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Techno-economic assessment and optimization of hybrid renewable energy systems for island electrification: Case studies of Perhentian and Tioman Islands, Malaysia

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Abstract

This study presents a techno-economic assessment of hybrid renewable energy systems for Perhentian and Tioman Islands, Malaysia, with the goal of reducing diesel dependency and supporting sustainable electrification. Using HOMER Pro simulation software, various configurations combining solar photovoltaic (PV), wind, and mini-hydropower sources with energy storage systems (ESS) were analyzed. For Perhentian, the optimal configuration consists of a 177.24 MW solar PV system and 23 ESS units, resulting in a Net Present Cost (NPC) of RM51.1 million and a Levelized Cost of Energy (LCOE) of RM0.839/kWh. For Tioman Island, the optimal system integrates 1.19 GW solar PV, 533 kW mini-hydro, and 293 ESS units, achieving an NPC of RM451 million and LCOE of RM0.803/kWh. Comparative analysis with diesel-based systems shows significant cost advantages and environmental benefits in favor of renewable-based configurations. These findings demonstrate the viability of hybrid renewable systems for remote island electrification and offer policy-relevant insights for Malaysia's National Energy Transition Roadmap (NETR) and rural decarbonization efforts.

Keywords: Energy storage system, HOMER Pro, Hybrid renewable energy system, Island electrification, Techno-economic analysis.

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1. Introduction

The global energy landscape is undergoing a significant transformation driven by the need to reduce greenhouse gas emissions, improve energy security, and promote sustainable development. Island communities, particularly in Southeast Asia, face unique energy challenges due to their geographical isolation, limited infrastructure, and dependency on imported fossil fuels. Diesel-based electricity generation remains the dominant energy source on many islands, leading to high operating costs, fuel logistics difficulties, and adverse environmental impacts [1, 2].

Malaysia, aligning with global sustainability objectives and the United Nations Sustainable Development Goals (SDGs), has introduced the National Energy Transition Roadmap (NETR) to guide its energy sector towards cleaner alternatives. The roadmap sets ambitious targets, including achieving 100% renewable energy penetration on selected resort islands by 2025 [3]. Despite these national efforts, islands such as Perhentian and Tioman continue to rely heavily on diesel generators, which are not only economically unsustainable but also contribute to air and noise pollution in ecologically sensitive environments [4].

Hybrid renewable energy systems (HRES), which integrate two or more renewable sources—such as solar photovoltaic (PV), wind, and mini-hydropower—combined with energy storage systems (ESS), offer a reliable and cost-effective solution for decentralized power generation on remote islands [5-8]. The complementary characteristics of these resources improve energy availability and grid stability, especially when coupled with advanced control and optimization tools. Among various tools available, HOMER Pro software is widely recognized for its robust capability to simulate and optimize hybrid systems based on technical and economic constraints [9-11].

Previous studies have demonstrated the viability of hybrid systems in island settings. For example, in the Philippines and Indonesia, hybrid solar–diesel systems have shown substantial cost reductions and emissions savings [12-15] while micro-hydro integration has improved base load reliability in regions with consistent water flow [16, 17]. The author in reference [18] conducted a study on the integration of solar PV with diesel generators for a Malaysian island. Using HOMER software, the study revealed that the hybrid system significantly reduced diesel fuel consumption and greenhouse gas emissions, demonstrating the environmental and economic benefits of partial renewable penetration. However, the study did not account for variability in seasonal demand or conduct sensitivity analyses that are essential for dynamic and tourism-dependent island contexts.

Similarly, the author in reference [19] analyzed a PV-wind-diesel-ESS configuration for a remote village in Algeria. Their HOMER-based optimization suggested that renewables could supply up to 80% of the load demand at a lower levelized cost of energy (LCOE) compared to diesel-only systems, underlining the viability of hybrid configurations in arid climates. Nonetheless, the absence of hydro integration and lack of real-time load data analysis limit its generalizability to more diverse or tropical regions.

