VICTORIA UNIVERSITY OF WELLINGTON TE HERENGA WAKA NEW ZEALAND
Archives of Sustainable Energy Systems
https://www.wgtn.ac.nz/sustainable-energy-systems

Techno-economic analysis of hybrid wave energy and floating photovoltaic systems in remote islands: A case study in Indonesia

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Abstract
Remote islands in Indonesia continue to face significant challenges in achieving reliable and sustainable electricity access, with diesel-based systems dominating energy supply despite high operational costs, limited availability, and environmental drawbacks. This research investigated the techno-economic feasibility of two renewable energy configurations for achieving 24-hour electrification on remote islands, using Pulau Enggano as a representative case. Scenario 1 combines a floating photovoltaic (FPV) system, a wave energy converter (WEC), and battery storage, while Scenario 2 relies solely on FPV and battery systems. Using the System Advisor Model (SAM) of NREL for performance simulation and an annuitizing method for Levelized Cost of Electricity (LCOE) analysis, both systems were designed to meet hourly and annual energy demands. Scenario 1 achieved an LCOE of USD 306/MWh, offering a more stable supply profile with reduced battery cycling. Scenario 2, though technically sufficient, resulted in a higher LCOE of USD 382/MWh due to larger storage requirements. Both scenarios were compared against the adjusted diesel generation cost of USD 246/MWh. Sensitivity analysis revealed that WACC and CAPEX are the most influential factors on economic performance, particularly for Scenario 2. Battery cost uncertainty also significantly impacted the LCOE of the battery-dependent system. This study concludes that hybrid renewable energy systems leveraging both solar and marine resources can deliver continuous power more economically and reliably than solar-only alternatives, especially when supported by appropriate financing mechanisms. The research highlights the need for targeted policy support—such as subsidy reforms and capital incentives—to enhance the competitiveness of clean energy in Indonesia's remote regions. Future research is recommended to assess the role of bioenergy alternatives like palm oil biodiesel and to expand real-world resource validation using long-term time series data.

Keywords: Hybrid electricity generation; Renewable energy; Remote island communities.

1 Introduction
Island nations often face unique challenges in meeting their energy needs due to their geographical isolation and limited access to conventional energy resources. These challenges often result in a heavy reliance on imported fossil fuels, leading to high energy costs, supply vulnerabilities, and significant environmental impacts (Gerrard and Wannier, 2013). Renewable energy has become a crucial component in addressing energy challenges, particularly in mitigating climate change and reducing dependency on fossil fuels. For remote islands, the reliance on diesel fuel for electricity generation presents not only environmental concerns, but also significant economic burdens (Jufri et al., 2021).

Indonesia, as the world's fourth most populous nation and an archipelago, exemplifies these issues with its transition from a net oil exporter to a net importer, heavily subsidised fossil fuel prices, and strong dependency on oil for its gross domestic production. Although, from a national perspective, the electrification ratio was already 99.78% in 2023 (MEMR, 2024), many of these islands are remote and face unique energy accessibility issues, making the transition to sustainable energy sources both necessary and complex (see Figure 1). In addition, the country's diverse and distributed power supply system presents significant logistical hurdles for energy distribution and management (Kunaifi et al., 2020). The country also set ambitious targets to increase its renewable energy share to 23% by 2025 (MEMR, 2024).

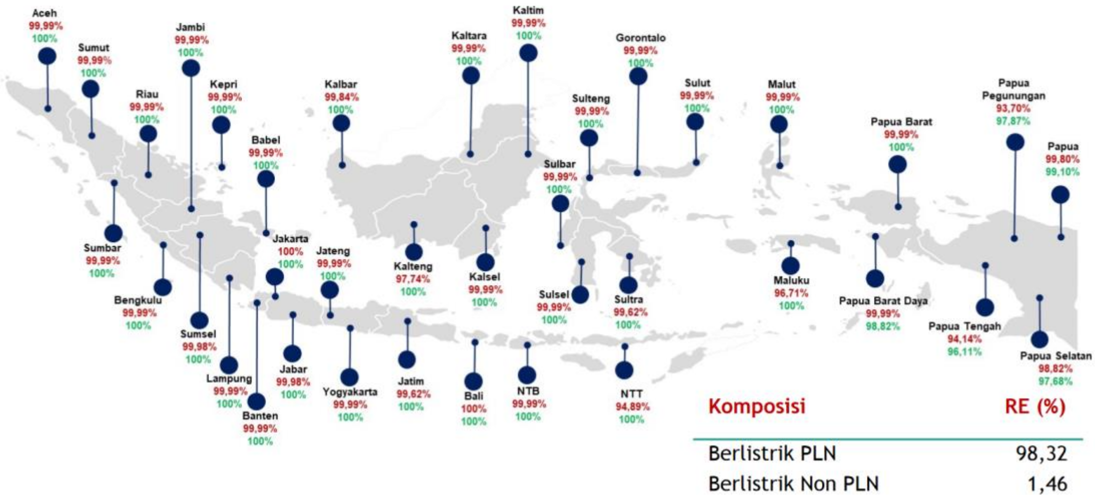

Figure 1. Indonesia's electrification ratio in 2023
(Source: MEMR, 2024)

Marine energy and floating photovoltaic (FPV) systems are promising solutions for these challenges. Marine energy such as tidal and wave energy can harness predictable and abundant energy from ocean tides and waves and offers a reliable source of power. However, FPV systems capitalise on the extensive water surfaces available around islands, thereby providing an efficient and space-saving method for generating solar power (Dzamesi et al., 2024; Liu et al., 2017). The integration of FPV systems within hybrid marine energy frameworks presents a promising avenue for sustainable energy generation. This research indicates that such systems not only optimise the use of marine space but also contribute to environmental conservation and economic feasibility. Advancements in FPV technology and its successful implementation in various regions suggest a strategic role in meeting renewable energy targets and supporting the transition to a cleaner energy future (Campana et al., 2018; Dzamesi et al., 2024; Liu et al., 2017; López et al., 2020; Singh, 2022; Srinivasan et al., 2024).

Indonesia has substantial solar energy potential, owing to its tropical location, which provides high solar irradiance year-round. The World Bank's solar resource mapping reveals that Indonesia receives an average of 4.5 to 5.5 kWh/m²/day of solar radiation, making it suitable for photovoltaic (PV) power generation. This consistent solar radiation can support utility-scale solar projects as well as off-grid systems for remote and rural areas. Additionally, Indonesia's government has been actively promoting solar energy through policy frameworks aimed at increasing the share of renewables in the national energy mix, with a target of 23% by 2025 (World Bank, 2017).

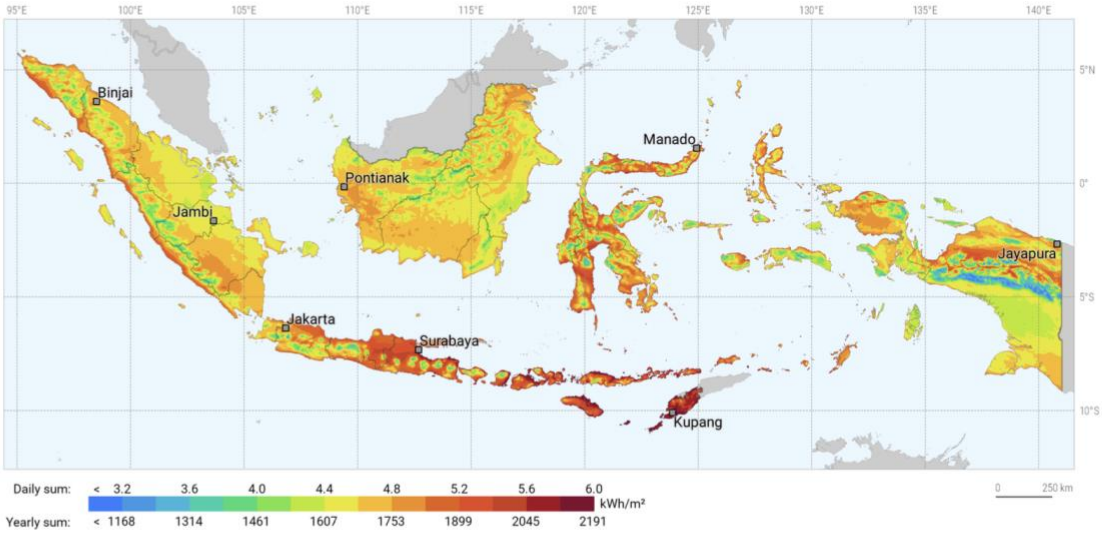

Figure 2. Global Tilted Irradiation at optimum angle – long-term average of daily and yearly totals
(Source: Solargis)

In addition to solar energy, Indonesia's vast marine resources offer significant potential for ocean renewable energy (ORE) development. Covering 70% of the nation's territory, the seas around Indonesia provide abundant energy from currents, tides, and waves. GIS-based studies have identified suitable locations for tidal and wave energy generation, particularly in eastern Indonesia, where ocean current speeds can reach up to 3 m/s, offering high potential for energy production (Purba et al., 2015). These ocean resources could complement solar power in hybrid energy systems, providing a continuous and reliable energy supply to remote islands. However, the development of marine energy technologies in Indonesia faces challenges related to the harsh ocean environment, as well as the need for advanced technology to capture and convert this energy efficiently.

