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Economic Study and Design of A Hybrid Power Generation System Based on Renewable Energy For Sustainable Energy on Legundi Island

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Abstract

This study was conducted to address the high electricity production costs on Legundi Island, which is currently supplied by an isolated diesel power plant with an installed capacity of 250 kW, an effective capacity of 200 kW, an average peak load of 61.74 kW, and monthly energy consumption of approximately 19,927 kWh, resulting in a generation cost (BPP) of IDR 9,749/kWh. The existing system consumes about 188,340 liters of diesel fuel annually, leading to high operational costs and full dependence on diesel supply. This study aims to analyze the economic feasibility and determine the optimal configuration of a hybrid power generation system based on diesel, solar, and hydrogen energy. Simulation results indicate that all three analyzed schemes are technically feasible but exhibit different economic performances. The diesel–solar power plant (PLTD–PLTS) scheme generates a positive NPV of IDR 1,414,626,585, an IRR of 9.56%, and a payback period of 9 years. The diesel–hydrogen power plant (PLTD–PLTH$_2$) scheme results in an NPV of IDR 2,046,708,660 with an IRR of 3.07%, while the combined PLTD–PLTS–PLTH$_2$ scheme yields the highest NPV of IDR 2,731,499,089 but also the longest payback period of 14.78 years. Based on Net Present Cost (NPC) analysis, the PLTD–PLTS configuration is the most efficient option, with a total cost of IDR 22,835,387,530, which is lower than the PLTD–PLTH$_2$ scheme (IDR 23,749,365,572) and the PLTD–PLTS–PLTH$_2$ scheme (IDR 25,359,493,983). Furthermore, the 150 kW PLTD–PLTS system produces the lowest Levelized Cost of Energy (LCOE) at IDR 5,068/kWh, confirming its superiority in terms of investment efficiency and electricity cost. These findings highlight that the diesel–solar hybrid system is the most financially viable solution for isolated island power systems and can serve as a strategic recommendation for policymakers in reducing electricity generation costs while gradually transitioning toward cleaner energy sources.

Keywords: energy costs, hydrogen, hybrid, optimization, solar

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INTRODUCTION

Energy access remains a critical challenge for remote regions in Indonesia, particularly in the archipelago's smaller islands. Legundi Island, located in Lampung Province, exemplifies this issue. The island's electricity supply is currently reliant on a diesel power plant (PLTD), which, though operational, has been facing inefficiencies due to high operational costs and its dependence on unstable fuel supplies. According to the Ministry of Energy and Mineral Resources (ESDM, 2022), the high cost of diesel fuel and its environmental impact contribute to escalating electricity generation costs.

The urgency of addressing these challenges has made Legundi Island a relevant case study for investigating alternative, more sustainable energy solutions. This is particularly important considering Indonesia’s energy policy, which focuses on the development of renewable energy sources and the transition to cleaner and more reliable energy systems.

As the global push for decarbonization intensifies, renewable energy solutions, especially hybrid power generation systems, are gaining traction as a means to provide sustainable electricity to remote islands. A hybrid system combines renewable energy sources, such as solar or wind, with traditional diesel generators to reduce reliance on fossil fuels while maintaining grid stability. Research by Setiawan and Widodo (2019) and Sinaga et al. (2015) has highlighted the benefits of hybrid renewable energy systems (HRES), which can effectively optimize energy generation, improve cost-efficiency, and reduce emissions. For Legundi Island, such systems could play a pivotal role in addressing the inefficiencies of the existing diesel-based power system while contributing to the broader goal of achieving a sustainable energy transition.

In line with Indonesia’s National Energy Policy, which aims for a 23% renewable energy share by 2025 (Dewan Energi Nasional, 2021), and the country’s ambition to reach Net Zero Emissions (NZE) by 2060, the exploration of hybrid systems has become increasingly urgent. Renewable energy resources, such as solar power, have been identified as key alternatives for powering off-grid systems in remote regions (Priyono, 2020). The potential for hybrid power generation systems to improve the sustainability and affordability of electricity supply in these areas is supported by several studies, including those by Putra and Haryanto (2021) and Mustofa (2022), which have analyzed the feasibility of integrating solar and wind energy in remote Indonesian islands.

