



## Optimizing Renewable Energy Integration in the 3T Region: The Impact of Hybridization of PLTS-PLTD in Maratua on Emissions and Costs

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### ABSTRACT

#### Keywords:

hybrid PV system;  
Maratua Island;  
renewable energy;  
energy storage system;  
levelized cost of  
electricity; CO<sub>2</sub>  
emissions

*Maratua Island in East Kalimantan is exploring the adoption of hybrid solar photovoltaic (PV) systems to support Indonesia's goal of achieving net zero emissions (NZE) by 2060. The island has long depended on diesel power plants (PLTD), resulting in high carbon emissions and operational costs. This study assesses the technical and operational feasibility of integrating a 300 kWp PV system with the existing diesel generator. The research employs a quantitative case study design using HOMER Pro simulation software to model hybrid system performance under tropical island conditions. Simulations using HOMER Pro show that the hybrid system significantly improves efficiency. The diesel generator, which currently consumes around 500 liters of fuel daily for a peak load of 499 kW, will reduce fuel consumption by over 70%, dropping to about 150 liters per day. CO<sub>2</sub> emissions will also decrease from 1,446 tons/year to 0,425 tons/year. Additionally, the levelized cost of electricity (LCOE) decreases from IDR 5,500/kWh to IDR 3,200/kWh. These findings suggest that hybrid PV systems are a cost-effective and sustainable energy solution for remote island regions, reducing fossil fuel reliance and carbon emissions. The study's methodology and findings offer replicable frameworks for other frontier, outermost, and disadvantaged (3T) regions across Indonesia, contributing to national energy transition policies and supporting evidence-based planning for renewable energy deployment in similar geographical contexts.*

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## INTRODUCTION

Indonesia, as an archipelagic country with more than 17,000 islands, faces major challenges in providing reliable, sustainable, and affordable electrical energy, especially in the 3T (Frontier, Outermost, and Disadvantaged) regions (Kusuma et al., 2021; Widodo & Nugroho, 2020). Efforts to realize national energy security and independence have become an important focus in Indonesia's development policies, especially in the context of the transition to clean and sustainable energy (Bappenas, 2020; Astuti & Hidayat, 2021). In the National Energy General Plan (RUEN), the government targets a significant increase in the mix of new and renewable energy (NRE) to support the achievement of Net Zero Emission (NZE) by 2060 (Yulianto et al., 2020; Sulisty, 2021). One of the main challenges in achieving this target lies in the provision of energy in archipelagic and remote areas that have been dependent on Diesel Power Plants (PLTD) as the main source of electricity (Nugroho & Pratama, 2021; Suryanto et al., 2020).

Equitable access to energy is a major challenge in the development of the energy sector in Indonesia, especially in the frontier, outermost, and disadvantaged (3T) regions (Prasetyanto et al., 2025; Saputra et al., 2025; Sipayung et al., 2024; Sutrisno et al., 2025; Wibowo et al., 2021). Reliance on diesel power plants (PLTD) still dominates the electricity system in these regions, although the technology is known to have high operating costs and significant carbon

emission contributions (IESR, 2021; PLN, 2023). In the context of the national energy transition and the target of a new and renewable energy (NRE) mix of 23% by 2025, the development of cleaner and more efficient energy solutions in the 3T region is very crucial (Ministry of Energy and Mineral Resources, 2020).

One of the emerging approaches to answer this challenge is the hybridization of PLTD systems with solar power plants (PLTS). This integration is expected to be able to reduce fossil fuel consumption, reduce operational costs, and reduce greenhouse gas emissions (BPSDM ESDM, 2021; Siregar et al., 2022). Maratua Island in East Kalimantan is one of the implementation locations for the PLTS-PLTD hybridization project, and represents geographical conditions and technical challenges that are common to other 3T regions (GIZ & ESDM, 2021). However, the effectiveness of hybridization of these systems still requires a thorough evaluation, especially in terms of its contribution to reducing emissions and optimizing electricity supply costs.

Based on the background description that has been submitted, this study focuses on carbon emission reduction strategies and improving energy performance in disadvantaged, frontier, and outermost (3T) areas, with Maratua Island as the study location. The focus of the analysis is directed at the evaluation of the technical performance of the integration of the hybrid system of the Solar Power Plant combined with the Battery Energy Storage System (PLTS-BESS), especially in reducing the use of fossil fuels and reducing CO<sub>2</sub> emissions. In addition, this study examines the potential reduction in electricity cost of production (BPP) resulting from the implementation of the hybrid system when compared to the Diesel Power Plant (PLTD) system which is still the backbone of electricity supply today.

In line with the focus of these problems, this study aims to carry out techno-economic optimization of the electricity system of Maratua Island in order to identify the most efficient and sustainable configuration of the PLTS-BESS hybrid system. The economic feasibility analysis is carried out by considering the main financial indicators, namely the payback period and Net Present Cost (NPC), as the basis for assessing the sustainability of investment. Through this approach, the research is expected to be able to produce system recommendations that not only support the reduction of emissions and dependence on fossil energy, but also be able to improve operational cost efficiency in the long term, making it relevant for the development of clean energy systems in the 3T region.