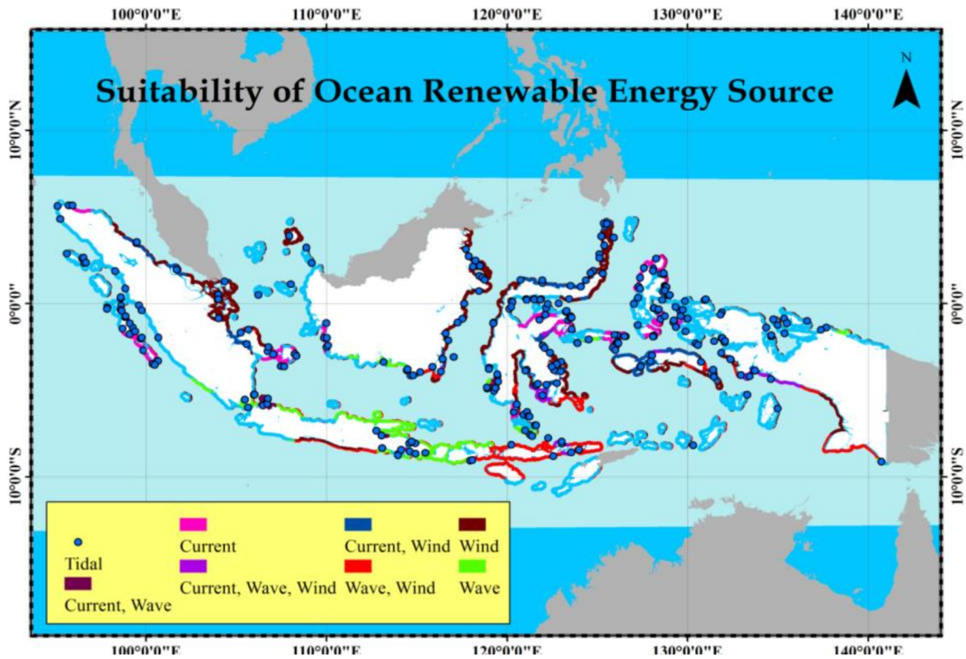

Figure 3. Map of potential locations of marine energy sources
(Source: Purba et al., 2015)

Despite advancements in renewable energy, there remains a critical gap in the research on hybrid systems that combine wave energy and FPV systems, specifically for remote island applications. Previous research has explored the technical and economic feasibility of individual renewable energy systems (Campana et al., 2018; Dzamesi et al., 2024). However, there is a lack of studies examining the potential benefits of combining these systems in a hybrid approach or focusing on island contexts. There is a need for further research on the techno-economic analysis of hybrid renewable energy systems, particularly in remote island areas where energy access is limited.

1.1 Objective of the paper

A preliminary review suggests that remote islands in Indonesia suffer from unreliable and unsustainable energy supplies owing to their dependence on diesel generators. This leads to high operational costs, frequent power outages, and significant environmental impacts. Despite the potential of renewable energy sources, such as waves and FPV systems, there is limited research on their combined application for the unique conditions of these islands.

The objective of this study is to evaluate the technical and economic viability of hybrid wave energy and FPV systems in a remote island area in Indonesia compared to existing systems and to identify potential policy implications for local, provincial, and national government. Specifically, this study aims to:

- Assess the technical feasibility and performance of a hybrid system;
- Conduct a comprehensive economic analysis, including the calculation of levelized cost of energy (LCOE); and
- Provide policy recommendations to facilitate the adoption and implementation of energy systems on remote islands.

2 Literature review

This section explores the key themes of renewable energy resource availability, characteristics and suitability of FPV and WEC technologies, methods of energy storage integration, and the financial and economic evaluation methodologies applicable to hybrid systems. Furthermore, knowledge gaps and opportunities that justify this research are identified. It ultimately serves to position the research clearly within the broader academic and practical discourse, highlighting the relevance and necessity of exploring integrated renewable solutions tailored specifically to island electrification challenges in Indonesia and similar settings globally.

2.1 Floating PV systems

The existing literature provides insights into the potential of FPV systems, highlighting their advantages, such as efficient land use, reduced water evaporation, and improved energy generation due to cooler operating temperatures (Agrawal et al., 2022; Dzamesi et al., 2024). The global capacity of FPV installations has been growing rapidly, reaching 2.6 GW in 2020 with projections of 4.8 GW by 2026 (Dzamesi et al., 2024). A conventional FPV system for offshore installations comprises of PV panels, inverters, floating platforms, mooring systems, and anchoring mechanisms (Srinivasan et al., 2024) as shown in Figure 4.

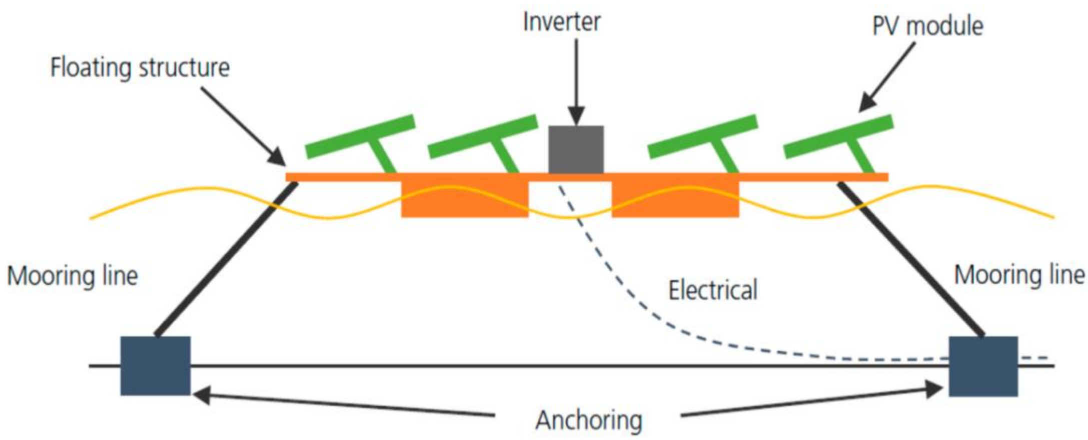

Figure 4. Typical floating solar PV system components
(Source: Srinivasan et al., 2024)

Different design configurations have been proposed for FPV systems. Dzamesi et al. (2024) described a floating structure using high-density polyethylene (HDPE) blocks for easy installation on water reservoirs, dams, small rivers, and lakes. They highlighted that these structures are designed to withstand typhoon conditions and resist corrosion and ultraviolet rays.

One of the key advantages of FPV systems is their potential for increased energy yield and efficiency compared to land-based PV systems. This improvement is primarily attributed to the cooling effect of water on the PV panels and reflected light in bifacial modules (Dzamesi et al., 2024). Srinivasan et al. (2024) reported an increase in annual energy yield of 2.31% for a floating PV system compared to an equivalent ground installation. They attributed this increased efficiency to the natural cooling effect of water on the PV panels, which helps maintain optimal operating temperatures.

Dzamesi et al. (2024) emphasized that floating photovoltaic (FPV) systems offer significant economic advantages over land-based installations in areas with high land costs, while simultaneously reducing social conflicts through minimal site preparation requirements. Furthermore, they highlighted FPV's potential to positively impact remote communities by harnessing underutilized water bodies for renewable energy generation, while noting the added benefit of reduced reservoir evaporation—a critical advantage for water-scarce regions.

However, FPV systems also face unique challenges in marine environments. Srinivasan et al. (2024) and Dzamesi et al. (2024) identified issues such as resistance to saltwater corrosion, coping with wave and wind loads, and maintaining stability in varying water levels. They suggested that solutions including the use of corrosion-resistant materials, optimized mooring systems, and elevated platform designs.

The implementation of FPV systems often falls under existing renewable energy policies. Agrawal et al. (2022) noted that in India, the government has set ambitious targets for solar power generation to 100 GW by 2022, which could drive the adoption of FPV technology. However, specific regulations for FPV systems, particularly in marine environments, are still developing in many regions.

2.2 Wave energy

Wave energy, generated by the movement of ocean waves, represents a significant renewable power source harnessed through wave energy converters (WECs). As waves traverse water, they transfer kinetic energy that can be captured for electricity generation or water pumping applications (Chen, 2023). The energy output depends critically on wave height, water density, and wave period parameters, with higher wave strength enhancing power generation efficiency. Wave energy converters (WECs) come in various forms, including oscillating water columns, overtopping devices, and oscillating surge wave converters (Chen, 2023; Khan, 2017). These systems typically range in capacity from 100 kW to several megawatts, though their performance varies substantially depending on local wave conditions (Astariz and Iglesias, 2015).