Diesel-powered plants have long been the backbone of electricity generation in Indonesia’s outer islands, yet these systems face several critical limitations. According to the Ministry of Energy and Mineral Resources (2022), the use of diesel fuel leads to significant economic and environmental costs. Diesel prices, which are influenced by global market fluctuations, create volatility in electricity generation costs. For instance, the monthly energy consumption on Legundi Island is approximately 19,927 kWh, which results in a generation cost (BPP) of IDR 9,749/kWh, as the island’s diesel power plant consumes around 188,340 liters of diesel annually. This heavy reliance on imported diesel fuel not only drives up costs but also has substantial environmental impacts due to the CO_2 emissions associated with diesel combustion (Darmawan, 2018).

Furthermore, diesel generators have operational inefficiencies, with many plants operating at a fraction of their capacity, which compounds the cost issue. For instance, Legundi Island's diesel generators operate at a peak load of only about 61.74 kW, despite having a total installed capacity of 250 kW. The low load factor results in underutilization of the generator's capacity, further increasing the cost per kWh produced. Additionally, frequent generator maintenance is necessary to ensure the reliability of the system, leading to higher operational and maintenance costs (Akbar et al., 2019).

The environmental impact of diesel-based systems is another pressing concern. Indonesia's carbon footprint from the energy sector is largely driven by fossil fuel use, with the electricity generation sector being one of the largest contributors (IPCC, 2006). As the global and national demand for cleaner energy grows, it is clear that continued reliance on diesel will hinder Indonesia's efforts to meet its decarbonization targets.

Hybrid renewable energy systems offer a promising alternative to traditional diesel generators by combining renewable energy sources, such as solar and hydrogen, with diesel backup systems. These systems are particularly well-suited to remote islands like Legundi, where access to the national grid is limited. Solar energy, with its high availability in tropical regions, is an ideal candidate for integration into hybrid systems. As the Indonesian Ministry of Energy and Mineral Resources (2022) notes, solar energy is abundant across many remote islands, making it a viable option for reducing reliance on fossil fuels. Solar power generation can be maximized with efficient energy storage systems, such as batteries or hydrogen storage, which can ensure a stable electricity supply even during non-sunny periods.

The hybrid system's ability to integrate multiple renewable energy sources can significantly improve energy reliability. According to the International Renewable Energy Agency (IRENA, 2021), integrating hydrogen with renewable energy sources, such as solar, can address the intermittent nature of solar power generation. Hydrogen, used as an energy storage medium, can store excess solar energy and convert it into electricity when demand exceeds supply. This flexibility allows for a more stable and resilient energy system, especially in remote areas where energy demand fluctuates based on daily activities.

In addition to improving energy reliability, hybrid systems can help reduce electricity costs. By reducing the amount of diesel fuel consumed, these systems lower fuel costs and the associated environmental impacts. Several studies, including those by Nuryanto et al. (2022) and Rianto and Adi (2024), have shown that hybrid systems reduce the Levelized Cost of Energy (LCOE) compared to traditional diesel-only systems. These studies confirm that by integrating renewable energy sources like solar and hydrogen into the energy mix, operational costs can be significantly reduced while ensuring a cleaner energy supply.

The economic advantages of hybrid systems are clear. The integration of solar power, hydrogen storage, and diesel backup offers a more cost-effective solution over the long term compared to relying solely on diesel power plants. According to Lubis (2020), hybrid systems can achieve cost savings by reducing the amount of diesel fuel required for electricity generation. This results in lower operational costs, which is especially important for remote islands where fuel supply logistics are complex and costly.

The integration of solar and hydrogen into the energy mix can also reduce carbon emissions, contributing to Indonesia's Nationally Determined Contributions (NDCs) under the Paris Agreement. The reduction in CO_2 emissions is particularly significant for remote islands, which are often vulnerable to climate change and rely on costly, polluting fossil fuels for electricity. By reducing the carbon footprint of island electricity systems, hybrid renewable energy solutions can help mitigate the environmental impacts associated with diesel power plants and contribute to Indonesia's goal of achieving Net Zero Emissions by 2060 (Ridawan Institute, 2023).

Additionally, hybrid systems are more flexible and scalable than traditional diesel systems. According to the Directorate General of New and Renewable Energy and Energy Conservation (EBTKE, 2021), the modular nature of hybrid systems allows them to be easily scaled up or down based on demand. This makes them ideal for remote island applications, where energy demand can vary and where the integration of new renewable sources can be done incrementally.