The development of hybrid energy systems in off-grid areas, especially the archipelago, is theoretically based on the concept of energy system optimization. This approach emphasizes designing an energy system that is able to reduce total costs throughout the system lifecycle while still ensuring the fulfillment of load needs and reliability of the electricity supply. Within this framework, optimization does not solely focus on the initial investment costs, but also includes the cost of operation and maintenance, fuel consumption, emissions generated, as well as the technical life of each component of the energy system used (Olympios et al., 2025).

One of the key concepts in energy system optimization is least-cost energy planning, which is a strategy to select a combination of power generation technologies that are able to produce the lowest Levelized Cost of Electricity (LCOE) without sacrificing system reliability. In remote areas that still rely on Diesel Power Plants (PLTD), high fuel prices and supply instability make pure diesel-based systems economically less profitable in the long run. Therefore, the merger of Solar Power Plants (PLTS) with Battery Energy Storage Systems

(BESS) is seen as a rational solution to reduce the marginal cost of electricity production through reducing fossil fuel consumption and increasing the use of renewable energy (Nurjaman & Purnama, 2022).

In the configuration of the PLTS–PLTD–BESS hybrid system, the existence of BESS has a strategic role as a balancing element of the system. Conceptually, BESS allows for higher penetration of solar energy without lowering the reliability level of the power supply. The excess energy generated by solar PV during periods of high radiation intensity can be stored and then released again when solar production decreases or the load increases. This mechanism reduces the need to operate PLTD under inefficient partial load conditions, resulting in a direct impact on reducing fuel consumption, emissions, and overall system operating costs (Hamzah & Saini, 2020). Furthermore, from the perspective of the energy transition framework, hybrid energy systems are positioned as a bridging technology that bridges the transition from fossil-based energy systems to low-carbon energy systems.

This approach is particularly relevant for regions that are not technically or economically feasible for the full application of renewable energy. The International Energy Agency (IEA) emphasizes that the implementation of hybrid systems on off-grid networks is a realistic transitional step to gradually reduce emissions, while maintaining the resilience and reliability of energy supply at the local level (IEA, 2021). Thus, the implementation of the PLTS–PLTD–BESS hybrid system on Maratua Island can not only be seen as a short-term technical solution, but also as a concrete application of the principles of energy system optimization, lowest cost-based planning, and conceptually established energy transition strategies. This framework of thought is the main foundation for interpreting the simulation results and explaining the reasons why certain system configurations are able to provide optimal performance, both from an economic and environmental perspective.

Despite numerous studies on renewable energy hybridization globally, limited research has specifically addressed the techno-economic optimization of PLTS-PLTD-BESS systems in tropical archipelagic contexts with small-scale isolated grids. Most existing studies focus on larger grid systems or different climatic conditions. This research fills that gap by providing empirical evidence from Maratua Island—a representative 3T region—demonstrating the practical viability of hybrid systems under real operational constraints including high fuel transportation costs, limited technical infrastructure, and variable load patterns typical of remote island communities.

The novelty of this study lies in its comprehensive integration of technical simulation with location-specific economic and environmental assessments. Unlike previous studies that examine hybrid systems in isolation, this research evaluates the complete lifecycle performance of the PLTS-PLTD-BESS configuration, incorporating sensitivity analyses for key variables such as fuel price volatility, battery degradation rates, and solar module performance under tropical maritime conditions. Furthermore, the study develops replicable methodological frameworks adaptable to other 3T regions, advancing both theoretical understanding and practical application of renewable energy transitions in underserved areas.

This study aims to analyze the impact of the integration of solar power in the PLTD system in Maratua on two main aspects: reducing carbon emissions and operational cost efficiency. Additionally, the study identifies optimal hybrid system configurations to support replication in other 3T regions across the Indonesian archipelago. The results of this study are

expected to contribute to the development of contextual and applicable NRE integration strategies in remote areas, strengthen the policy basis for accelerating inclusive and sustainable energy transitions in Indonesia (IESR, 2023; Ministry of National Development Planning/Bappenas, 2021), and provide technical guidelines for system operators and policymakers in similar geographical contexts.

## **METHOD**

This study uses a case study approach with a focus on the electricity system of Maratua Island as a pilot area for the implementation of a hybrid PLTS-PLTD system. The method used consists of three main stages: field data collection, technical simulation using HOMER Pro software, and environmental and economic impact analysis. Simulation Model Assumptions and Sensitivity Analysis Modeling of PLTS–PLTD–BESS hybrid energy systems in this study is prepared based on a set of technical and economic assumptions that reflect the operating conditions of off-grid electricity systems in the medium term. The use of these assumptions is a common approach applied in the study of energy system optimization, given the limited availability of long-term historical data and the high uncertainty of future energy price developments (Ortiz-pimiento & Montes-p, 2022). The main assumptions used include the price of diesel fuel of Rp13,000 per liter, the energy inflation rate of 3% per year, the technical life of the solar power plant system for 20 years with a module degradation rate of around  $\pm 0.5\%$  per year, and the technical life of the Battery Energy Storage System (BESS) for 10 years.