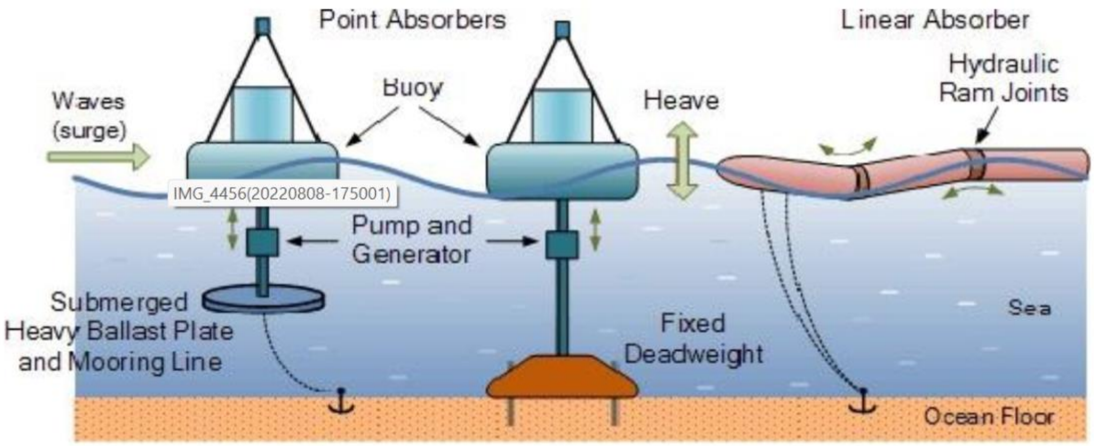

Figure 5. Generation of wave energy
(Source: Chen, 2023)

Despite its considerable potential, wave energy faces significant economic challenges. The levelized cost of energy (LCOE) ranges from 90–490 €/MWh, far exceeding costs of established renewables like solar PV (Astariz and Iglesias, 2015). Both capital expenditures and operational costs remain elevated due to the harsh marine environment. Nevertheless, opportunities for cost reduction exist through hybrid system configurations and shared infrastructure (Roy et al., 2018). Technical hurdles compound these economic challenges, including device survivability under high axial stresses identified by Bahaj and Myers (2003), corrosion resistance requirements, mooring system durability, and grid integration of variable outputs. Current research focuses on energy management system, sizing optimization, and more robust engineering designs to address these limitations (Roy et al., 2018).

Globally, marine renewable energy (MRE) policy frameworks coalesce around three interdependent pillars: research and innovation support, market-based incentives, and regulatory streamlining, each addressing deployment barriers exacerbated in remote island contexts. Research and innovation policies prioritize public funding to de-risk growing technologies, exemplified by Germany's allocation of €34.6M for offshore wind R&D in 2008 (Portman, 2010) and Portugal's Wave Energy Centre in 2003, which advanced wave converters resilient to island conditions in the Azores (Portman, 2010). These efforts mitigate intermittency challenges inherent in remote island areas by using hybrid systems, such as solar-wave-tidal, which reduce diesel dependency (Roy et al., 2018). Portman (2010) mentions further that market incentives, such as Portugal's technology-specific feed-in tariff (€0.23/kWh for wave energy) and the UK's Wave and

Tidal Stream Energy Demonstration Scheme, offset capital costs and enhance investor certainty. For islands, such mechanisms are critical to overcoming levelized cost of energy (LCOE) disparities.

Regulatory efficiency is achieved through jurisdictional consolidation (e.g., the UK's Marine Management Organisation subsuming 14 permits) and Germany's presumption-of-approval model, mandating approval absent explicit environmental risks (Portman, 2010). Portugal's Maritime Pilot Zone that started in 2008 demonstrates how pre-zoned ocean space integrates environmental assessments and grid corridors to expedite permitting (Portman, 2010), directly addressing island-specific constraints like fragmented governance and prohibitive grid-connection costs (Roy et al., 2018). Crucially, these policies enable energy sovereignty by displacing diesel imports, creating local maintenance jobs, and stabilizing supply, though persistent obstacles include unbalanced technology maturity and high storage costs for hybrid systems (Roy et al., 2018). Policy transferability thus requires adaptation to island socioecological contexts, particularly in balancing rapid deployment with environmental safeguards.

2.3 Battery storage technologies

Battery storage is indispensable for stabilizing energy supply in hybrid wave-FPV systems, particularly in remote island contexts where intermittent renewable generation demands reliable energy shifting. Among available technologies, lithium-ion batteries (Li-ion) and vanadium redox flow batteries (VRFB) represent two prominent solutions with distinct operational profiles.

Lithium-ion batteries dominate stationary storage deployments due to their high energy density of around 250 Wh/kg and high round-trip efficiencies (85–95%), making them suitable for space-constrained island sites (Zakeri and Syri, 2015). However, they exhibit accelerated degradation in high temperature which consistent on tropical climate, with risk of capacity and power fade (Samadani et al., 2015; Saxena et al., 2021). Resource scarcity of cobalt and nickel, a critical Li-ion components, also raises supply-chain vulnerabilities and ethical mining concerns due to their high depletion impacts, geopolitical concentration, and co-extraction of ecotoxic byproducts during ore processing (Peters and Weil, 2016). Despite these constraints, Li-ion's minimal maintenance requirements remain advantageous for remote deployments.

Vanadium redox flow batteries (VRFB) present a compelling alternative through their decoupled energy/power scaling and aqueous electrolyte chemistry. Their non-flammable vanadium sulphate solutions eliminate combustion hazards, while recyclable electrolytes enable exceptional longevity exceeding 20,000 cycles with minimal capacity fade (World Bank, 2024). This translates to lifespans of 20–25 years in humid environments, outperforming Li-ion in durability (World Bank, 2024). Nevertheless, VRFBs suffer from lower energy density around 10–50 Wh/kg, requiring larger footprints, and higher capital costs (USD 275–300/kWh) compared to Li-ion equivalents (Alotto et al., 2014; World Bank, 2024).

When evaluating suitability for Indonesian island contexts, VRFB's resilience in humid environments and superior cycle life often offset higher initial investments, particularly for long-duration storage (>6 hours) where lifetime cost parity becomes achievable (World Bank, 2024; Zakeri & Syri, 2015;). Lithium-ion batteries retain advantages in space-constrained installations, but their viability depends critically on robust thermal control systems. These contrasting performance characteristics between storage technologies highlight the necessity of context-driven battery selection for hybrid energy systems.

2.4 Hybrid systems

While different sources in literature discuss the optimisation and feasibility of FPV systems in various contexts, including their integration with pumped storage hydroelectric systems (Shyam and Kanakasabapathy, 2022) and their use in offshore facilities (Srinivasan et al., 2024), there is no direct mention of their combination with wave energy systems. The lack of exploration into the combined use of waves and FPV systems presents an interesting gap in research. Such a combination could potentially address the limitations inherent in each, such as the intermittency of solar power and the site-specific nature of tidal energy.

Existing literature on techno-economic analyses of hybrid renewable energy systems, including FPV systems, provides valuable insights into the feasibility and performance of these technologies in various contexts. Srinivasan et al. (2024) presents a techno-commercial feasibility study of an battery-integrated system for an offshore platform, with Levelized Cost of Electricity (LCOE) of 261 USD/MWh a payback period of 9.5 years. These studies focused on FPV systems and other hybrid configurations, such as photovoltaic mini-grid systems (PMs), hybrid wind/PV/diesel/battery power systems, and FPV integrated with shrimp farming operations (Akinyele, 2017; Campana et al., 2018; Dedoussis, 2022; Uddin et al., 2021).

Interestingly, while these studies do not discuss hybrid waves and FPV systems in combination, they do offer case studies and analyses of FPV and other renewable systems in remote and island locations. For instance, Dedoussis (2022) examined the techno-economic aspects of hybrid electricity power supply systems on isolated Greek islands with an average LCOE of 168 €/MWh, and Campana et al. (2018) evaluated the integration of FPV systems into a shrimp farm in Thailand. These studies highlight the potential of FPV systems to contribute to the energy mix in remote areas and offer insights into their economic viability and environmental benefits. Jufri et al. (2021) evaluated hybrid renewable energy for Indonesian remote areas and showed that they can decrease the cost of electricity generation by 50%. Syafii et al. (2021) investigated the potential of hybrid PV and wind turbines in remote islands in Sumatera with an LCOE of $96/MWh with relatively low investment and operating cost.

While these costs are higher than conventional grid-connected systems, they may be competitive in the context of remote island electrification where traditional grid extension is not feasible. Currently, the cost of electricity production in remote Indonesian islands ranges between $165-200 USD/MWh in 2017 without subsidies (Setyawan, 2018), making renewable alternatives like FPV and hybrid systems increasingly attractive due to the high costs associated with diesel-generated power. However, with government subsidies, the actual price paid by consumers in these regions can drop to as low as USD $39/MWh, creating a significant pricing gap that renewable projects must address to remain competitive.

The combination of FPV systems with wave energy converters offers several potential synergies. As highlighted by Roy et al. (2018), hybrid systems can leverage the complementary nature of different renewable sources to improve overall reliability and efficiency. For Indonesia's remote islands, this could mean more consistent power generation throughout the day and night, as tidal or wave energy can complement the intermittent nature of solar power.

While specific examples of integrated FPV-wave systems are not available in literature, the potential benefits of such hybrid configurations can be inferred from the works of Astariz and Iglesias (2015) and Roy et al. (2018). These include increased energy reliability through diversified sources, improved capacity factors and overall system efficiency, shared infrastructure and reduced costs for installation and maintenance, more consistent power output by leveraging complementary resource availability, and enhanced grid stability through combined output smoothing.