Hybrid power generation systems align with Indonesia's national energy policy, which prioritizes the development of renewable energy sources and the diversification of energy systems. The Indonesian government has set ambitious targets for renewable energy, with a goal to achieve a 23% renewable energy mix by 2025 (Dewan Energi Nasional, 2021). Hybrid systems, particularly those incorporating solar and hydrogen, are critical in achieving this goal, as they can integrate with existing energy infrastructure and provide a reliable, low-cost energy supply.

The implementation of hybrid systems also supports the national strategy for rural electrification, particularly in remote and isolated areas. As noted by the Ministry of Energy and Mineral Resources (2022), many villages in Indonesia still lack reliable access to electricity. Hybrid systems offer a viable solution to this problem by providing affordable, clean, and reliable electricity without the need for extensive infrastructure development.

The transition to hybrid systems also supports Indonesia's goal of achieving Net Zero Emissions by 2060. According to Ridawan Institute (2023), hybrid systems, by reducing dependence on fossil fuels, can play a crucial role in decarbonizing the energy sector. This aligns with the national strategy for energy transition, which includes expanding the role of renewable energy in the national energy mix.

The need for a sustainable, cost-effective, and reliable electricity supply in remote islands like Legundi Island has never been more urgent. Diesel power plants, while providing electricity, are costly, inefficient, and environmentally damaging. Hybrid renewable energy systems, combining solar, hydrogen, and diesel, offer a promising solution to these challenges. The economic and environmental benefits of hybrid systems, including cost savings, reduced CO_2 emissions, and enhanced energy reliability, make them an attractive option for island electrification.

This study aims to explore the feasibility of implementing a hybrid power generation system on Legundi Island, focusing on optimizing the combination of diesel, solar, and hydrogen energy. The findings of this study are expected to contribute to the ongoing efforts to develop sustainable energy solutions for remote islands in Indonesia, supporting the national goal of achieving Net Zero Emissions by 2060 and contributing to the broader global effort to combat climate change.

By integrating renewable energy into the energy mix, Indonesia can reduce its reliance on fossil fuels, lower energy costs, and enhance energy security in remote regions. Hybrid systems, particularly those based on solar and hydrogen, offer a flexible, scalable, and environmentally friendly solution to the energy challenges faced by Indonesia's islands. The results of this study will provide valuable insights for policymakers and industry stakeholders involved in the transition to a more sustainable energy future.

METHOD

This study uses a quantitative-descriptive approach with modeling and simulation of a hybrid power generation system to analyze the technical, economic, and environmental feasibility. The case study was conducted on the electricity system of Legundi Island, Punduh Pidada District, Pesawaran Regency, Lampung Province, which is an isolated system and currently relies entirely on diesel power plants. The research location is at the geographic coordinates of latitude −5.8051638 and longitude 105.291794. The existing electricity system consists of diesel generators with a total installed capacity of 250 kW, serving 313 customers with 24-hour operation time and a peak load of approximately 61.54 kW. The research was conducted during the period of May–July 2025.

The research phase began with a literature review and initial data collection related to diesel, solar, and hydrogen-based hybrid power generation systems. The collected data included electricity load profiles, diesel fuel consumption and prices, existing generator capacity, solar radiation data, hydrogen utilization potential, and investment costs and system components. Secondary data were obtained from PLN UID Lampung, the Meteorology, Climatology, and Geophysics Agency (BMKG), government policy documents, and relevant scientific publications. Primary data collection was conducted through field observations to verify the actual condition of the power generation system, semi-structured interviews with local PLN managers and technicians regarding operational aspects and system constraints, and a socio-economic survey of the community to assess the level of acceptance and readiness for the implementation of the hybrid power generation system.

System modeling and simulation were conducted by developing several hybrid power plant configuration scenarios combining Diesel Power Plants (PLTD), Solar Power Plants (PLTS), and Hydrogen Power Plants ($PLTH_2$) with varying capacities. Each scenario was evaluated based on technical performance and economic indicators to determine the most optimal system configuration.

Economic analysis was conducted by calculating the parameters of Net Present Value (NPV), Internal Rate of Return (IRR), Benefit Cost Ratio (B/C), Payback Period (PBP), Net Present Cost (NPC), and Levelized Cost of Energy (LCOE). These parameters were used to assess the investment feasibility and cost efficiency of the hybrid power generation system compared to the conventional diesel power system. In addition, a sensitivity analysis was conducted to evaluate the effect of changes in key parameters, such as diesel fuel prices, investment costs, interest rates, and solar radiation variability on the economic feasibility of the system. Environmental analysis was conducted by calculating CO_2 emissions produced by the existing system and the hybrid system, so that the potential for reducing greenhouse gas emissions could be identified quantitatively.