The values of such assumptions are conservatively established with reference to international literature and common practices widely used in the study of hybrid energy systems in remote areas. However, to ensure the reliability of the simulation results, it is necessary to analyze the extent to which changes in these key parameters affect the economic and environmental performance of the system. Therefore, this study is complemented by a qualitative and comparative sensitivity analysis of the main variables that have a significant influence on the value of Levelized Cost of Electricity (LCOE) and the level of diesel fuel consumption. Sensitivity to Diesel Fuel Prices Diesel fuel prices are the most influential variable in determining the economic feasibility of a hybrid energy system. The increase in fuel prices will directly increase the operating costs of PLTD-based systems, while the impact on hybrid systems is relatively small because some of the energy needs have been met by solar PV and BESS.

Research by Rangel et al (2023) showed that an increase in diesel prices by 20–40% was able to reduce the LCOE of hybrid systems by about 30% when compared to pure diesel systems. Thus, if the price of fuel on Maratua Island exceeds the value of the basic assumption, then the economic advantages of the hybrid system in this study will be even more prominent. Sensitivity to BESS Lifespan and Cost The determination of the technical life of the battery for 10 years has a direct implication on the amount of replacement cost in the calculation of Net Present Cost (NPC). A decrease in battery life will increase the total lifecycle cost of the system, but it does not change the main trend that hybrid systems remain more economical than diesel-only configurations. Studies show that although BESS is still the largest investment component, the downward trend in battery prices globally continues to improve the economic viability of hybrid energy systems over time. Sensitivity to Solar Degradation The degradation

rate of solar modules of  $\pm 0.5\%$  per year is a conservative assumption commonly used in the study of solar PV. If the degradation rate increases, the annual energy production of solar PV will decrease gradually, but the effect on the LCOE of the system as a whole is relatively limited. This is due to the role of solar power plants that remain significant in reducing diesel fuel consumption. A long-term study by Jordan and Kurtz (2013) showed that variations in solar module degradation in the range of 0.3–1% per year did not substantially change the economic conclusions of hybrid systems over an operating horizon of up to 20 years.

Sensitivity to Energy Inflation Energy inflation affects the projection of long-term operational costs of the electricity system. In the diesel-only system, the increase in energy inflation has a direct impact on the increase in electricity production costs. In contrast, in a hybrid system, the influence of inflation is relatively more controlled, as the largest portion of costs is in the initial investment. This condition strengthens the argument that hybrid systems have a better level of economic resilience to energy price fluctuations and uncertainties than conventional diesel-based systems (Alnavis et al., 2024). Implications for the Robustness of the Simulation Results Based on the results of the sensitivity analysis, it can be concluded that although the absolute values of LCOE and NPC have the potential to change due to variations in assumptions, the main direction and trends of the simulation results remain consistent. The PLTS–PLTD–BESS hybrid system generally shows superior economic and environmental performance compared to the PLTD-only system. Thus, the findings of this research can be considered quite robust and worthy of being used as a basis in the preparation of technical and policy recommendations, especially for the development of electricity systems in the archipelago and 3T areas.

Data collection is carried out comprehensively through a combination of primary and secondary data.

- a. Primary data was obtained through direct observation of the actual load, PLTT power output, solar power system performance, and energy storage system operating conditions (BESS).
- b. Secondary data includes internal technical reports, load history, as well as literature studies and references of similar projects in the 3T region.

The details of the data collected include:

1. Existing PLTD Operational Data (2024):
  - a. Daily peak load:  $\pm 499$  kW
  - b. Daytime load:  $\pm 398$  kW
  - c. Fuel consumption:  $\pm 500$  liters/day
  - d. PLTD efficiency:  $\pm 3.6$  kWh/liter
2. Solar Irradiation and Local Climate Data:
  - a. Average irradiation:  $\pm 5.1$  kWh/m<sup>2</sup>/day
  - b. Temperature range: 27–33°C
  - c. Source: NASA POWER, BMKG, and EBTKE Data Center
3. Technical Specifications of Solar Power Plant and BESS Systems:
  - a. Solar Power Plant Capacity: 300 kWp
  - b. BESS: 600 kWh (Li-ion)
  - c. Inverters and controllers follow similar project standards in the tropics
4. Investment and Operational Cost Data:

- a. CAPEX PLTS: IDR 13 million/kWp
- b. BESS: IDR 6 million/kWh
- c. Fuel price (subsidized estimate): IDR 13,000/liter
- d. Sources: IRENA (2021), HOMER Energy (2020), national literature
5. Energy Price and Energy Inflation Assumptions:
  - a. Energy price inflation:  $\pm 3\%$  per annum
  - b. Source: Indonesia Energy Outlook, Ministry of Energy and Mineral Resources

All data obtained were analyzed using HOMER Pro software to simulate the technical and economic performance of the PLTD–PLTS–BESS hybrid system. Three main scenarios are simulated:

- a. Scenario 1 – Existing PLTD (Diesel-only): The system runs entirely on PLTD without the integration of renewable energy.
- b. Scenario 2 – 300 kWp + PLTD (without battery): PLTS solar power plants support daytime loads, while PLTD remains dominant outside of irradiation time.
- c. Scenario 3 – 300 kWp solar power plant + 600 kWh BESS + PLTD (Full Hybrid): Optimal combination with energy storage to improve efficiency and reduce PLTD dependence.