3 Research methods

The research approach combined site selection based on multi-criteria evaluation, energy system simulation using the System Advisor Model (SAM) of NREL, and economic analysis based on Levelized Cost of Electricity (LCOE).

The study adopted a scenario-based simulation model. Two technical configurations were developed to assess the generation adequacy and economic viability of hybrid and standalone renewable systems. The analysis was conducted using secondary data and simulation models, reflecting what would have been implemented under those design conditions.

3.1 Site selection criteria

Identifying a suitable location was a critical step in assessing the feasibility of a hybrid renewable energy system integrating FPV and wave energy technologies. The site selection process was guided by a set of criteria focused on both technical potential and socio-economic impact.

First, the selected site needed to demonstrate sufficient renewable resource availability. Specifically, high solar irradiance levels (typically above 4.5 kWh/m^2/day) and consistent wave activity with adequate energy periods and significant wave height were required to support stable generation from both FPV and wave energy converters. These resource characteristics needed to be available throughout the year, with minimal seasonal variation that could compromise supply reliability.

Second, the site was expected to have limited or unreliable access to grid-based electricity, often seen in remote or isolated island communities. Preference was given to locations currently reliant on diesel-based power generation, where high operational costs, fuel transport challenges, and environmental concerns present compelling reasons for a renewable energy transition.

Socio-economic factors were also integral to the selection process. The target location needed to have a small- to medium-sized population whose development prospects were constrained by limited energy access. A high dependency on subsidized fossil fuels and low electricity supply duration (e.g., less than 24 hours per day) were indicative of regions where renewable energy systems could offer transformative benefits.

Geographical characteristics were evaluated to ensure compatibility with floating PV deployment—such as the availability of calm, protected water bodies—as well as sufficient coastal space and bathymetry to support wave energy installations.

Accessibility for future maintenance and technology deployment, including distance from the mainland or logistical hubs, was also considered.

Ultimately, the site selection process aimed to identify a location where the implementation of hybrid renewable energy could deliver meaningful improvements in energy security, economic sustainability, and environmental performance, while also serving as a replicable model for similar communities across Indonesia's archipelagic regions.

3.2 Data collection

This study relied on secondary data sources. No primary data collection was undertaken, and all input data were compiled from publicly available databases, published research, and simulation tools. Key data categories included renewable resource profiles, technical performance benchmarks, economic cost parameters, and hourly load.

3.2.1 Solar and wave resource data

Solar resource data were sourced from the National Solar Radiation Database (NSRDB), which is directly accessible through the System Advisor Model (SAM) interface. The NSRDB provides satellite-derived solar radiation data specific to geographic coordinates, including Global Horizontal Irradiance (GHI), Direct Normal Irradiance (DNI), and weather variables at hourly intervals. For this study, the location accurate NSRDB dataset was selected to represent conditions over the selected island region, ensuring alignment with the floating PV system simulation inputs.

Wave energy data were extracted from published joint probability tables that classify wave heights (Hs) and energy periods (Te) over an annual cycle. These data were transformed into hourly time series representing Significant Wave Height (Hs) and Energy Period (Te) using a Monte Carlo-based probabilistic sampling method. The reconstructed time series consisted of 8,760 hourly values covering a full representative year, enabling simulation of wave energy generation in SAM.

3.2.2 Load profile estimation

The load profile used in this study was based on existing data from previous research and national utility reports. Specifically, daily load distribution was derived from documented operational records and visual load curve references from PLN (Indonesia's state electricity company) and relevant academic studies of diesel-powered systems operating in remote islands. These sources provided a typical 24-hour consumption pattern, characterized by early morning and evening peaks, consistent with residential and small commercial usage in isolated communities (see the Supplementary Material).

The base year for the available data corresponded to 2021, during which the annual electricity consumption and number of active customers were recorded. To reflect present-day conditions, this data was updated by incorporating more recent customer growth figures available from local statistical agency and applying an average national economic growth rate of 5% per annum to estimate increased electricity demand. These adjustments allowed the calculation of a revised annual consumption value, which served as the energy demand target for system sizing and simulation.

The daily load curve was normalized and scaled to match the updated annual energy requirement. It was then extended into an hourly time series for the full simulation year (8,760 hours), assuming consistent daily patterns throughout. While the profile does not account for potential seasonal or event-based variations in demand, it accurately represents the typical diurnal load dynamics observed in small island systems within Indonesia's archipelago.

3.2.3 Economic input data

Capital expenditures (CAPEX), operational expenditures (OPEX), and component-specific replacement costs were collected from the Technology Catalogue for the Indonesian Power Sector (MEMR and DEA, 2024) and academic literature. All costs were normalized to 2023 USD and scaled according to system size. Financial parameters such as a 10% Weighted Average Cost of Capital (WACC), 11% annuity factor, and 25-year system lifetime were applied consistently across both scenarios.

3.3 System configuration and scenario design

To assess the technical and economic feasibility of hybrid renewable energy systems suitable for small island electrification in Indonesia, two configuration scenarios were conceptualised. These scenarios represent conceptually distinct approaches to meeting the full hourly electricity demand of a remote community using locally available renewable resources and energy storage.

The first configuration models a hybrid system combining FPV, wave energy, and battery energy storage. This setup was developed to leverage the complementary characteristics of solar and marine energy resources—where solar generation typically peaks during midday, while wave energy provides a more continuous supply across the day and night. The inclusion of both energy sources allows for a reduction in battery capacity requirement by minimizing the gap between generation and demand during non-solar hours.

The second configuration simulates a system relying solely on FPV and battery storage, without any contribution from marine energy. In this scenario, battery capacity is scaled to ensure full coverage of the electricity load during early morning, nighttime, and extended periods of low solar irradiance. The FPV component is oversized relative to the hybrid scenario to charge the batteries sufficiently during peak sun hours.

Both configurations were modelled using the System Advisor Model (SAM), which allows for the integration of custom resource data and detailed hourly simulation. The design process was iterative: component sizes were adjusted until each system was able to meet the hourly load across all days of the year, including under challenging seasonal or climatic conditions. To validate reliability, system performance was evaluated on selected reference days representing equinox and solstice conditions, capturing the natural variability of solar and wave resources.

This scenario-based simulation approach enabled a comparative analysis of how different configurations perform in terms of energy adequacy, operational flexibility, and economic efficiency, providing insights into the optimal design of renewable energy systems for remote and off-grid applications in Indonesia.

3.4 Economic evaluation method

To assess the cost-effectiveness of the proposed energy system configurations, the Levelized Cost of Electricity (LCOE) was used as the principal economic indicator. LCOE is a widely applied metric that expresses the average cost per megawatt-hour (MWh) of electricity over the lifetime of a power-generating system. It enables consistent comparison across technologies with different sizes, operational characteristics, and financial structures. The LCOE reflects all relevant cost components—including capital expenditure (CAPEX), fixed and variable operation and maintenance (O&M) costs, replacement and ancillary costs, and, where applicable, fuel expenses—expressed in terms of constant dollars per unit of energy delivered.

LCOE can be computed using two standard approaches: the discounting method and the annuitizing method. The discounting approach calculates the present value of all costs and divides it by the present value of all energy outputs across the project's lifetime:

$$LCOE_{Discounting} = \frac{\sum_{y=0}^{n} \frac{C_y}{(1+r)^y}}{\sum_{y=0}^{n} \frac{E_y}{(1+r)^y}} \tag{1}$$

Where:
- C_y is the total cost in year y;
- E_y is the electricity output in year y;
- r is the discount rate; and
- n is the project lifetime in years.

Alternatively, the annuitizing method expresses total system costs as a fixed annual cost using a capital recovery factor, and divides it by the average annual energy generation:

$$LCOE_{Annuitizing} = \frac{Capex \cdot \left(\frac{r \cdot (1+r)^n}{(1+r)^n - 1}\right) + fO\&M + O_c}{\left(\frac{\sum_{y=1}^{n} E_y}{n}\right)} + vO\&M + F_c \tag{2}$$

Where:
- fO&M and vO&M are the fixed and variable operating and maintenance costs;
- O_c represents other recurring annual costs;
- F_c is the fuel cost per MWh (which is zero for renewable scenarios); and
- The capital recovery factor converts CAPEX into an equivalent annual cost.

The annuitizing method was adopted in this study following the methodology presented in the Technology Catalogue for the Indonesian Power Sector (MEMR and DEA, 2024). This approach is well-suited for hybrid renewable energy systems that include storage, as it allows additional cost layers (e.g., battery replacement, degradation effects) to be incorporated within a unified annual cost framework. When using a consistent discount rate and assuming stable annual generation, both the discounting and annuitizing methods produce equivalent LCOE values. Given these conditions hold in this study, the annuitizing approach was selected for its alignment with prior hybrid energy modelling applications.

4 Results and discussion

The technical feasibility, economic viability, and practical implications of replacing an island's existing diesel-based electricity system with renewable energy was evaluated.