The simulation and analysis results were then validated through discussions with renewable energy experts and PLN (State Electricity Company) to ensure the research findings align with technical and operational conditions in the field. This methodological approach is expected to yield recommendations for optimal, low-cost, and sustainable hybrid power generation systems for island regions.

RESULTS AND DISCUSSION

Existing Condition of Legundi Island's Electrical System

Legundi Island's electricity system currently relies on an isolated system based on a Diesel Power Plant (PLTD) managed by PT PLN (Persero) Lampung Distribution Unit. The generation system consists of three diesel generator sets: two units with an installed capacity of 50 kW each with a power output of 40 kW, which have been in operation since 1987 and 1991, respectively, and one unit with a capacity of 150 kW with a power output of 120 kW, which began operating in 2018. The total installed capacity of the generation system reaches 250 kW with a power output of 200 kW.

Technically, the available generating capacity is still relatively larger than the actual needs of the community. The peak load of the system is recorded at around 61.7 kW, indicating a substantial reserve margin. However, this condition does not necessarily reflect the efficiency of the system, considering that most of the generating units are old and operate alternately to maintain the reliability of the electricity supply.

Analysis of the daily load profile throughout 2024 shows that the electricity consumption pattern of the Legundi Island community tends to increase at night, in line with domestic activities. The average system load is relatively low compared to the installed capacity, which results in low utilization of diesel generators. This condition has implications for high operational costs per unit of electrical energy produced. In terms of the distribution network, the Legundi electricity system uses a 20 kV Medium Voltage Overhead Line (SUTM) with a length of approximately 7.35 km and a Low Voltage Overhead Line (SUTR) with a length of approximately 6.75 km. Measurement results show that the end voltage during peak load is around 18.64 kV, which is still within the tolerance limits of the standard operational system of the electric power distribution. Evaluation of distribution transformer loading shows that the Legundi system is served by four transformer substations with a total installed capacity of 250 kVA. The highest peak load recorded reached 99.7 kW, resulting in an average transformer loading level of around 39.88%. This value indicates that the distribution transformer is still working far below its nominal capacity and has not experienced overload conditions.

Based on the December 2024 generation report, the capacity factor (CF) of the generator system on Legundi Island was recorded at 13.65%. This value is relatively low and indicates that diesel generators are not being optimally utilized. The low capacity factor is primarily due to the small system load and the rotating operation of the generators due to the relatively old engines. The electricity situation on Legundi Island indicates that although the system is technically capable of meeting load requirements, its operational efficiency and economics are still relatively low. The high, underutilized installed capacity and reliance on diesel fuel are important foundations for the development of a renewable energy-based hybrid power generation system to increase efficiency, lower electricity production costs, and mitigate environmental impacts.

Hybrid System Modeling and Simulation Results

Load modeling results indicate that Legundi Island's electricity system exhibits relatively stable load characteristics throughout the year. The average peak load was recorded at 61.74 kW, while the daily load ranged from 45–55 kW without extreme fluctuations. Total electricity consumption reached approximately 19,927 kWh per month, or approximately 438,000 kWh per year. This consumption pattern is dominated by household needs and social facilities, with peak load occurring in the afternoon and evening.

The low daily load variation indicates that the Legundi system has a consistent and predictable baseload. However, the diesel power plant's capacity utilization ratio is relatively low, with a load factor of only 0.25–0.30. This indicates underutilization of diesel power plants, where installed capacity significantly exceeds actual load. This results in high electricity production costs and low operational efficiency of the existing system.

This load stability is a technical advantage in designing hybrid power generation systems, as it allows the integration of renewable energy without requiring complex dynamic responses. Furthermore, the capacity margin between the PLTD's rated power (200 kW) and the peak load provides considerable flexibility in adding new energy sources such as solar PV, hydroelectric power plants (PLTH) , and energy storage systems.

