen Fuel Cell system powered by Green Hydrogen.

Figure 6. Hydrogen Fuel Cell Operation

The introduction of the Fuel Cell system provides two major benefits:

1. Fuel and Emission Reduction: The Fuel Cell generates electricity with zero emissions, directly replacing part of the diesel generator's function and contributing to emission reduction targets. The projected reduction in fuel consumption at this stage is 30–40%.
2. Verification of Safer Hydrogen Logistics: This stage serves as a pilot project for hydrogen logistics to an isolated island. Unlike the multi-stage and risk-prone diesel supply chain—susceptible to leakage, loss, and contamination—the transport of compressed hydrogen cylinders offers a cleaner, safer, and more controllable alternative. This step is a crucial prerequisite for the full-scale implementation in Stage 3.

Stage 3: Full Integration of PV–BESS–Hydrogen (100% GREEN)

The final stage involves the complete replacement of diesel generators, achieving 100% green electrification.

1. 24/7 Hybrid System: The total hybrid system capacity is designed to independently meet the maximum nighttime peak load of 558 kW.
   a. Photovoltaic (PV): Acts as the primary daytime energy source. A detailed feasibility study will determine the optimal PV capacity, considering the limited available land area (1,920 m²), which may require floating PV or rooftop PV solutions.
   b. Battery Energy Storage System (BESS): Provides short-term grid stability and stores excess PV energy.
   c. Hydrogen Fuel Cell: Functions as a reliable baseload and backup power source during nighttime or cloudy conditions.
2. Long-Term Reliability: The integration resolves PV intermittency and fuel dependency, creating a more resilient and reliable power system. The technical feasibility is supported by a similar 24/7 hybrid system in Chiang Mai, Thailand, successfully operating for over 10 years (Kabir et al., 2023).
3. Total Risk Elimination: Achieving Stage 3 ensures zero fossil fuel use and zero emissions, permanently eliminating the financial risks associated with high diesel production costs (BPP) and environmental, health, and safety hazards from fuel logistics.

Long-Term Financial Implications

Although the renewable hybrid system (PV–BESS–H_2) requires high initial capital investment (CAPEX), the exceptionally high generation cost (BPP) of the current isolated system justifies the transition. In the long run, the elimination of 100% fuel costs (OPEX), stabilized energy pricing, and achievement of national climate commitments will result in significant net operational savings and sustainable strategic benefits for PLN and Indonesia.

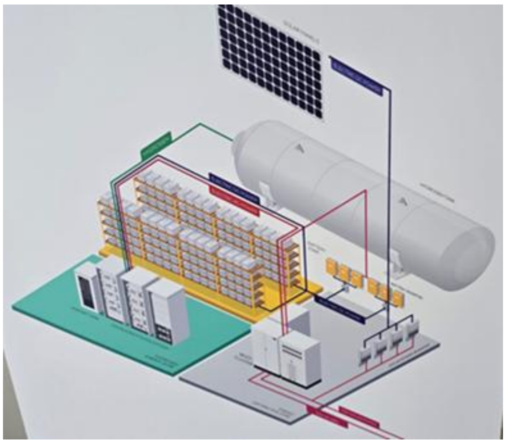

Figure 7. Hydrogen PV BESS Integration

Figure 8. Hydrogen Storage

Figure 9. Electrolyzer

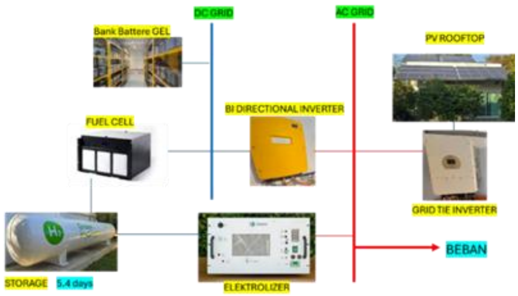

Figure 9. PV BESS Hydrogen Combination

Table 2. Main Component Functions of the Hydrogen PV BESS Hybrid System

Components	Main Function
PV Panels (Solar Panels)	Generates DC electricity from solar energy.
Batteries (BESS)	Stores short-term excess power and balances daily loads.
Electrolyzers	Converts excess electricity from PV into hydrogen (H_2) and oxygen (O_2) gas through water electrolysis.
H_2 Storage Tanks	Store H_2 gas under high pressure for long-term use (seasonal storage).
Fuel Cells	Converts stored hydrogen back into DC electricity and heat, especially at night or on cloudy days.

Table 3. Advantages of Each Hydrogen PV BESS Hybrid System Technology

Time	Process	The Role of Technology
Daytime	PV panels generate electricity. The electricity is used to power household loads, charge batteries, and excess power is fed to an electrolyzer.	PV (Production), Batteries, Electrolyzers (Conversion to H_2 for Long-Term Storage).
Nighttime	When the PV panels are not producing electricity, electricity is drawn from the batteries and fuel cells.	Batteries (Handling rapid demand surges), Fuel Cells (Providing long-term baseload power by converting H_2 back into electricity and water).

CONCLUSION

The Gili Ketapang decarbonization project represents a strategic transformation that turns operational challenges—such as power deficits and extreme fuel logistics risks—into an opportunity to lead Indonesia's clean energy transition. The phased PV–BESS–Hydrogen model provides a comprehensive solution:

1. Ensuring reliability by addressing the 88 kW deficit and accommodating new

customers through BESS peak shaving (Stage 1);

2. Reducing high generation costs and emissions through partial hydrogen-based dedieselization (Stage 2); and
3. Achieving 100% GREEN electrification by eliminating fossil fuel dependence and environmental risks linked to diesel logistics (Stage 3).

Recommendations

1. Prioritize and Accelerate BESS Implementation: Install a 170 kW / 800 kWh BESS immediately to resolve the projected power deficit and improve diesel efficiency.
2. Hydrogen Logistics Feasibility Study: Conduct an in-depth technical and financial assessment of the hydrogen supply chain and storage to ensure its cost per kWh is more competitive than diesel.
3. PV Land Optimization: Explore innovative PV solutions such as floating or rooftop PV to overcome the limited 1,920 m² area of the existing PLTD site.
4. Development of Local Renewable Sources: In the long term, integrate potential wind and tidal energy resources around the Madura–Probolinggo region into a larger mini-grid system.

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