4.1 Selected site overview: Enggano Island

Enggano Island was selected due to its favourable renewable resource potential, the urgent need for improved energy infrastructure, geographic isolation, and alignment with national renewable energy policies. The criteria guiding site selection included renewable resource availability, existing infrastructure, accessibility, local energy demand and data availability. Enggano Island meets these criteria, demonstrating substantial potential for both floating photovoltaic and wave energy technologies.

4.1.1 Geographical and socio-economic profile of Enggano Island

Enggano Island is situated approximately 110 nautical miles off the coast of Bengkulu Province in Indonesia, within the Indian Ocean (see Figure 6). Geographically isolated, the island spans approximately 400.6 km^2 and is home to around 4,189 residents (BPS Bengkulu Utara, 2024). The island's economy primarily revolves around agriculture, fisheries, and modest tourism activities. The limited infrastructure and transportation access significantly influence local socio-economic dynamics, reinforcing the necessity for a stable, reliable, and sustainable energy supply.

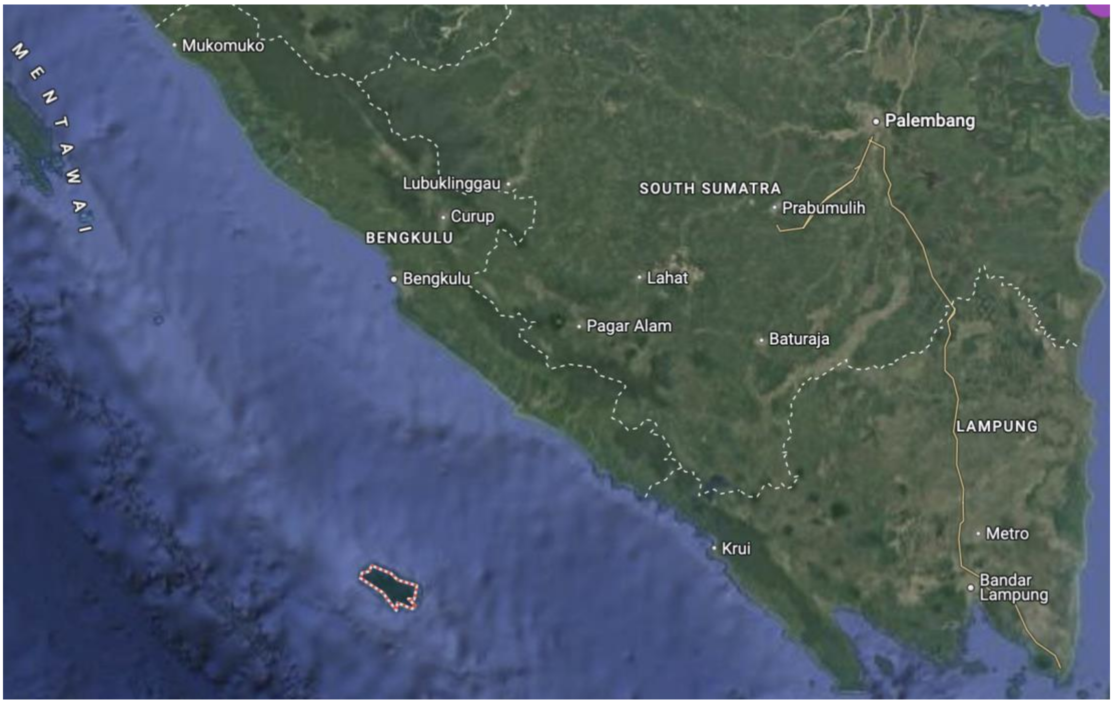

Figure 6. Enggano Island Location
(Source: GoogleMaps)

The socio-economic conditions are characterized by low income, limited employment opportunities, and challenges in accessing basic services. Energy supply improvements can directly enhance quality of life, economic productivity, and educational opportunities, furthering sustainable socio-economic development objectives.

Currently, Enggano Island relies on a diesel-based power plant (PLTD) with an installed capacity of approximately 730 kW. This diesel power system served around 1,050 customers and generated approximately 1,097,883 kWh annually as of 2021 (Sari et al., 2022). By 2023, the number of customers increased to approximately 1,266 (BPS Bengkulu Utara, 2024), driving annual energy demand up to approximately 1,458,432 kWh, reflecting local economic growth and historical electricity consumption patterns.

However, the existing diesel-based power generation infrastructure presents significant economic, operational, and environmental challenges. Economically, the diesel generation cost was approximately $200 per MWh in 2017 (Setyawan, 2018). Adjusting for cumulative inflation of approximately 23% by 2023, this cost increased to around $246 per MWh, illustrating growing economic inefficiency. Operationally, the diesel-based system provides electricity only intermittently, typically limited to about 16 hours daily. This intermittent supply severely restricts economic productivity, social activities, and the overall convenience and quality of life for the residents. Additionally, diesel generation has considerable environmental impacts, contributing substantially to air pollution and greenhouse gas emissions. These emissions negatively affect local air quality and undermine the island's environmental sustainability.

These critical economic, operational, and environmental challenges highlight the strategic necessity for transitioning Enggano Island's energy supply toward renewable energy solutions. Integrating hybrid renewable systems, particularly Floating Photovoltaics (FPV) and wave energy converters, can (potentially) offer a robust, reliable, economically feasible, and environmentally sustainable alternative to diesel generation.

Figure 7. Proposed site locations
(Source: Modified from GoogleMaps)

4.1.2 Enggano Island energy potential

Enggano Island possesses substantial solar energy potential, characterized by high solar irradiance averaging between 4.0 to 5.5 kWh/m^2/day (Sari et al., 2022). This level of solar irradiance provides favourable conditions for deploying floating photovoltaic systems, allowing efficient energy generation to reliably support local electricity demand. Moreover, Enggano's geographic location in the Indian Ocean provides a promising wave energy potential. Wave energy assessments indicate substantial resource availability, with wave heights typically ranging between 1 to 3 meters and wave periods from 6 to 8 seconds (see Table 1), creating good conditions for the deployment of wave energy converters such as the Oscillating Surge Wave Converter (OSWC). Utilizing these abundant and complementary renewable resources offers a significant opportunity to address Enggano Island's pressing energy challenges comprehensively, reducing reliance on imported fossil fuels and mitigating associated environmental impacts (Sari et al., 2022). Figure 7 indicates the potential sites for the deployment of the technology systems.

Table 1. Wave distribution on Enggano Island (2012-2016)
(Source: Setyawan, 2018)

Hs (m)	Tz (s)										
	0 - 1,0	1,0 - 2,0	2,0 - 3,0	3,0 - 4,0	4,0 - 5,0	5,0 - 6,0	6,0 - 7,0	7,0 - 8,0	8,0 - 9,0	9,0 - 10,0	> 10,0
0 - 0,5	0	0	88	0	0	0	0	0	0	0	0
0,5 - 1,0	0	0	0	0	11	26	2	0	0	0	0
1,0 - 1,5	0	0	0	0	16	158	195	63	0	0	0
1,5 - 2,0	0	0	0	0	0	150	322	187	74	13	0
2,0 - 2,5	0	0	0	0	0	12	141	117	76	44	13
2,5 - 3,0	0	0	0	0	0	0	22	46	22	26	11
>3,0	0	0	0	0	0	0	1	3	10	3	8

The numerical values in each cell represent the number of occurrences (frequency) within the periods for specific combinations of significant wave height (Hs, in meters) and wave energy period (Tz, in seconds). This joint probability distribution table was subsequently processed into an hourly wave climate time series using a probabilistic sampling approach. The resulting hourly wave dataset was then applied as input for wave energy converter simulations.

Table 2. Hourly wave dataset sample

	21 March		21 June		21 December	
Hour	**Hs**	**Te**	**Hs**	**Te**	**Hs**	**Te**
0	1.85	7.70	1.03	6.93	1.48	6.67
1	2.94	7.80	1.38	6.79	3.89	20.52
2	1.75	7.33	2.80	18.26	1.76	5.60
3	2.12	7.50	1.92	6.51	1.75	5.60
4	1.27	6.63	2.85	8.93	2.64	7.71
5	2.00	6.54	1.64	8.14	1.52	5.07
6	1.37	7.35	2.08	18.14	1.39	6.82
7	1.49	5.34	1.62	6.51	1.63	5.97
8	1.53	5.90	1.54	9.56	1.48	7.78
9	0.49	2.24	4.84	9.62	2.12	8.50
10	2.99	8.51	2.19	9.10	2.12	8.69
11	1.92	6.78	2.16	7.06	1.62	6.24
12	0.19	2.78	1.73	6.50	0.15	2.89
13	2.02	7.31	1.10	4.66	2.76	9.31

	21 March		21 June		21 December	
Hour	**Hs**	**Te**	**Hs**	**Te**	**Hs**	**Te**
14	2.93	18.62	2.05	7.22	0.66	5.28
15	2.24	7.80	1.42	7.16	1.23	6.54
16	2.20	8.21	1.54	7.40	1.91	8.79
17	1.59	6.78	2.93	8.24	1.95	5.82
18	1.15	5.04	0.17	2.34	1.85	5.07
19	2.37	9.38	1.85	6.77	1.26	5.90
20	1.71	9.49	1.65	7.56	2.29	8.26
21	2.75	16.86	0.10	2.90	1.10	6.97
22	5.00	21.80	0.71	5.71	1.80	6.34
23	1.32	7.58	1.66	6.89	1.03	6.88

4.2 Technical analysis

4.2.1 Hybrid system configuration

The hybrid energy system proposed for Enggano Island is carefully sized to reliably match the island's hourly electricity demand throughout the year (see the Supplementary Material). Unlike conventional system sizing methods that often rely solely on annual energy production totals, this analysis addresses the island's hourly load profile to ensure continuous electricity supply without deficit periods. Figure 8 illustrates Enggano Island's current typical daily load profile, featuring two distinct peaks occurring in the morning (06:00–09:00) and evening hours (18:00–21:00), with lower baseload demand during the night and early afternoon periods.