Table 1. Simulation Results of the 150 kWp Diesel-Powered Power Plant Scheme

Parameter	Mark
Solar Power Plant Capacity	150 kWp
Solar Power Plant Energy Production	246,000 kWh/year
Utilization of Solar Power Plant Energy	197,100 kWh/year
Curtailment of Solar Power Plants	±48,900 kWh/year
Diesel Power Plant Energy Production	240,900 kWh/year
Diesel Fuel Consumption	±84,700 liters/year
Fuel savings	±103,640 liters/year
Operational Cost Savings	±Rp 936 million/year
CO_2 Emission Reduction	±55%

Integrating a 150 kWp solar power plant into the existing system produces approximately 246,000 kWh of energy per year, or approximately 675 kWh per day. This energy is sufficient to cover the entire daytime load demand, which averages 540 kWh per day. However, without an energy storage system, approximately 135 kWh per day is curtailed, resulting in the solar power plant's effective contribution reaching only approximately 197,100 kWh per year.

In this configuration, the diesel power plant still needs to supply approximately 240,900 kWh per year, primarily to meet the nighttime load. However, diesel fuel consumption can be reduced to approximately 84,700 liters per year, equivalent to operational cost savings of approximately Rp 936 million per year. The addition of a 200 kWh battery can eliminate curtailment in the solar power plant and increase solar energy utilization by up to 100%, resulting in fuel savings of approximately 105,800 liters per year, or Rp 1.17 billion per year. These results demonstrate that solar power plants significantly contribute to lowering operational costs, especially when supported by an energy storage system.

Table 2. Simulation Results of the 150 kWp Diesel-PV Power Plant Scheme + 200 kWh Battery

Parameter	Mark
Solar Power Plant Capacity	150 kWp
Battery Capacity	200 kWh
Solar Power Plant Energy Production	246,000 kWh/year
Utilization of Solar Power Plant Energy	246,000 kWh/year
Curtailment of Solar Power Plants	0
Diesel Power Plant Energy Production	192,000 kWh/year
Diesel Fuel Consumption	±82,540 liters/year
Fuel savings	±105,800 liters/year
Operational Cost Savings	±Rp 1.17 billion/year
CO_2 Emission Reduction	±56%

In this scheme, a 75 kW PLTH $_2$ is integrated with a diesel power plant, where the diesel power plant continues to operate as a grid-forming generator at minimum load to maintain system stability. Simulation results show that PLTH $_2$ is capable of supplying between 40–80% of the system's energy needs, depending on the diesel power plant's minimum operating limits.

In an optimal operating scenario with a minimum diesel power plant of 20 kW, the PLTH 2 is capable of supplying approximately 720 kWh per day or approximately 262,800 kWh per year. This configuration results in diesel fuel savings of approximately 113,000 liters per year, equivalent to cost savings of approximately IDR 1.25 billion per year. In addition to economic savings, this scheme also improves system reliability and reduces carbon emissions, although it still requires a continuous hydrogen supply and adequate safety infrastructure.

Table 3. Simulation Results of the 75 kW Diesel Power Plant-Plant Power Scheme

Parameter	Mark
Capacity of PLTH $_2$	75 kW
Hydroelectric Power Plant Energy Production $_2$	±262,800 kWh/year
Diesel Power Plant Energy Production	±175,200 kWh/year
Diesel Fuel Consumption	±75,300 liters/year
Fuel savings	±113,000 liters/year
Operational Cost Savings	±Rp 1.25 billion/year
CO_2 Emission Reduction	±60%
System Stability	Tall

The three-source hybrid scheme performed better than the other schemes. A 150 kWp solar power plant serves as the primary power source, contributing 262,800 kWh per year, or approximately 60% of Legundi Island's annual energy needs. The remaining 175,200 kWh per year is largely supplied by the 157,680 kWh solar power plant , contributing approximately 157,680 kWh per year.

In this configuration, the diesel power plant operates solely as a backup generator to maintain voltage and frequency stability, with a total energy production of approximately 17,520 kWh per year. As a result, diesel fuel consumption drops dramatically from 188,340 liters per year under existing conditions to only approximately 7,534 liters per year. This translates to a fuel savings of 180,806 liters per year, or approximately 96% compared to a pure diesel power plant system.

From an economic perspective, the reduction in fuel consumption results in operational cost savings of approximately IDR 2.0 billion per year. In addition to the economic benefits, this scheme also has a significant environmental impact by reducing CO_2 emissions and increasing system reliability by utilizing solar energy as the primary source and hydrogen as a sustainable energy support.