In the Philippines, the study in reference [20] examined solar-wind-battery systems in several off-grid island communities. The authors employed HOMER Pro software to perform techno-economic analysis and found that renewable penetration rates could exceed 70%, contingent on proper energy storage integration. The study highlighted the role of energy storage in stabilizing intermittent energy generation, thereby improving the reliability of supply in isolated grids. While this study effectively highlighted the importance of ESS, it offered limited insights into policy alignment and seasonal consumption patterns.

The author in reference [21] focused on integrating micro-hydropower and solar PV systems for a small housing area in India. The study demonstrated that the presence of consistent hydropower flow significantly enhanced base load reliability while reducing battery dependence, which led to a more cost-efficient system design. This finding underscores the advantages of incorporating hydro resources in regions with adequate water availability. While the study demonstrated the economic viability of combining hydro with solar, it lacked integration with wind resources and omitted the application of advanced dispatch optimization.

The study of author in reference [22] investigated a hybrid PV-wind-diesel system for a remote area in Saudi Arabia, utilizing both HOMER and MATLAB software for system modeling. Their analysis emphasized fuel savings and emissions reduction, revealing that a 50% decrease in fuel consumption and a 47% reduction in CO_2 emissions could be achieved through proper configuration and resource utilization. However, the system design was optimized for a deserted climate, limiting its applicability to humid or tropical island settings.

A similar study as author in reference [22] was conducted by author in reference [23] by integrating HOMER with MATLAB using a linked controller to develop a new dispatch strategy for wind/diesel/battery hybrid energy systems. This approach addresses the limitations of HOMER's default dispatch strategies, particularly in accommodating continuous fuel price fluctuations. The proposed method has been compared against HOMER's built-in dispatch algorithms in terms of both techno-economic and environmental performance. A sensitivity analysis was also conducted considering variations in critical system parameters. Findings indicate that the MATLAB-linked dispatch strategy is more realistic and results in superior economic and environmental outcomes compared to HOMER's default methods.

Another study in reference [23] addressed rural electrification challenges in Malaysia evaluated hybrid energy system implementation for Malawali Island. The study assessed four system scenarios: diesel generator only, PV/wind/battery/diesel, PV/battery/diesel, and PV/wind/battery, using techno-economic and environmental analysis. Among these, the PV/wind/battery/diesel configuration yielded the most favorable performance, with a net present cost of USD 188,814 and a cost of energy of USD 0.198/kWh, while also demonstrating reduced emissions. A sensitivity analysis was conducted to examine the system's long-term sustainability under varying parameters. However, the study lacks detailed seasonal load profiling and real-time demand forecasting, which are critical for ensuring system reliability in tourism-driven or variable-demand regions such as Malaysian islands.

Table 1.
Summary of Relevant Studies on Hybrid Renewable Energy Systems.

Ref	**Site Location**	**Hybrid Configuration**	**Software Used**	**Operating Mode**	**Key Findings**	**Limitations**
Halabi, et al. [18]	Malaysia (Island)	PV–Diesel	HOMER	Grid-connected	35% fuel reduction	No seasonal or sensitivity analysis
Kaabeche and Ibtiouen [19]	Algeria (Remote)	PV–Wind–Diesel–ESS	HOMER	Off-grid	80% RE share, \$0.21/kWh LCOE	No hydro, lacks dynamic demand modeling
Lozano, et al. [20]	Philippines (Islands)	PV–Wind–Battery	HOMER	Off-grid	76% RE share, \$0.25/kWh LCOE	Minimal policy alignment, no seasonal load
Rajadurai, et al. [21]	India (Residential)	PV–Micro-Hydro	HOMER	Off-grid	Reduced battery dependency, \$0.18/kWh LCOE	No wind integration, basic dispatch strategy
Rehman and El-Amin [22]	Saudi Arabia (Remote)	PV–Wind–Diesel–ESS	HOMER, MATLAB	Off-grid	50% fuel and 47% CO_2 reduction	Site-specific to arid region
Aziz, et al. [23]	Simulated (Generic)	Wind–Diesel–Battery	HOMER–MATLAB Link	Off-grid	Realistic dispatch, improved cost/environment	Not focused on island case, no seasonal demand
See, et al. [24]	Malaysia (Malawali Island)	PV–Wind–Battery–Diesel	HOMER	Off-grid	\$0.198/kWh COE, low emissions	No seasonal profile, lacks real-time demand forecasting