The simulation was carried out by taking into account the variability of daily loads, solar irradiation, and the characteristics of investment and operational costs.

Evaluations were carried out on:

1. System efficiency
2. Fuel consumption
3. Carbon emissions (CO<sub>2</sub>)
4. Cost of Electricity Production (BPP)
5. Net Present Cost (NPC)
6. Investment payback period

### 3. Analysis of the Impact and Advantages of Hybridization

The simulation results show that hybrid system integration provides significant savings, including:

- a. Reduction in diesel consumption: from  $\pm 500$  litres/day to  $\pm 150$  litres/day ( $\pm 70\%$ )
- b. Reduction in CO<sub>2</sub> emissions: from  $\pm 1,446$  tons/year to  $\pm 425$  tons/year ( $\pm 1,021$  tons/year or 71%)
- c. Reduction in BPP: from  $\pm \text{Rp}5,500/\text{kWh}$  to  $\pm \text{Rp}3,200/\text{kWh}$  ( $\pm 42\%$ )
- d. Fuel cost savings:  $\pm \text{IDR } 1.66$  billion/year
- e. Payback period for hybrid system investment:  $\pm 4.5$  years
- f. Reduction in Net Present Cost (NPC):  $\pm \text{IDR } 12\text{--}15$  billion over a 20-year horizon.

### 4. Comparative Evaluation and Recommendations

Comparative analysis was carried out between existing conditions and post-hybrid implementation. The positive impact on the cost, environment, and reliability aspects of the system is the basis for formulating technical recommendations for hybrid system replication in other archipelago regions that face similar challenges. In addition, the results of this study

support policies to accelerate the energy transition and achieve NZE targets in remote areas of Indonesia. Although the HOMER Pro software does not directly display the amount of error margin in the form of a statistical deviation indicator, previous studies have reported that the difference between the results of the HOMER simulation and the actual operational data is generally in the range of  $\pm 5\text{--}10\%$  for both fuel consumption and energy production parameters. The magnitude of this deviation is greatly influenced by the accuracy level of the input data, the quality of the load profile, and the temporal resolution used in the modeling. In this study, the potential differences between the simulation results and real conditions in the field are mainly influenced by fluctuating daily load dynamics, variations in diesel engine performance during operation, and degradation of system components that cannot be fully represented in the annual simulation model. However, the magnitude of the deviation is not seen as changing the main trend of the study results, especially in the comparative analysis of relative performance between PLTD-only systems and hybrid system configurations.

## RESULTS AND DISCUSSION

**Geographical Location** It is located in the Sulawesi Sea, about 50 km off the east coast of East Kalimantan. It is included in the area of Maratua District, Berau Regency, East Kalimantan Province, Indonesia. With Coordinates: About  $2^{\circ}15' \text{ N}$  and  $118^{\circ}38' \text{ E}$ . **General Characteristics** It is an atoll island (horseshoe-shaped ring of corals) that surrounds a large lagoon. The land area is  $\pm 24 \text{ km}^2$  with a long coastline and white sand beaches. It is included in the Derawan Islands group, which consists of Derawan, Kakaban, Sangalaki, and Maratua.

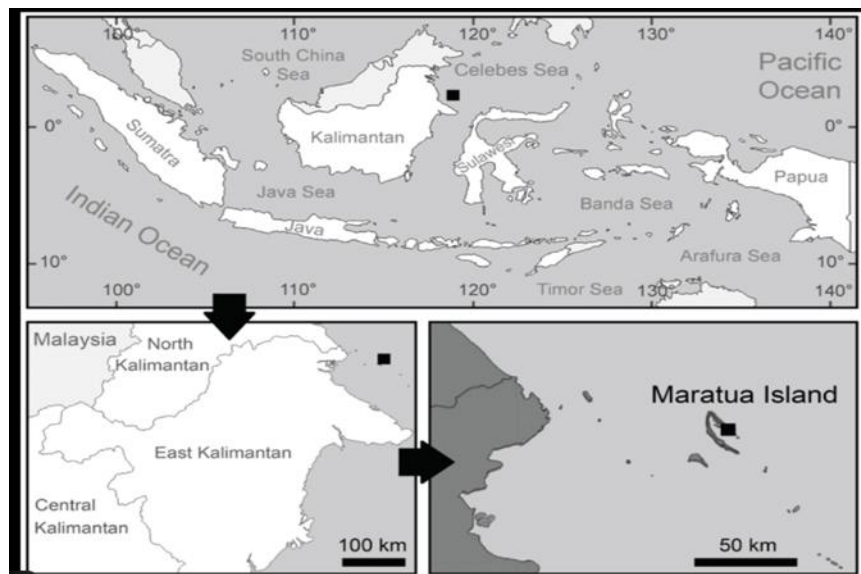


**Figure 1.** Map of Indonesia with the experimental site on Maratua Island (indicated by black square)

**Table 1. Project Location and Solar Energy Parameters**

| No. | Parameter                               | Data                                                      |
|-----|-----------------------------------------|-----------------------------------------------------------|
| 1   | Location                                | Maratua, Berau Regency, East Kalimantan Province          |
| 2   | Coordinates                             | $2^{\circ}14.7' \text{ N}$ , $118^{\circ}34.0' \text{ E}$ |
| 3   | Solar energy potential (annual average) | 1975 kWh/m <sup>2</sup> /year                             |