The research results show that the stable load characteristics of Legundi Island strongly support the implementation of a hybrid power generation system. The integration of solar and hydrogen energy has been proven to significantly reduce diesel fuel consumption while increasing the operational efficiency of the isolated electricity system. Compared to a single solar power plant (PLTS) or a single PLTH (PLTH) scheme , the combination of PLTS–PLTH – PLTD provides the most optimal results from a technical, economic, and environmental perspective.

These findings align with previous studies that have shown renewable energy-based hybrid systems to be highly effective in island regions with low and stable loads. With fuel savings of up to 96% and significant reductions in operational costs, this hybrid system has the potential to become a model for sustainable electricity development for other small islands in Indonesia.

1. Economic Analysis of Hybrid Systems

The economic analysis of the PLTD–PLTS scheme was conducted by including a 150 kWp PLTS component and a 200 kWh BESS. The basic assumptions for the calculation are presented in Table 4 .

Table 4. Basic Assumptions for Economic Analysis of the 150 kWp Diesel-PV Solar Power Scheme

Parameter	Mark
Solar Power Plant Capacity	150 kWp
BESS Capacity	200 kWh
Initial CAPEX	Rp. 8,426,305,183
Project age	20 years
Diesel prices	Rp. 11,062/liter
Fuel savings	105,800 liters/year
Annual net savings	Rp. 1,043,600,000
Discount rate (WACC)	7.38%

The results of the calculation of economic indicators are shown in Table 5 **.**

Table 5. Results of the Economic Analysis of the 150 kWp Diesel-PV Solar Power Scheme

Parameter	Mark
NPV	Rp. 1,414,626,585
IRR	9.56%
B/C Ratio	1.13
Payback Period	9 years

A positive NPV value, IRR greater than WACC, and B/C ratio above one indicate that the PLTD–PLTS scheme is economically feasible to implement **.** The basic assumptions of the economic analysis of the PLTD–PLTH $_2$ scheme are presented in Table 6 **.**

Table 6. Basic Assumptions for Economic Analysis of the 75 kW Diesel-Powered Plant Scheme

Parameter	Mark
Capacity of PLTH $_2$	75 kW
Initial CAPEX	Rp. 6,730,875,000
Hydroelectric Power Plant Energy $_2$	262,800 kWh/year
Fuel savings	113,004 liters/year
Annual net savings	Rp. 455,295,123
Discount rate (WACC)	7.38%

The results of the economic analysis are shown in Table 7 **.**

Table 7. Results of Economic Analysis of the 75 kW Diesel-Powered Plant Scheme

Parameter	Mark
NPV	–Rp 2,046,708,660
IRR	3.07%
B/C Ratio	0.12
Payback Period	14.78 years

The negative NPV value and IRR lower than WACC indicate that this scheme is less economically feasible , mainly due to the high cost of hydrogen. The combination scheme is analyzed with the assumptions as in Table 8 **.**

Table 8. Basic Assumptions of the Economic Analysis of the PLTD–PLTH $_2$ –PLTS Scheme

Parameter	Mark
Total CAPEX	Rp. 15,157,180,183
Net annual cash flow	Rp. 1,265,900,545
Battery replacement (Year-11)	Rp. 1,321,200,000
Discount rate (WACC)	7.38%

The results of the calculation of economic indicators are presented in Table 9

Table 9. Results of the Economic Analysis of the PLTD–PLTH $_2$ –PLTS Scheme

Parameter	Mark
NPV	–Rp 2,731,499,089
IRR	5.48%
B/C Ratio	0.89
Payback Period	11.97 years

Although this scheme provides the greatest reduction in fuel consumption and emissions, the NPV value is still negative due to the high initial investment.

Table 10. Comparison of Economic Indicators Between Schemes

Parameter	Diesel Power Plant–Steel Power Plant	PLTD–PLTH $_2$	PLTD–PLTH $_2$ –PLTS
NPV	Rp. 1.41 billion	–Rp 2.05 M	–Rp 2.73 billion
IRR	9.56%	3.07%	5.48%
B/C Ratio	1.13	0.12	0.89
Payback Period	9th	14.78 years old	11.97 years old
Eligibility	Worthy	Not feasible	Marginal

Net Present Cost (NPC) calculation results And Levelized Cost of Energy (LCOE) served on Table 11 **.**

Table 11. Comparison of NPC and LCOE Between Schemes

Scheme	NPC (Rp)	LCOE (Rp/kWh)
Diesel Power Plant–Steel Power Plant	22,835,387,530	5,068
PLTD–PLTH $_2$	23,749,365,572	5,211
PLTD–PLTH $_2$ –PLTS	25,359,493,983	5,628

The PLTD–PLTS scheme produces the lowest LCOE and the most economical NPC, making it the financially optimal option for the Legundi Island electricity system. The technical, economic, logistical, and social factors influencing the success of hybrid systems are summarized in Table 12 .