Table 1 summarizes the key characteristics and outcomes of these relevant studies. These studies consistently suggest that hybrid renewable energy systems are capable of delivering lower levelized costs of energy and reduced environmental impacts compared to conventional single-source configurations. Nevertheless, critical gaps remain in the current body of research, particularly in addressing localized load dynamics, optimized resource allocation, and operational characteristics under real-world off-grid conditions. A notable shortfall in many prior studies is the absence of real-time, location-specific load data when proposing hybrid system designs. This omission undermines the practical applicability of system configurations, as they may fail to accurately reflect actual demand patterns and variability.

However, comprehensive techno-economic assessments of fully renewable-based hybrid systems for Malaysian islands remain limited in the literature. This study aims to address this gap by conducting a simulation-based assessment of hybrid renewable energy systems for Perhentian and Tioman Islands. To address the identified gaps, the present study proposes a comprehensive techno-economic optimization of hybrid renewable energy systems for Perhentian and Tioman Islands, Malaysia. This study integrates solar PV, wind, and mini-hydro sources with an energy storage system (ESS) under a fully off-grid configuration using HOMER Pro. Distinct from prior work, this research includes:

- Integration of multi-source renewable energy configuration: Unlike previous studies that primarily focused on two-component hybrid systems, this research incorporates solar photovoltaic (PV), wind energy, and mini-hydropower in combination with a battery-based energy storage system (ESS). This multi-source configuration is designed to optimize generation across varying resource availability conditions, enhancing system reliability and reducing dependence on diesel generators.
- Development of seasonal load profiles based on tourism trends: A key innovation of this study lies in the formulation of load profiles that reflect seasonal fluctuations in energy demand driven by tourism. Using available tourism and local consumption data, the study develops demand models that account for both peak and off-peak periods. This addresses a major gap in previous research, which often relies on static or estimated average loads.
- Application of HOMER Pro for advanced system simulation and optimization: The study employs HOMER Pro software to simulate various hybrid system configurations. The tool enables comprehensive optimization by considering economic, technical, and operational constraints. Sensitivity analysis is also performed to understand how changes in fuel price, load, and renewable resource availability influence system performance.
- Incorporation of policy-aligned renewable energy targets: This research aligns its system design objectives with the targets set by Malaysia's National Energy Transition Roadmap (NETR), which includes achieving 100% renewable energy use on selected islands by 2025. By linking modeling parameters and system performance benchmarks to national policy frameworks, the study ensures that its outcomes are practically applicable and policy relevant.
- Contribution to environmental and economic sustainability: In addition to cost optimization, the proposed hybrid systems are evaluated for their potential to reduce greenhouse gas emissions and improve long-term energy sustainability. The dual consideration of economic and environmental performance enhances the study's contribution to sustainable energy planning for island communities.

By bridging the technical, economic, and policy aspects, this study offers novel insights into designing resilient and low-carbon island energy systems in Southeast Asia.

2. Methodology

This research proposes a systematic framework to develop an optimized hybrid renewable energy system (HRES) that addresses the variable and seasonally fluctuating load demand of remote island communities. To ensure an effective and sustainable deployment, the system is designed with a strong emphasis on both techno-economic viability and environmental sustainability.

The preliminary phase serves as a foundational step for designing an HRES tailored to the specific characteristics of island energy needs. In this study, Perhentian and Tioman Islands were selected as the case study sites due to their heavy reliance on diesel-based generation and the Malaysian government's policy direction toward achieving full renewable penetration in selected islands.