Figure 2. Map of Maratua Island (wikipedia.com)

## Technical Simulation

Simulations were performed using HOMER Pro software version 3.14 to:

- Modeling the integration of a 300 kWp solar power plant system with an existing PLTD system;
- Determine the optimal configuration of the hybrid system based on the parameters of energy efficiency, LCOE (Levelized Cost of Electricity), and CO<sub>2</sub> emission reduction;
- Evaluate system performance in various solar energy load and penetration scenarios.

Technical Simulation Steps with HOMER Pro

### 1. Existing System Data Input

- Load profile data: Daily or monthly, usually at hourly intervals.
- Existing PLTD system data: Capacity, efficiency, fuel consumption per kWh.
- Solar irradiation data: Input per coordinate location, HOMER Pro is integrated with NASA data.
- Fuel prices, electricity tariffs, and energy inflation.
- Solar PV and BESS component data: Including investment cost, service life, inverter efficiency, battery capacity, etc.

### 2. Hybrid System Design

- Define integration scenarios, for example:
  - 300 kWp solar power plant
  - Existing PLTD 500 kW
  - BESS 500 kWh
- HOMER will simulate thousands of component combinations and optimize configurations based on specific criteria (e.g.: lowest LCOE, lowest emissions, or least total cost).

### 3. Optimization and Simulation

- a. HOMER ran hourly simulations for 1 full year (8760 hours), calculating every system condition.

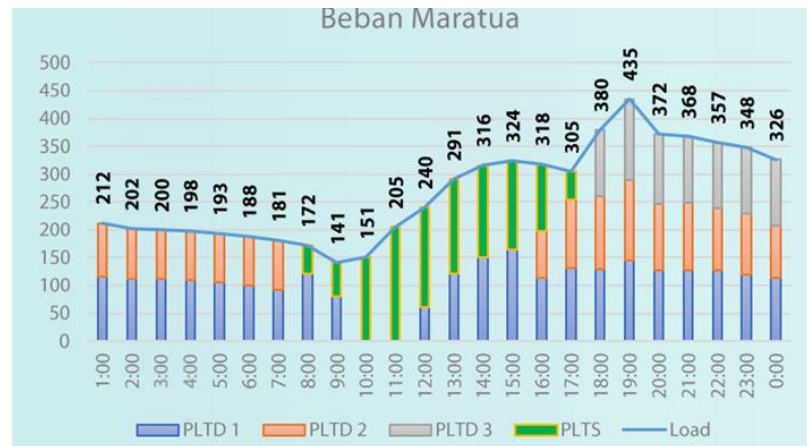


**Diagram 1. Maratua Island Load**  
(archive of PLN Nusa Daya Calculation December 2024)

- b. Its outputs include:
  - Energy production from each component
  - Fuel consumption
  - Unmet load (unmet energy)
  - Battery cycle dan status charge
  - CO<sub>2</sub> emissions
  - Levelized Cost of Energy (LCOE)

### Emissions and Cost Analysis

The analysis was performed for:

- a. Calculating the reduction in fossil fuel consumption and CO<sub>2</sub> emissions after system integration;
- b. Assessing changes in the cost of electricity supply (BPP) before and after the implementation of the hybrid system;
- c. Determine the economic value of the system (NPV and payback period) hypothetically.

**Table 2. Cost of Hybrid Solar Power Plants**  
(archive of PLN Nusa Daya Calculation December 2024)

| NO                 | COST DESCRIPTION                           | VALUE (IDR)          | FUNDING SOURCE     |
|--------------------|--------------------------------------------|----------------------|--------------------|
| <b>A</b>           | <b>EPC Cost</b>                            | <b>7,858,127,253</b> |                    |
| 1                  | Solar PV Modules                           | 1,637,100,000        | Equity             |
| 2                  | Supporting Panel                           | 1,070,000,000        | Equity             |
| 3                  | Battery                                    | 2,615,627,253        | Equity             |
| 4                  | EMS, Transformer and Hybrid Control        | 915,400,000          | Equity             |
| 5                  | Junction Box, Cabling, and M&E Accessories | 640,000,000          | Equity             |
| 6                  | Shipping and Installation Cost             | 980,000,000          | Equity             |
| <b>B</b>           | <b>Non-EPC Cost</b>                        | <b>0</b>             |                    |
| 1                  | Land Acquisition                           | 0                    | Existing PLTD Land |
| <b>Total</b>       |                                            | <b>7,858,127,253</b> |                    |
| <b>VAT 11%</b>     |                                            | <b>864,393,997</b>   |                    |
| <b>Grand Total</b> |                                            | <b>8,722,521,250</b> |                    |

## Validation and Comparison

To ensure the validity of the simulation results, a comparison was made with the findings from similar studies in the Indonesian archipelago (Suwono et al., 2020; Pramudya & Yulianingsih, 2021), and analyzed its suitability with national policies listed in Presidential Regulation of the Republic of Indonesia Number 112 of 2022 concerning the Acceleration of Renewable Energy Development for the Provision of Electricity.