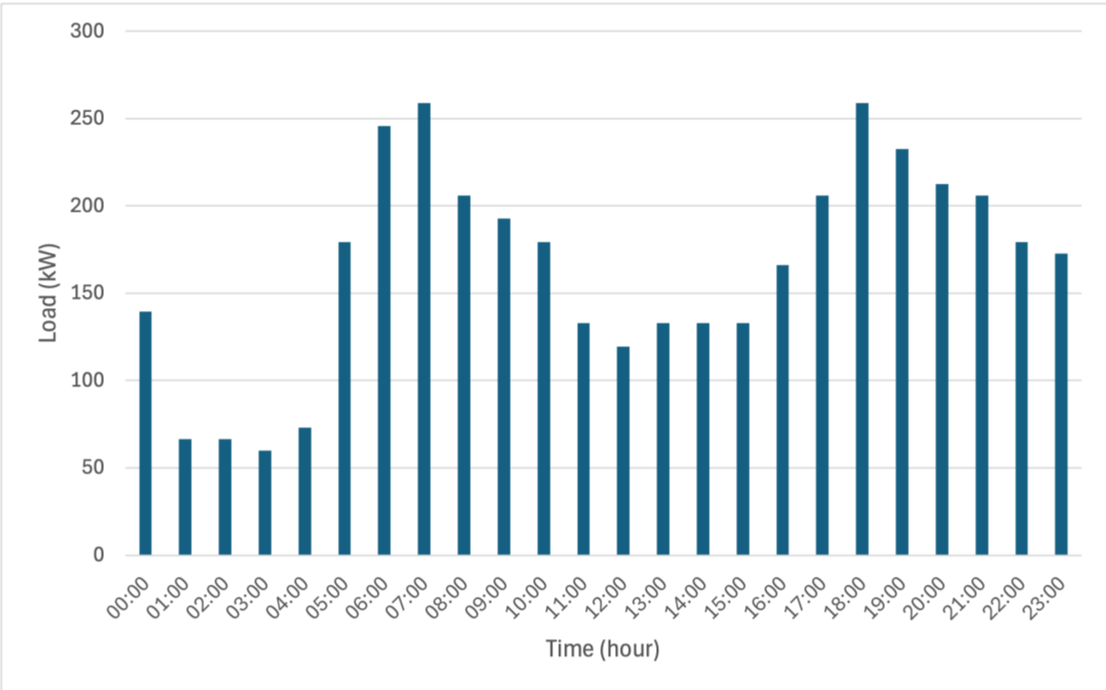

Figure 8. Enggano Island daily load
(Source: Modified from Sari et al., 2022)

To determine the optimal hybrid system sizes, detailed hourly simulations were conducted using the System Advisor Model (SAM), a renewable energy performance modelling tool developed by the National Renewable Energy Laboratory (NREL). Two distinct renewable energy scenarios were analyzed to achieve the desired level of reliability at the lowest possible installed capacities.

Scenario 1 integrates a 500 kW Wave Energy Converter (WEC) utilizing Oscillating Surge Wave Converter (OSWC) technology alongside a 1,350 kW Floating Photovoltaic (FPV) array and a battery storage system sized at 1.4 MW. The wave energy capacity was determined based on site-specific wave resource analysis as shown on Table 4.1, ensuring consistent power generation throughout the year. Due to the relatively fixed and complex nature of wave energy infrastructure sizing, adjustments in wave energy capacity are considerably more challenging once installed. Hence, the wave component was conservatively sized to meet consistent baseload requirements, leaving dynamic energy balancing largely to the FPV and battery systems.

The FPV and battery components, in contrast, were iteratively optimized through simulation to achieve the smallest feasible sizes that reliably cover all hourly demand, considering variations across seasons and daily solar resource fluctuations. This sizing approach aimed to achieve a configuration that precisely matches Enggano Island's demand peaks and troughs throughout the year, thus avoiding unnecessary overinvestment and reducing overall system cost.

Scenario 2 explores a system solely comprising FPV and battery storage, involving a larger 4 MW FPV system complemented by 2.9 MW (approximately 11.6 MWh) of battery storage. Given the absence of a complementary wave energy source in Scenario 2, the FPV system and battery capacities were significantly increased. The FPV size and associated battery storage were methodically scaled up through multiple iterations of SAM simulations, ensuring that even under challenging daily scenarios, the daily and hourly electricity demands could be consistently met without supply gaps.

Ultimately, both scenarios' system configurations reflect optimization to minimize installed capacity while fully meeting the island's specific hourly load patterns. It is important to note that floating PV and battery storage systems offer substantial modularity and flexibility. Thus, they can be more readily scaled or adjusted post-installation compared to wave energy systems, whose infrastructure is more capital-intensive, rigid, and less amenable to resizing.

4.2.2 Energy yield results

Annual energy yields for both renewable energy scenarios were assessed through detailed hourly simulations conducted with the System Advisor Model (SAM). These simulations considered local resource data, system efficiencies, and system sizes determined earlier. Scenario 1, combining a 1,350 kW Floating Photovoltaic (FPV) system with a 500 kW Wave Energy Converter (WEC), demonstrates a reliable complementary renewable energy mix, while Scenario 2 relies exclusively on a larger 4 MW FPV system.

For Scenario 1, the FPV component yields an annual AC energy production of approximately 2,117,632 kWh in the first year, corresponding to an 18% capacity factor. This energy yield is indicative of the favourable solar irradiation conditions at the Enggano Island site. The wave energy system contributes an additional annual production of approximately 885,200 kWh, operating with a capacity factor of 20%. The relatively modest capacity factor for the wave energy system reflects the limitations of the available simulation configurations within SAM, where the restricted technology options for WEC may not fully capture the site-specific wave resource potential of Enggano Island. Nonetheless, this stable and predictable energy production complements the intermittent nature of solar PV.

The combined annual renewable generation in Scenario 1 thus totals approximately 3,002,832 kWh. When compared to Enggano Island's projected annual electricity demand of 1,458,432 kWh, Scenario 1 provides a significant energy surplus. This surplus capacity is critical in effectively charging the battery storage systems, ensuring a continuous supply even during periods of lower renewable energy availability, and providing flexibility to accommodate future demand growth.

Scenario 2, involving a substantially larger FPV system of 4 MW capacity without any complementary wave energy, yields an annual AC energy production of around 6,379,162 kWh, reflecting the same 18% capacity factor observed in Scenario 1. This significantly larger production capacity primarily arises from the necessity to manage periods of reduced solar irradiance and longer-duration battery storage requirements. Consequently, Scenario 2 also generates substantial energy surplus beyond the island's demand.

The substantial excess generation in both scenarios is intentional, reflecting the design requirement to reliably fulfil Enggano Island's electricity needs across varying seasonal conditions and hourly demand profiles. The hybrid renewable mix of Scenario 1, however, demonstrates a balanced approach, utilizing the complementary characteristics of wave and solar resources, thus minimizing excess generation compared to the FPV-only approach of Scenario 2. The consistent output from wave energy provides substantial operational stability, reducing the battery storage requirement and limiting excessive oversizing of solar generation.

Overall, the analysis of these energy yield results highlights the importance of considering hourly and seasonal resource variability, local demand patterns, and the complementary nature of renewable resources when designing renewable energy systems for remote island contexts.

4.2.3 Performance and reliability analysis

To evaluate how effectively the two system configurations maintain continuous energy supply, three representative days—21 March, 21 June, and 21 December—were selected to reflect seasonal variations in resource availability. These daily snapshots provide insight into system performance across equinox and solstice conditions, focusing on the ability to meet hourly demand, prolong battery life, and ensure reliable operation without curtailment or shortage (see Figure 9).