Key input data were gathered during this stage, including meteorological variables such as solar irradiance, wind speed, and rainfall (for micro-hydro feasibility), sourced from the Malaysian Meteorological Department and NASA's meteorological database. Additionally, diesel generator fuel consumption rates and operating patterns were documented to establish a realistic baseline scenario. For both islands, comprehensive electric load profiles were developed based on seasonal variation in tourist arrivals, daily residential usage, and commercial energy consumption trends. Load data were categorized according to peak (tourist season) and off-peak demand periods to simulate dynamic usage throughout the year.

The second phase involves simulation and optimization using HOMER Pro software. Various hybrid configurations were designed by integrating solar PV, wind turbines, micro-hydro, diesel generators, and battery energy storage systems. Technical and cost parameters of each system component including capital cost, replacement cost, operational lifetime, and efficiency were sourced from manufacturer datasheets and recent literature to reflect practical implementation scenarios.

The simulation was conducted over a 25-year project lifespan to ensure comprehensive lifecycle analysis. Two dispatch strategies such as Load Following (LF) and Cycle Charging (CC) were employed to optimize the operation of the energy system based on system economics and reliability. The main goal was to determine the configuration with the lowest Levelized Cost of Energy (LCOE) and Net Present Cost (NPC) while maintaining a high renewable energy fraction and minimizing emissions.

In addition to base-case modeling, a sensitivity analysis was conducted. Parameters such as fuel price, solar radiation levels, wind speed variability, and demand fluctuations were varied to evaluate their effect on system performance. This phase helps identify robust configurations that remain economically and technically viable under uncertain conditions.

The final phase of the methodology framework is the evaluation and validation stage. The simulation results from HOMER Pro were analyzed to identify the most technically sound and economically feasible system configuration. This analysis included performance metrics such as annual fuel consumption, renewable energy contribution, battery throughput, emissions (CO_2, NO_x), and unmet load.

This phase also considered alignment with Malaysia's National Energy Transition Roadmap (NETR), which targets 100% renewable energy penetration for off-grid islands. The environmental and financial sustainability of the proposed configurations were assessed to ensure they meet national policy goals and contribute to long-term energy resilience. The final selection of the optimal configuration was made based on its ability to satisfy load demands with minimal cost and environmental impact while offering operational flexibility across seasonal load conditions.