## Research Output

This research yielded:

1. Technical electrical profile of Maratua Island;
2. Recommendations for optimal hybrid solar power system configuration;
3. Projected emission reductions and operating costs;
4. Recommendations for model replication to other 3T regions.

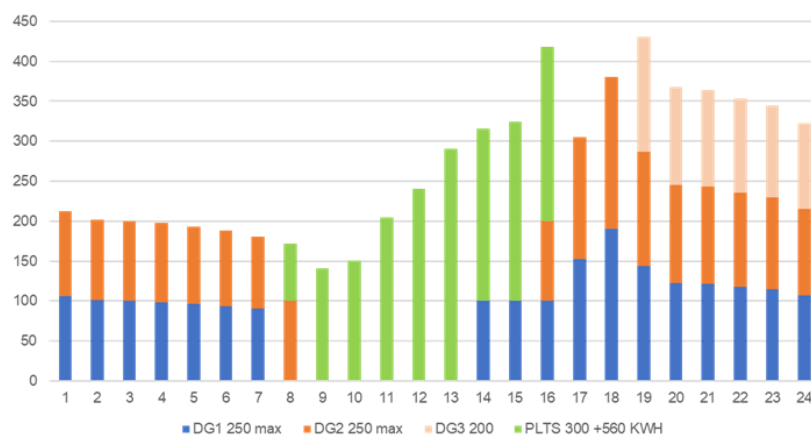


**Diagram 2.** Energy Hybrid Solar Power Plant Maratua Source of research archive PLN Nusa Daya December 2024

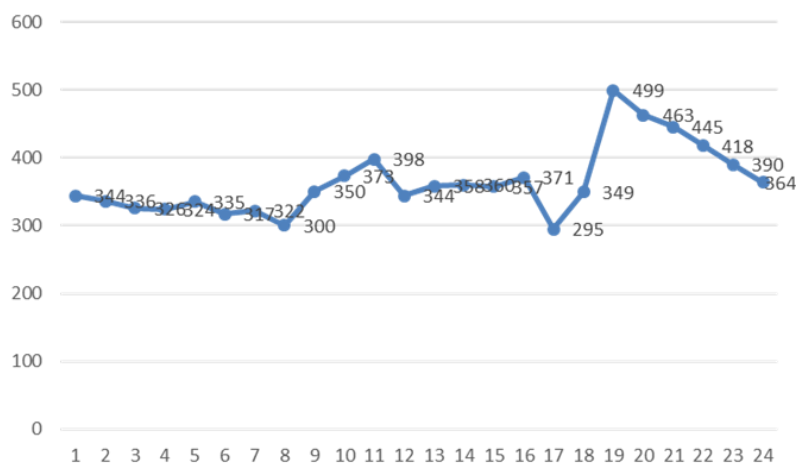


**Diagram 3.** Profile Maratua system load Source of research archive PLN Nusa Daya December 2024

From the data above, the average electricity consumption during the day is 398 kW. The peak load occurred at 20:00 which was 499 kW. Thus, from the results of the hybridization of the Maratua Island system, fuel cost savings reach Rp 5,449,800 per day or Rp 163,494,000

per month. From the price: The price of non-subsidized diesel (Pertamina Dex / Dexlite) for industry usually ranges from IDR 14,000 – IDR 17,000 per liter (prices can change depending on the region and policies as of June 2025). Daytime electricity consumption of 398 kW covers about 79.76% of the load when calculating an increase in the non-fossil energy mix of 26% of the kwh production produced.

**Optimization Analysis of PLTS–PLTD–BESS Hybrid System Configuration** The results of the system modeling show that the combination of a solar power plant with a capacity of 300 kWp with a BESS of 600 kWh produces the most optimal performance when viewed from a technical, economical, and environmental perspective. This level of optimality is not determined solely by the amount of installed renewable energy capacity, but by the right balance between the characteristics of the electrical load, solar energy production patterns, energy storage capabilities, and the total cost of the system throughout its life cycle. Reasons for the Configuration of 300 kWp and 600 kWh BESS Solar Power Plants as the Optimal Choice The capacity of 300 kWp of solar power plants is considered the most suitable because it is able to meet most of the load needs during the daytime period on Maratua Island, which has an average load of around 398 kW, without producing excessive excess energy. If the capacity of solar power plants is increased beyond this value, energy production at peak irradiation does increase, but not all additional energy can be utilized due to limited load and storage capacity. This condition leads to curtailment, which ultimately increases LCOE values without providing additional systemically significant benefits. This phenomenon is in line with the concept of optimal sizing in hybrid energy systems, which states that renewable energy generation with too large capacity can actually reduce economic efficiency if it is not balanced with adequate energy utilization and storage.