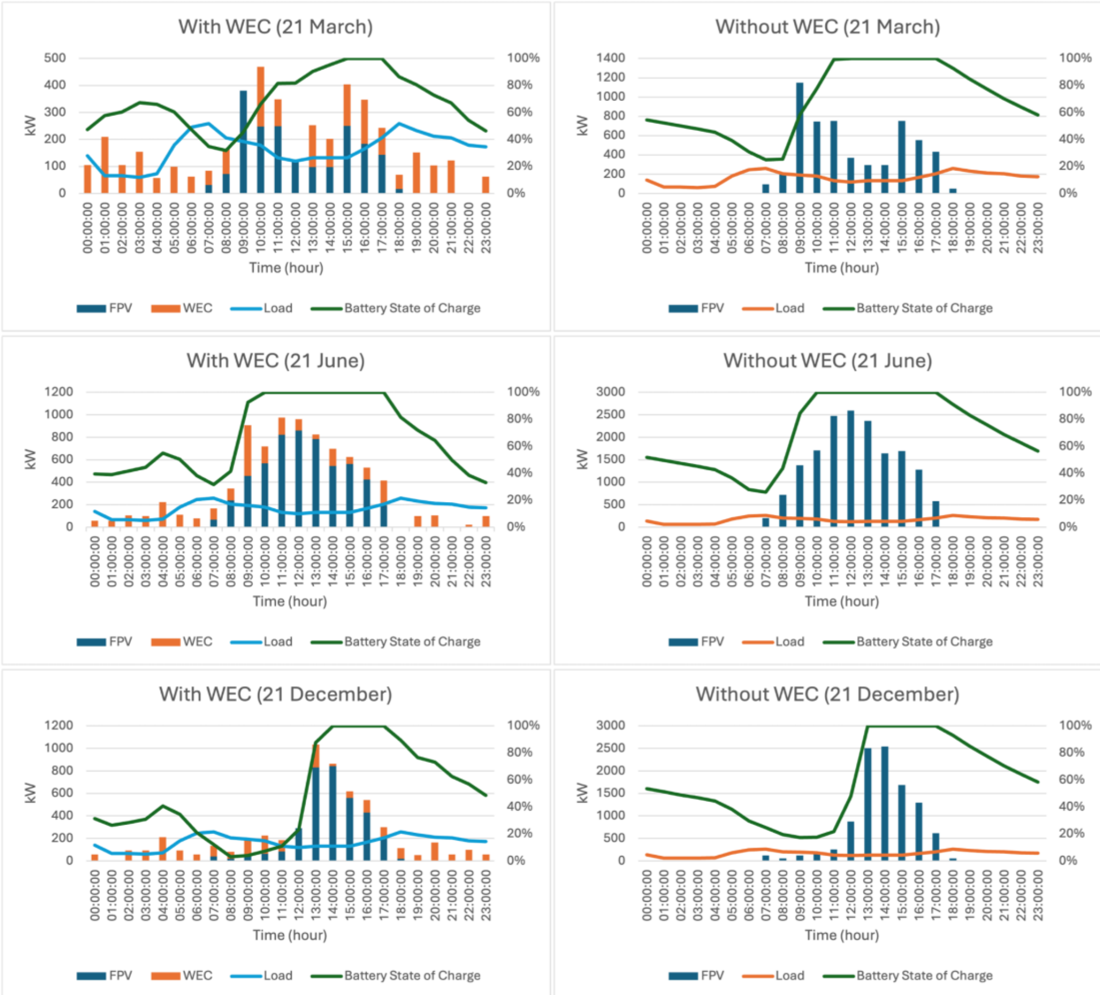

Figure 9. Generation and load profile comparison

Across all three days, Scenario 1 demonstrates a balanced operational profile. The combination of FPV generation during daylight hours and wave energy generation throughout the day allows the system to closely align with the load profile. On 21 March, a seasonally neutral day, FPV provides a strong midday contribution while wave energy steadily supports the morning and evening periods. This reduces the need for early and late battery discharge and enables the battery to function primarily as a buffer for short-term fluctuations, rather than the sole source of energy outside sunlight hours.

Contrary to typical assumptions for higher-latitude regions, 21 June in Indonesia does not correspond to reduced solar resource availability due to its equatorial position. In fact, based on the simulation results, FPV generation on this day was the highest among the three representative samples. The system exhibits excellent synergy: wave energy maintains consistent generation during early and late hours, while the FPV array contributes a strong and sustained midday peak. This ample combined generation allows the battery to operate in a shallow charge-discharge cycle, minimizing strain and ensuring full load coverage without any signs of underperformance. The system shows clear headroom and resilience, underscoring the benefit of resource complementarity in maximizing efficiency and reliability.

On 21 December, simulation results for this day show significantly reduced FPV output during the early morning period, which can be attributed to persistent cloud cover on rainy season, high humidity and atmospheric scattering at low solar angles—all of which are known to affect solar irradiance (Shi et al., 2012; Emetere et al., 2016). Despite this, the hybrid system performs reliably. The continuous generation from the wave energy component bridges the morning gap in solar production, ensuring uninterrupted supply without over-reliance on the battery. As PV output ramps up later in the day, surplus energy is stored and dispatched to meet the evening demand, preserving battery health and maintaining system stability. This performance highlights the resilience of the hybrid system under seasonally challenging meteorological conditions.

The key operational advantage of Scenario 1 lies in its ability to spread generation across the full 24-hour cycle. The consistent presence of wave energy flattens generation variability and ensures that the battery operates within more stable bounds. As a result, the system avoids deep cycling and maintains reserve capacity, contributing to both technical reliability and long-term economic sustainability.

In contrast, Scenario 2, which depends solely on FPV and battery storage, presents a more variable and storage-dependent performance profile. On 21 March, the generation profile aligns reasonably well with the load, with FPV covering daytime demand and batteries supplying the night and early morning periods. However, the system requires careful battery management to ensure adequate charge levels before evening peaks, particularly during consecutive days of suboptimal irradiance.

On this same day, Scenario 2 benefits from strong FPV performance, with higher energy output than on 21 March or 21 December. The midday peak is particularly broad and high, allowing for complete battery charging well before sunset. While the system still requires battery discharge to meet early morning and evening demand, the storage component is less stressed compared to the other days. The absence of wave energy, however, continues to make the system more reliant on precise battery sizing and short-term forecasting, especially to avoid energy shortfalls during consecutive overcast days. Still, under these conditions, the FPV-only system operates reliably and with a relatively stable performance profile.

On 21 December, morning solar output is significantly diminished, likely due to heavy and prolonged cloud cover typical of Indonesia's wet season. This delay in PV ramp-up forces the battery system to discharge more aggressively during early hours, increasing its depth of discharge and overall cycling stress. Although the PV system eventually recovers output by midday and produces enough energy to meet the daily load, the reliability of this configuration hinges heavily on battery sizing and availability during unpredictable weather. The scenario underscores the vulnerability of a PV-only system to localized climate effects, particularly when solar availability becomes inconsistent.

While Scenario 2 maintains supply reliability under average conditions, its dependence on storage makes it more vulnerable to resource variability. Without the continuous support of a secondary generator, battery stress increases, particularly during seasons with lower solar availability or higher variability.

Scenario 1 offers a more stable and resilient operational profile across the seasonal spectrum. The inclusion of wave energy flattens fluctuations in solar output, distributes generation across the entire day, and reduces the strain on battery systems. This minimizes deep discharge cycles and extends storage longevity, contributing to long-term reliability and operational efficiency. Scenario 2, although functionally adequate, demonstrates greater performance volatility and deeper storage dependency. It performs well under optimal solar conditions but becomes increasingly fragile during low-irradiance periods, requiring larger storage buffers and stricter energy management.

In essence, the hybrid architecture of Scenario 1 improves both temporal generation diversity and system resilience, which are essential for standalone renewable energy systems in remote island settings. The comparison underscores the value of complementing variable solar energy with stable marine resources to ensure year-round performance reliability.

4.3 Economic analysis

The Levelized Cost of Electricity (LCOE) is used as the central metric to evaluate and compare the economic feasibility of the two proposed system configurations for Enggano Island. It represents the average cost of generating one megawatt-hour (MWh) of electricity over the system's lifetime, incorporating capital investment, operating and maintenance costs, and performance degradation, all adjusted for the time value of money.

Based on the system performance simulations from SAM and a 25-year financial modelling framework developed by MEMR and DEA as part of the Technology Catalogue for the Indonesian Power Sector in 2024, the LCOE for each scenario was calculated using annuitizing methodology.

Table 3. Financial parameter for hybrid systems

Financial Data	FPV	WEC
Nominal investment (MUSD/MWe)	1.20	2.54
– of which equipment	0.90	–
– of which installation	0.10	
Fixed O&M (USD/MWe/year)	9,000	46,000

(Source: MEMR and DEA, 2024; modified from Pykälä-Aho, 2021)

Table 1. Financial parameter for battery systems

Financial Data	Value
Total investment (MUSD/MWh)	0.4713
– energy component (MUSD/MWh)	0.3470
– power component (MUSD/MW)	0.3290
– other project costs (MUSD/MWh)	0.0420
Fixed O&M (USD/MW/year)	15,000
Variable O&M (USD/MWh)	2

(Source: MEMR and DEA, 2024)

The LCOE for Scenario 1, which combines a 1,350 kW FPV array, a 500 kW WEC, and 1.4 MW of battery storage, is estimated at USD 306/MWh. This figure reflects a balanced generation profile, where the contribution of wave energy reduces the need for largescale battery storage and mitigates deep battery cycling. As a result, overall investment costs are optimized, and operational stability is enhanced.