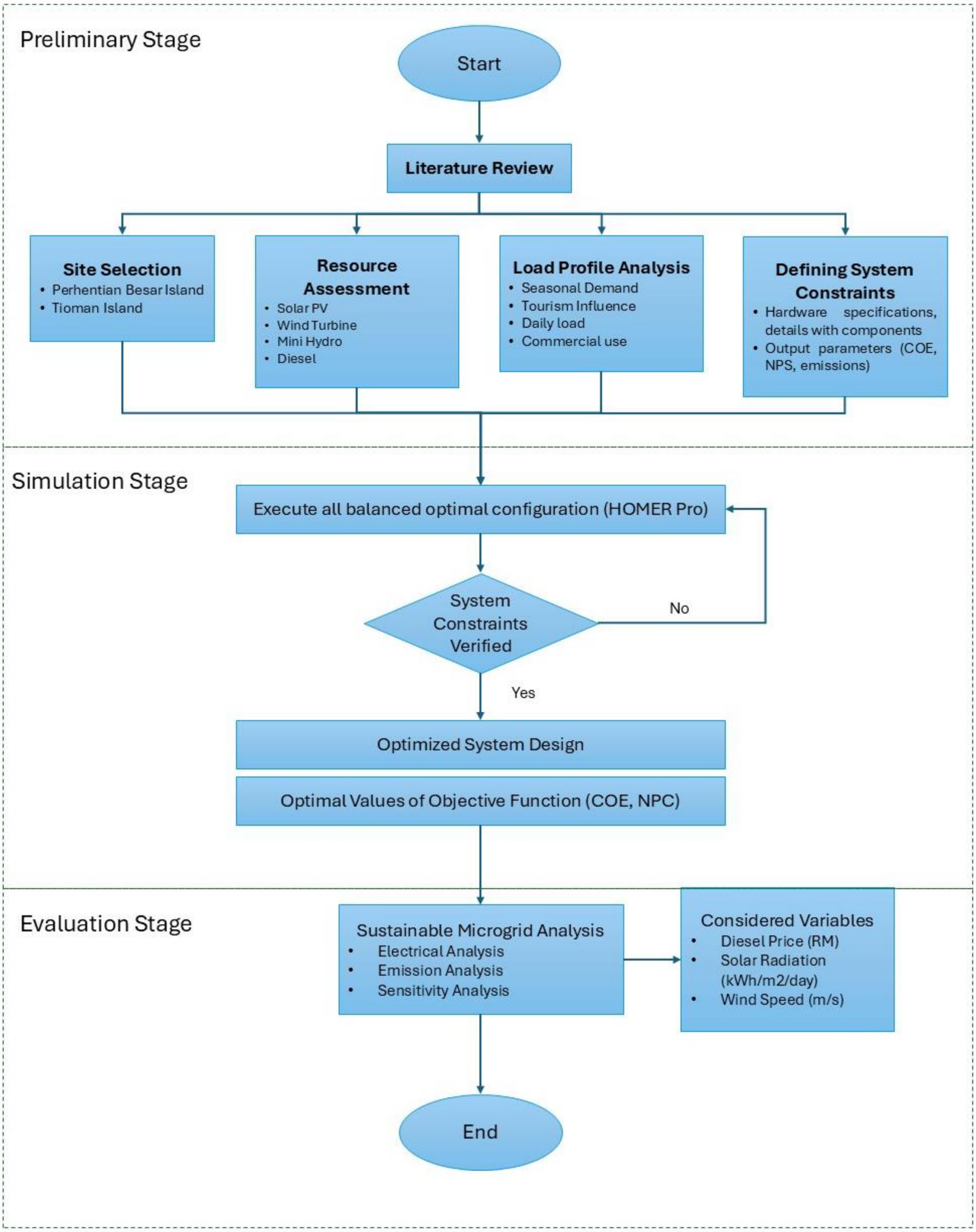


Figure 2.
Methodological approach for this study.

2.1. Proposed System Design for the Hybrid Renewable Energy System

This section outlines the preliminary phase of the study, which forms the foundation for the development of a reliable and optimized hybrid renewable energy system (HRES) for remote island applications. The proposed design considers the unique energy challenges faced by Perhentian and Tioman Islands, including seasonal load fluctuations, limited access to the national grid, and high dependency on diesel-based generation. The system design process begins with an in-depth assessment of the target locations, including site-specific resource availability such as solar irradiance, wind speed, and micro-hydro potential. It also includes the development of detailed load profiles that incorporate both residential and tourism-driven demand variations. By systematically evaluating these parameters in the preliminary stage, the study aims to ensure that the HRES configurations modeled in subsequent simulations are technically feasible, economically viable, and environmentally sustainable. This initial groundwork is crucial for tailoring system configurations that can realistically meet the energy demands of these islands throughout the year.

2.1.1. Study Site

Perhentian Island (Figure 3) is located approximately 21 kilometers off the northeastern coast of Peninsular Malaysia, in the state of Terengganu, within the South China Sea. The islands are surrounded by coral reefs, making them a popular destination for snorkeling, scuba diving, and ecotourism. The population is relatively small, consisting of local fishing communities and seasonal tourism workers [25].

The island is entirely dependent on mainland supply chains and diesel-powered electricity generation, with minimal renewable energy integration. There are also growing concerns related to freshwater scarcity, marine pollution, waste management issues, and habitat degradation due to unregulated tourism development. The island’s infrastructure is modest and insufficient to support sustainable resource management during peak tourist seasons [26].