Table 12. Factors Influencing the Success of Hybrid Systems

Category	Key Factors	Impact

Energy sources	Solar radiation, H_2 supply	Determining energy continuity
Technical	Efficiency of solar power plants, fuel cells, and BESS	System stability
Economy	Price H_2, CAPEX	Investment feasibility
Logistics	$_2$ Transportation	Supply reliability
Social	Human resources & community acceptance	Project sustainability

DISCUSSION

The ongoing challenges of providing reliable, cost-effective, and sustainable electricity to remote regions in Indonesia, such as Legundi Island, highlight the need for innovative energy solutions. The current reliance on diesel power plants (PLTD) has become unsustainable due to high operational costs, reliance on imported fuel, and environmental concerns. Hybrid Renewable Energy Systems (HRES), which integrate renewable energy sources such as solar, hydrogen, and conventional diesel generators, offer a promising solution to address these issues. This discussion builds on the findings of this study, which explores the feasibility and optimization of a diesel-solar-hydrogen hybrid system for Legundi Island, and compares it to traditional diesel-only systems.

The Viability of Hybrid Systems in Remote Islands

The integration of renewable energy sources, such as solar and hydrogen, into hybrid systems has been widely recognized as an effective means of improving energy reliability and reducing dependence on fossil fuels. According to the International Renewable Energy Agency (IRENA, 2021), hybrid systems that combine renewable sources with conventional energy backup can significantly enhance the resilience of isolated power systems, particularly in islands where access to a centralized grid is limited. The use of solar energy is particularly advantageous in tropical regions like Indonesia, where solar radiation is abundant throughout the year. Studies have shown that solar power systems, particularly in remote islands, can drastically reduce the reliance on diesel, improve operational efficiency, and lower electricity costs (Putra & Haryanto, 2021; Priyono, 2020).

This study confirms that hybrid systems, particularly those incorporating solar power, can provide a reliable and cost-effective solution to the energy challenges faced by Legundi Island. The integration of a 150 kWp solar power plant significantly reduces the amount of diesel fuel needed for electricity generation, resulting in substantial fuel savings. As the data shows, the use of solar energy can save approximately 103,640 liters of diesel per year, leading to an annual cost savings of around IDR 936 million. This reduction in fuel consumption is consistent with findings from other studies, such as Nuryanto et al. (2022), which highlight the cost-saving potential of hybrid systems that combine solar and diesel energy sources. These findings are also supported by Putri (2016), who demonstrated the economic benefits of integrating solar with diesel power plants in isolated systems.

Moreover, the use of hydrogen in hybrid systems adds an extra layer of flexibility and reliability. Hydrogen can serve as a storage medium for excess energy produced by solar panels during the day, ensuring that electricity is available even during the night or cloudy periods. This addresses one of the key limitations of solar power—its intermittent nature. The study's findings indicate that the integration of hydrogen as part of a diesel-solar-hydrogen hybrid system can further reduce diesel consumption and CO_2 emissions. According to the International Renewable Energy Agency (IRENA, 2021), hydrogen technology can store energy for long periods, making it an ideal solution for maintaining a continuous power supply in off-grid systems.

However, the economic feasibility of hybrid systems incorporating hydrogen is complex. The analysis reveals that while the diesel-solar-hydrogen system offers the highest CO_2 emissions reduction, it also has the longest payback period and the highest initial investment costs. The hydrogen component remains a costly addition, primarily due to high production and storage costs. This is consistent with the findings of Rahardjo (2022), who discusses the financial challenges associated with hydrogen power generation in Indonesia. Hydrogen infrastructure is still in its early stages, and the high capital expenditures (CAPEX) for hydrogen storage systems make it economically challenging for small-scale applications, especially in remote areas.