In comparison, Scenario 2, which consists of a 4 MW FPV array and 2.9 MW of battery storage without wave energy, results in a higher LCOE of USD 382 per MWh. Although this configuration generates more total energy annually, the absence of a complementary generation source leads to a heavier reliance on oversized battery capacity to meet evening and nighttime demand. This increases both capital and operational costs, ultimately making the system less cost-efficient.

Both LCOEs values exceed the adjusted cost of diesel-based generation on Enggano Island, estimated at USD 246 per MWh in 2023 after inflation adjustment from the 2017 baseline of USD 200 per MWh. However, these LCOEs must be interpreted within a broader context of long-term benefits. Unlike the current diesel-based generation, which provides only intermittent electricity supply, the proposed renewable energy systems ensure continuous, reliable 24-hour electricity availability. This improvement in supply reliability significantly enhances local energy security, eliminates dependence on volatile fuel prices, and substantially reduces environmental and logistical challenges associated with diesel generation in remote island settings.

Scenario 1 presents a more favourable economic profile by optimizing resource complementarity and reducing dependence on storage. While Scenario 2 remains technically viable, its higher cost may pose a barrier to implementation without external support or policy incentives.

4.4 Sensitivity analysis

To evaluate the robustness and reliability of the economic analysis, a sensitivity analysis was conducted on key parameters: the weighted average cost of capital (WACC), capital expenditure (CAPEX), and battery storage costs. Each parameter was adjusted to plausible ranges to test their impact on the Levelized Cost of Electricity (LCOE) outcomes of both scenarios.

Table 2. Sensitivity parameters and variation ranges

Parameter	Low Case	Base Case	High Case
WACC	7%	10%	13%
CAPEX	−20%	+0%	+30%
Battery Cost	−20%	+0%	+30%

Table 6. LCOE sensitivity analysis results (USD/MWh)

Parameter	Scenario	Low Case LCOE	Base Case LCOE	High Case LCOE	Variation (%) from Base Case
WACC	Scenario 1	267	306	348	-12.7% / +13.7%
	Scenario 2	329	382	439	-13.9% / +14.9%
CAPEX	Scenario 1	280	306	346	-8.5% / +13.1%
	Scenario 2	365	382	407	-4.5% / +6.5%
Battery Cost	Scenario 1	295	306	323	-3.6% / +5.6%
	Scenario 2	351	382	429	-8.1% / +12.3%

The sensitivity analysis shows that WACC has a substantial impact on both scenarios. Scenario 1 demonstrates significant sensitivity, with a 7% WACC decreasing the LCOE by

12.7% from the base case (USD 306 to USD 267/MWh), and a 13% WACC increasing it by 13.7% (USD 348/MWh). Scenario 2 experiences even greater sensitivity due to its higher initial capital intensity and substantial battery storage. Reducing WACC to 7% decreases its LCOE by approximately 13.9% (USD 329/MWh), while an increased WACC of 13% raises it by about 14.9% (USD 439/MWh). This clearly illustrates the importance of favourable financing conditions and cost of capital, especially for storage-dependent configurations like Scenario 2.

Variations in capital expenditure (CAPEX) have a notable impact on the LCOE of both scenarios, underscoring the critical role of upfront investment costs. Scenario 1 is particularly sensitive to CAPEX changes, with its LCOE decreasing from USD 306/MWh to USD 280/MWh (−8.5%) under a 20% cost reduction and increasing to USD 346/MWh (+13.1%) under a 30% CAPEX increase. This heightened sensitivity is largely attributable to the higher initial investment required for integrating wave energy converters, which are more capital-intensive than PV systems and add significant infrastructure costs.

In contrast, Scenario 2 exhibits slightly lower sensitivity to CAPEX changes. Its LCOE improves by 4.5% (USD 365/MWh) in the low-CAPEX case and increases by 6.5% (USD 407/MWh) in the high-CAPEX scenario. While Scenario 2 also requires substantial capital investment, especially for battery and PV scale-up, the absence of marine energy infrastructure makes its cost profile less variable in relation to CAPEX shifts. These results emphasize the importance of securing cost efficiencies—particularly in marine energy deployment—to keep hybrid systems economically viable. Policy measures such as targeted subsidies or concessional financing for wave energy infrastructure could be instrumental in reducing cost-related sensitivity in Scenario 1.

Battery cost variations significantly affect Scenario 2, which relies heavily on battery storage. Scenario 1, benefiting from the hybrid configuration, displays lower sensitivity to battery price changes; a 20% cost reduction leads to only a 3.6% decrease in LCOE (USD 295/MWh), while a 30% increase results in a modest rise of 5.6% (USD 323/MWh). Scenario 2, however, is notably sensitive; a 20% battery cost reduction results in a substantial LCOE decrease of 8.1% (USD 351/MWh), and a 30% increase in battery cost raises LCOE significantly by 12.3% (USD 429/MWh). This underscores the critical vulnerability of storage-intensive solutions to battery cost uncertainty and the necessity for strategic procurement and forecasting to mitigate economic risks.

Overall, this sensitivity analysis highlights essential economic considerations. Both renewable scenarios exhibit notable sensitivity to economic conditions, particularly financing terms (WACC) and capital costs (CAPEX). The hybrid design of Scenario 1 provides better overall economic resilience against battery cost fluctuations, whereas Scenario 2's economic viability significantly depends on securing competitive battery pricing. Thus, scenario planning should prioritize favourable financing conditions, robust CAPEX management, and stable battery supply agreements to ensure sustainable and economically viable implementation of renewable energy systems for remote islands.

5 Conclusion and recommendations

This research set out to evaluate the technical and economic feasibility of hybrid renewable energy systems integrating floating photovoltaic (FPV) and wave energy conversion (WEC) technologies for 24-hour electrification of remote islands in Indonesia. Two configurations were assessed: a hybrid system combining FPV, WEC, and battery storage (Scenario 1), and a solar-only system with FPV and larger battery capacity

(Scenario 2). Both configurations were designed to meet annual and hourly load requirements through renewable generation, replacing intermittent diesel-based systems.

The simulation results demonstrated that both systems could reliably meet energy demand throughout the year, including peak morning and evening loads. Scenario 1 achieved this with a total annual generation of just over 3 GWh and a Levelized Cost of Electricity (LCOE) of USD 306/MWh. Scenario 2, while technically viable, required significantly larger installed capacity and storage to compensate for the absence of marine generation, resulting in a higher LCOE of USD 382/MWh. Although these values exceed the adjusted cost of diesel-based generation (USD 246/MWh in 2023), the proposed systems offer long-term benefits, including uninterrupted 24/7 electricity supply, reduced reliance on imported fuels, environmental sustainability, and improved system resilience.

Importantly, the sensitivity analysis revealed that both configurations are notably influenced by economic parameters such as WACC and CAPEX. WACC variations had the most significant impact, with Scenario 2's LCOE ranging from USD 329 to USD 439/MWh and Scenario 1 from USD 267 to USD 348/MWh. CAPEX fluctuations also affected both systems, particularly Scenario 1, which showed an LCOE increase of up to 13% under high-CAPEX conditions. Battery cost sensitivity was most pronounced in Scenario 2, where a 30% increase raised LCOE by 12.3%, compared to just 5.6% in Scenario 1. These findings highlight the economic vulnerability of storage-heavy configurations and the comparative stability of hybrid systems with diversified generation sources.

Overall, the research demonstrates that hybrid renewable energy systems are not only technically feasible but also economically advantageous when designed to optimize resource complementarity and minimize battery dependency. The study supports the case for shifting from diesel-based systems to integrated renewable solutions in remote Indonesian islands, if financing conditions and capital cost management are addressed effectively.

5.1 Recommendations

The technical and economic feasibility demonstrated by this study, particularly the resilience advantages of hybrid FPV-WEC-battery systems (Scenario 1), provides a roadmap for transforming energy access in Indonesia's remote islands. To accelerate adoption, policymakers should prioritize hybrid systems for critical infrastructure on vulnerable islands such as Enggano, which faced a four-month isolation in 2025 due to port siltation in Bengkulu. Deploying decentralized renewables would mitigate such crises by ensuring 24/7 power independence from fragile logistics chains. Complementing this, subsidy reforms must redirect fossil fuel support toward renewables, introducing island-specific feed-in tariffs and low-interest financing via partnerships with development banks. Simultaneously, permitting processes require drastic simplification; a single-window approval system managed by regional PLN offices could cut project timelines from years to months, enabling rapid response to infrastructure emergencies.

For transitional resilience, scaled biodiesel-FPV-WEC pilots should leverage Indonesia's palm oil capacity. Blending certified sustainable biodiesel (B30-B50) with marine renewables in palm-rich regions like Sumatra would reduce diesel imports while utilizing existing infrastructure—offering Enggano-like islands a buffer during extended supply disruptions. However, long-term success hinges on localized research, including detailed wave/solar mapping for Enggano-scale sites and weather-resistant engineering standards for FPV/WEC platforms. Further studies should optimize biodiesel-renewable hybrids and develop community ownership templates, training islanders as technicians to sustain projects. Enggano's geographic isolation exemplifies a critical vulnerability rather than an exception. This case demonstrates that hybrid renewable systems serve as essential infrastructure for energy sovereignty in climate-vulnerable regions that extend beyond mere economic viability to become strategic priorities.

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