Perhentian Island was selected as a study site due to its environmental sensitivity, isolated micro-grid potential, and high tourism pressure, which make it a representative model of small island communities struggling with sustainable development. This site allows for the investigation of integrated renewable energy systems, decentralized water treatment, community participation in conservation, and eco-tourism to transition toward a sustainable island model. Its vulnerability to climate change impacts, such as rising sea levels and coral bleaching, further justifies its relevance in a study aimed at future-proofing island sustainability.

Figure 3.
Perhentian Island.
Source: Google Earth.

Tioman Island (Figure 4) lies about 56 kilometers off the east coast of Pahang, Malaysia, and is the largest of the state’s offshore islands. It spans approximately 136 square kilometers and is part of the Tioman Marine Park. The island is home to several villages, with Kampung Tekek being the most developed. Unlike Perhentian, Tioman has a permanent population with basic infrastructure such as roads, schools, clinics, and a small airport. The island's natural beauty, including rainforest ecosystems, waterfalls, coral reefs, and unique geological features makes it a major hub for domestic and international tourism [27].

Despite its development, Tioman faces significant sustainability challenges. Energy generation relies heavily on diesel generators, contributing to greenhouse gas emissions and high operational costs [28]. The island’s solid waste management and wastewater treatment systems are underdeveloped, resulting in periodic environmental pollution. Tourism expansion has also led to deforestation, land-use change, and increased pressure on marine resources [27].

Tioman Island was selected as a study site due to its strategic position as a relatively developed island with potential for transitioning to a sustainable model without compromising its economic vitality. The presence of local governance structures protected marine zones, and community-based tourism enterprises offer a conducive environment to evaluate sustainable energy interventions, waste-to-resource strategies, and stakeholder-inclusive environmental management approaches. The island's complexity, in terms of balancing economic growth with ecological conservation, presents a rich case for analyzing sustainable development pathways for mid-sized tropical islands.

Figure 4.
Tioman island.
Source: Google Earth.

2.1.2. Renewable Energy Resource Assessment

2.1.2.1. Solar Energy

To thoroughly assess the feasibility of solar energy as a sustainable electricity source for Perhentian and Tioman Island, it is essential to analyze the amount of solar radiation received at these locations. Solar radiation plays a crucial role in determining the efficiency and overall electricity generation capacity of photovoltaic (PV) panels. The intensity and duration of sunlight directly influence the energy output of solar panels, making site selection a critical factor in optimizing energy generation. By strategically placing PV panels in areas with high solar radiation, it is possible to maximize energy capture throughout the year, ensuring efficient and reliable solar power generation.

The solar radiation and clearness index used for this analysis has been collected over a 22-year period and sourced from the NASA POWER database [29] and were subsequently used in the HOMER Pro. HOMER Pro uses the clearness index calculated from latitude and longitude data for Perhentian and Tioman Island. The long-term dataset provides valuable insights into seasonal variations in solar radiation, which are crucial for determining the feasibility and effectiveness of PV configuration deployment on these islands. Understanding solar energy fluctuations throughout the year will help in designing systems that can account for seasonal variations and ensure consistent electricity generation.

On average, Perhentian Island recorded a daily radiation of 4.771 kWh/m^2/day with a clearness index of 0.478. Tioman Island on the other hand had recorded daily radiation of 5.173 kWh/m2/day with a clearness index of 0.518. Further details on the solar radiation levels, seasonal trends, and their implications for solar PV configuration development on Perhentian Island and Tioman Island can be found in subsequent Figure 5 and Figure 6. These data-driven insights will inform decision-making regarding solar panel placement, configuration capacity, and integration with existing energy infrastructure, ultimately contributing to a more sustainable and resilient energy system for both islands.