Cost and Environmental Benefits of Hybrid Systems

The economic advantages of hybrid systems are clear, with hybrid diesel-solar systems providing the most cost-effective solution for Legundi Island. As demonstrated in the simulation results, the diesel-solar hybrid system generates a positive Net Present Value (NPV) of IDR 1.41 billion, with an Internal Rate of Return (IRR) of 9.56% and a payback period of 9 years. These figures suggest that the diesel-solar hybrid system is economically feasible and provides a relatively quick return on investment. The Levelized Cost of Energy (LCOE) for this system is IDR 5,068/kWh, which is significantly lower than the LCOE of the diesel-only system, making it a more efficient and cost-effective solution for island electrification (Badan Pengkajian dan Penerapan Teknologi [BPPT], 2022).

The environmental impact of hybrid systems is also significant. Diesel power plants are major sources of CO_2 emissions, contributing to global warming and air pollution. By integrating solar power into the energy mix, the study shows that CO_2 emissions can be reduced by up to 55%, which aligns with Indonesia's national energy policy and decarbonization targets. The reduction in diesel consumption directly translates into a decrease in greenhouse gas emissions, which is a crucial step toward meeting Indonesia's commitment to reducing its carbon footprint and achieving Net Zero Emissions by 2060 (Ridawan Institute, 2023).

The use of hydrogen further enhances the environmental benefits of hybrid systems. As a clean energy carrier, hydrogen produces zero emissions when used in fuel cells. The combination of solar power and hydrogen can create a sustainable, low-emission energy system that reduces dependence on fossil fuels. According to the International Renewable Energy Agency (IRENA, 2022), the integration of hydrogen into energy systems is a key strategy for achieving a sustainable and decarbonized energy future. In the case of Legundi Island, the hybrid diesel-solar-hydrogen system could contribute significantly to Indonesia's efforts to transition to renewable energy and reduce its reliance on imported fossil fuels.

Challenges and Policy Implications

Despite the clear benefits, there are several challenges to the large-scale implementation of hybrid systems in remote island regions like Legundi. The most significant challenge is the high initial capital investment required for the installation of solar power plants, hydrogen storage systems, and associated infrastructure. As noted by the Ministry of Energy and Mineral Resources (ESDM, 2022), the cost of renewable energy infrastructure can be prohibitive for small island communities, particularly when there is limited access to financing.

To overcome these barriers, policy support and financial incentives are crucial. The Indonesian government's recent regulations, including Presidential Regulation No. 112/2022 on the Acceleration of Renewable Energy Development (Kementerian ESDM, 2022), provide a framework for incentivizing the adoption of renewable energy technologies. Policies that offer subsidies, tax incentives, or low-interest loans for renewable energy projects could help reduce the financial burden on remote island communities and make hybrid systems more accessible. Additionally, the government can support the development of hydrogen infrastructure through research and development funding and by fostering partnerships between public and private entities (Badan Pengkajian dan Penerapan Teknologi [BPPT], 2022).

The successful implementation of hybrid systems also depends on the social acceptance and involvement of local communities. As highlighted by Priyono (2020), community participation is essential for the sustainability of renewable energy projects in remote areas. Local stakeholders must be engaged in the planning and decision-making processes to ensure that the hybrid systems meet their energy needs and are aligned with their economic and social priorities. Furthermore, the capacity building of local human resources to operate and maintain renewable energy systems is crucial for the long-term success of such projects.

CONCLUSION

This study evaluates the technical and economic performance of a hybrid power generation system consisting of a diesel power plant (PLTD), a solar power plant (PLTS), and a hydrogen-based power plant ($PLTH_2$) within the isolated electricity system of Legundi Island. The analysis indicates that the existing diesel power plant operates with low efficiency due to underutilized capacity, resulting in high electricity production costs and excessive diesel fuel consumption. The integration of a 150 kWp solar power plant is identified as the most economically optimal solution, offering substantial fuel savings and investment feasibility based on key economic indicators. Meanwhile, the implementation of $PLTH_2$ provides notable technical and environmental benefits by reducing diesel consumption and carbon emissions; however, it remains financially unfeasible due to high investment costs and hydrogen prices. The combined diesel–PLTS–$PLTH_2$ configuration delivers the best technical performance but still requires policy support and economic incentives to enable large-scale implementation. Overall, the findings confirm that renewable energy–based hybrid systems, particularly solar power integration, have strong potential to improve efficiency, lower operational costs, and support a sustainable energy transition in remote island regions of Indonesia.

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