Thus, optimal configuration is achieved at the point of the system's lifecycle cost balance, rather than at the highest penetration of solar energy. The Strategic Role and Optimal Limit of BESS 600 kWh BESS with a capacity of 600 kWh serves as a key element in maintaining system balance, especially in maximizing the utilization of solar energy and suppressing PLTD's partial operations. This capacity is enough to store surplus energy during the day and redistribute it in the afternoon to evening period, when solar PV production decreases while the load begins to increase. However, the addition of battery capacity above 600 kWh no longer provides comparable economic benefits. The increase in investment costs and battery replacement was not offset by a significant decline in diesel fuel consumption. This is in accordance with the findings Neigum & Wang (2024) which states that the economic benefits of batteries in off-grid systems tend to decline after passing a certain optimal capacity, especially when battery prices are still relatively high. Therefore, the 600 kWh capacity reflects the best compromise point between technical advantages and investment cost burdens. **Explanation of Reduction in CO<sub>2</sub> Emissions Around 71%** The reduction in CO<sub>2</sub> emissions of approximately 71% is a direct consequence of the reduced operating hours of PLTD, especially during the daytime period when solar PV is able to take over most of the energy supply. This decrease does not reach 100% because PLTD still acts as the main backup source at night and during low irradiation conditions to maintain system reliability. The magnitude of the emission reduction is influenced by the alignment between the load profile and solar energy production, energy storage capacity, and PLTD's operating strategy.

In the context of Maratua Island, the high daytime load allows for a significant contribution of solar power plants in replacing diesel-based generation, off-grid hybrid systems are generally able to reduce CO<sub>2</sub> emissions in the range of 60–80%, depending on the penetration rate of renewable energy and battery capacity. Therefore, the achievement of 71% in this study is within a realistic range and in line with the literature. Capacity Trade-off between Solar Power Plant and BESS The analysis also revealed a clear trade-off relationship between solar and BESS capacity. Increasing the capacity of solar power plants without adding storage capacity has the potential to increase wasted energy and reduce cost efficiency. On the other hand, increasing the capacity of BESS without increasing the supply of renewable energy actually increases investment costs without making a significant contribution to reducing emissions or fuel consumption. This characteristic is a common feature of hybrid energy systems and forms the basis of the optimization algorithm in the HOMER Pro software, which focuses on minimizing the Net Present Cost (NPC) and LCOE of the system (HOMER Energy, 2020). Empirical studies by Rivera-durán et al (2023) Hybrid systems on small islands also show that the optimal configuration is always at the point of compromise between generation and storage, not at the maximum capacity of one of the components. Analytical Implications Thus, this study not only proves the advantages of the PLTS–PLTD–BESS hybrid system over conventional PLTD systems, but also describes the optimization mechanism behind it. These findings confirm that designing an effective hybrid system should consider the dynamic interaction between loads, generation sources, energy storage, and cost structures in an integrated manner, rather than focusing solely on increasing renewable energy capacity.

## CONCLUSION

This study highlights the substantial techno-economic and environmental advantages of hybridizing a 300 kWp solar photovoltaic (PV) system with a 600 kWh battery energy storage system (BESS) and the existing diesel (PLTD) power plant on Maratua Island, achieving approximately 70% reductions in diesel fuel consumption and annual CO<sub>2</sub> emissions (about 1,021 tons or 71%), while lowering the levelized cost of electricity (LCOE) from IDR 5,500/kWh to IDR 3,200/kWh, generating IDR 1.66 billion in annual savings, and offering a 4–4.5-year payback period. These results affirm hybrid PLTS-PLTD-BESS systems as a viable, sustainable strategy for Indonesia's remote, outermost, and disadvantaged (3T) regions, advancing national emissions reduction and energy security goals. For future research, longitudinal real-world monitoring of deployed systems under tropical conditions is recommended to validate simulations, alongside explorations of wind/ocean energy integration, advanced management strategies, second-life batteries, and socio-economic community impacts to refine scalable policies across the archipelago.

## REFERENCES

- Alnavis, N. B., Wirawan, R. R., Solihah, K. I., & Nugroho, V. H. (2024). Energi listrik berkelanjutan: Potensi dan tantangan penyediaan energi listrik di Indonesia. *IJMESE Journal of Innovation Materials, Energy, and Sustainable Engineering*, 1(2), 119–139.
- Astuti, E., & Hidayat, S. (2021). National energy policy in Indonesia: Challenges and strategies for achieving renewable energy targets. *Energy Policy*, 146, 111805. <https://doi.org/10.1016/j.enpol.2020.111805>