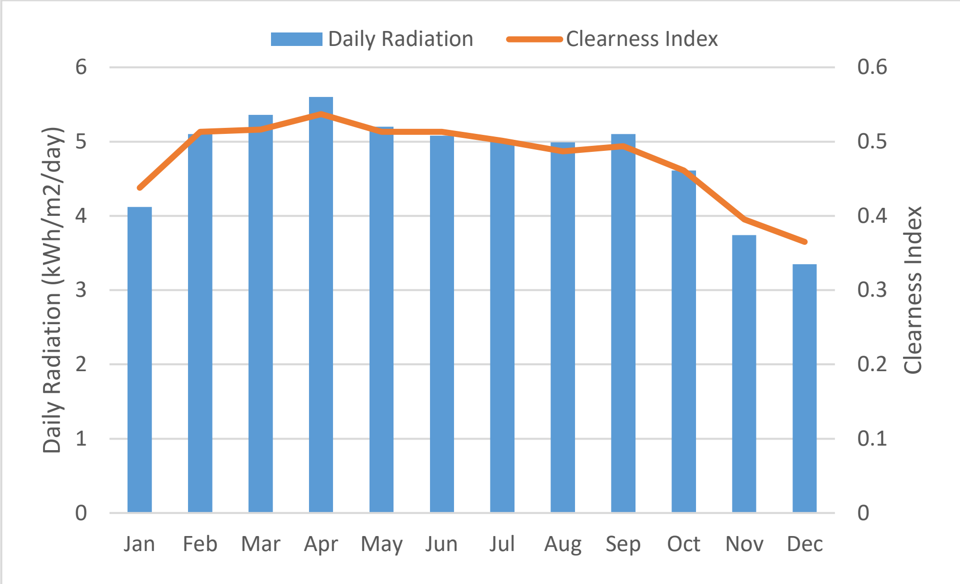


Figure 5.
Monthly Solar Radiation and Clearness Index of Perhentian Island.

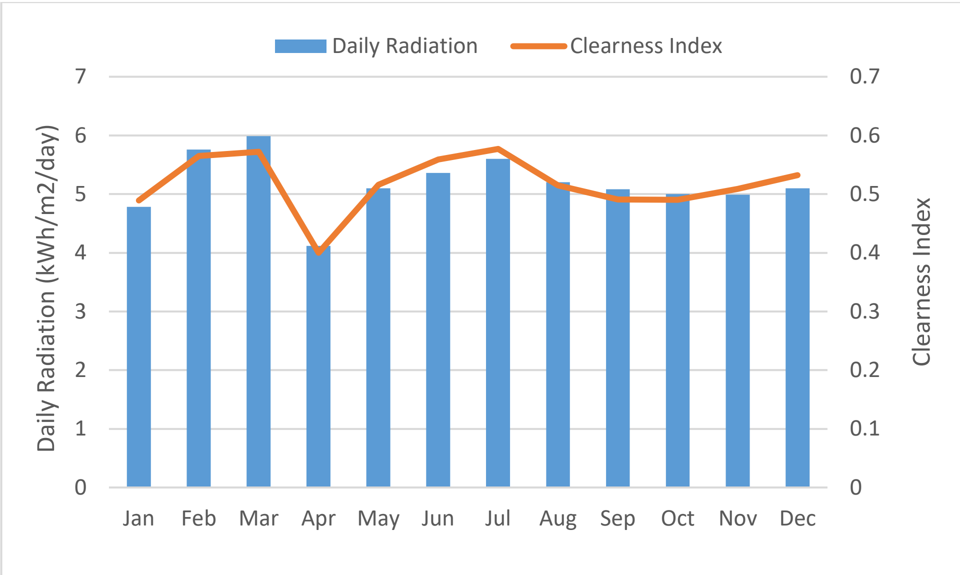


Figure 6.
Monthly Solar Radiation and Clearness Index of Tioman Island.

2.1.2.2. Wind Energy

The wind speed measurements were recorded as daily average wind speeds, using a cup anemometer positioned at a height of 10 meters above ground level. To ensure optimal site selection for wind turbine installation, one location on each island was carefully chosen based on geographical and meteorological factors. The selected locations are the highest peaks on both islands, as these sites naturally experience higher wind speeds due to elevation effects and reduced obstructions. By selecting these high-altitude sites, the wind turbines will have access to stronger and more consistent wind flows, maximizing their energy output and operational efficiency. Additional factors such as turbulence intensity, seasonal variations, and proximity to the energy grid will be considered in the final site assessment to ensure efficient integration of wind power into the island's energy system. Figure 7 provides detailed insights into the chosen locations and their respective wind speed characteristics.