- Bappenas. (2020). *National energy general plan (RUEN): Indonesia's roadmap for renewable energy development*. Ministry of National Development Planning of the Republic of Indonesia.
- Hamzah, N., & Saini, M. (2020). Penggunaan bahan bakar high speed diesel dan marine fuel oil terhadap biaya operasi PLTD. *Jurnal SINERGI*, 18(1), 8–19.
- HOMER Energy by UL. (2020). *HOMER Pro version 3.14 user manual*. UL LLC.
- International Energy Agency. (2021). *Net zero by 2050: A roadmap for the global energy sector*. IEA.
- Kusuma, H. D., Widyastuti, H., & Dewi, S. (2021). Energy access in Indonesia's remote regions: A review of challenges and opportunities. *Renewable and Sustainable Energy Reviews*, 145, 111053. <https://doi.org/10.1016/j.rser.2021.111053>
- Neigum, K., & Wang, Z. (2024). Technology, economic, and environmental analysis of second-life batteries as stationary energy storage: A review. *Journal of Energy Storage*, 103, 114393. <https://doi.org/10.1016/j.est.2024.114393>
- Nugroho, A., & Pratama, P. (2021). Diesel power plants in Indonesia: Challenges and opportunities in the transition to renewable energy. *Journal of Energy and Environmental Economics*, 29(3), 124–135. <https://doi.org/10.1016/j.jee.2021.03.004>
- Nurjaman, H. B., & Purnama, T. (2022). Pembangkit listrik tenaga surya (PLTS) sebagai solusi energi terbarukan rumah tangga. *Jurnal Edukasi Elektro*, 6(2), 136–142.
- Olympios, A. V., Mersch, M., Kourougianni, F., Markides, C. N., Pantaleo, A. M., Kyprianou, A., & Georgiou, G. E. (2025). A stochastic optimisation framework for integrating photovoltaic systems, heat pumps, and energy storage in buildings. *Applied Thermal Engineering*, 278, 122035.
- Ortiz-Pimiento, N. R., & Montes-P, E. G. (2022). National energy system optimization modelling for decarbonization pathways analysis: A systematic literature review. *Renewable and Sustainable Energy Reviews*, 162, 112406. <https://doi.org/10.1016/j.rser.2022.112406>
- Pramudya, Y., & Yulianingsih, D. (2021). Analisis potensi reduksi emisi CO<sub>2</sub> melalui implementasi sistem PLTS hybrid di pulau terpencil. *Jurnal Energi dan Kelistrikan Indonesia*, 10(1), 23–30.
- Prasetyanto, K., Suryanto, S., Mulyanto, M., & Rahayu, S. A. T. (2025). Energy poverty: Analysis of infrastructure and geographic factors in rural areas of Indonesia. *International Journal of Energy Economics and Policy*, 15(5), 532–538.
- Rangel, N., Li, H., & Aristidou, P. (2023). An optimisation tool for minimising fuel consumption, costs, and emissions from diesel–PV–battery hybrid microgrids. *Applied Energy*, 335, 120748. <https://doi.org/10.1016/j.apenergy.2023.120748>
- Rivera-Durán, Y., Berna-Escriche, C., Córdova-Chávez, Y., & Muñoz-Cobo, J. L. (2023). Assessment of a fully renewable generation system with storage to cost-effectively cover the electricity demand of standalone grids: The case of the Canary Archipelago by 2040. *Machines*, 11(3), 351. <https://doi.org/10.3390/machines11030351>
- Saputra, A. H., Aziz, A., & Harjito, B. (2025). The effectiveness of Pertamina's BBM One Price Program in equalizing energy access in 3T regions (underdeveloped, frontier, and outermost areas). *International Journal of Social Science and Humanity*, 15(2), 85–92.
- Sipayung, B., Muhdar, M., & Sabaruddin, A. K. (2024). Aspects of environmental justice in construction regulations for new renewable energy development in remote villages in Indonesia. *Innovative: Journal of Social Science Research*, 4(3), 9284–9296.
- Sulistyo, W. (2021). Achieving net zero emission in Indonesia: The role of renewable energy in the national energy strategy. *Journal of Sustainable Energy*, 19(2), 78–85. <https://doi.org/10.1016/j.jse.2021.01.005>
- Suryanto, A., Rendra, I., & Samudra, I. (2020). Transitioning from diesel to renewable energy:

- Policy and technological considerations for Indonesia. *Energy for Sustainable Development*, 56, 148–159. <https://doi.org/10.1016/j.esd.2020.08.004>
- Sutrisno, P. A., Zulfah, S., & Njatrijani, R. (2025). Analysis of sustainable investment regulation for Indonesia's 3T regions: Underdeveloped, frontier, and outermost. *IOP Conference Series: Earth and Environmental Science*, 1537(1), 012035. <https://doi.org/10.1088/1755-1315/1537/1/012035>
- Suwono, A., Nurhadi, I., & Kusuma, A. (2020). Studi simulasi integrasi PLTS dan PLTD untuk wilayah kepulauan menggunakan HOMER. *Jurnal Teknik Elektro dan Komputer*, 9(2), 95–104.
- Widodo, A., & Nugroho, A. (2020). The role of renewable energy in achieving energy independence in Indonesia: Current status and future prospects. *Energy Reports*, 6, 101–113. <https://doi.org/10.1016/j.egy.2020.03.002>
- Wibowo, A., Doloksaribu, A. H., & Rahman, A. C. K. (2021). Access to environmentally friendly energy and capacity building for communities in the 3T frontier, outermost, and least developed region through the corporate social responsibility program. *SPE Asia Pacific Oil and Gas Conference and Exhibition*. <https://doi.org/10.2118/205293-MS>
- Yulianto, D., Tohari, S., & Rosadi, K. (2020). Indonesia's energy transition: Achieving sustainable energy goals for 2060. *Journal of Renewable and Sustainable Energy*, 12(4), 042001. <https://doi.org/10.1063/1.5143222>