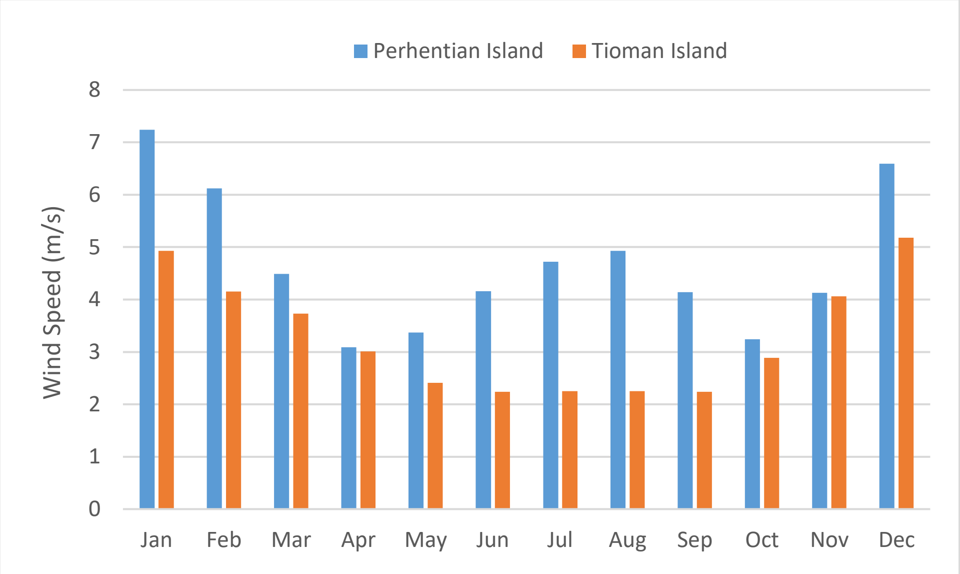


Figure 7.
Average Wind Speed for Perhentian and Tioman Islands.

The monthly wind speed distribution for both Perhentian and Tioman Islands demonstrates a distinct seasonal pattern influenced by monsoonal climatic conditions. Perhentian Island experiences its maximum wind speeds during the northeast monsoon months, particularly in January (7.3 m/s) and December (6.6 m/s). These values are well above the minimum threshold required for efficient operation of small to medium-scale wind turbines, indicating high potential for wind energy harvesting during these periods. The lowest wind speeds occur between April and May, with values dropping to approximately 3.0–3.3 m/s, coinciding with the transition from monsoon to the dry season.

In contrast, Tioman Island exhibits generally lower wind speeds across all months, with the highest values observed in December (5.2 m/s) and January (5.0 m/s). The wind speed drops significantly during the peak tourist season from May to September, reaching as low as 2.2–2.8 m/s. This seasonal decline implies a limited standalone feasibility for wind energy during periods of high electricity demand unless supported by complementary resources.

Between June and August, when tourism and electricity consumption typically peak, Perhentian Island maintains moderate wind speeds ranging from 4.1 to 5.0 m/s, whereas Tioman Islands continues to record lower values below 3.0 m/s. This highlights Perhentian's comparatively stronger potential for year-round wind integration, particularly in hybrid configurations where wind acts as a supplementary source to solar and other renewables.

2.1.2.3. Mini Hydro Energy

Mini hydro power was found to be viable in Tioman Island only as it is the only Island in this study that has a river source. There are three potential rivers that have been identified for assessment of mini hydro energy namely Sungai Air Seler, Sungai Nipah, and Sungai Paya. These rivers were selected based on their average stream flow rates, which play a crucial role in determining hydropower feasibility. The monthly stream flow variations for each river are detailed in Figure 8, which provides an overview of seasonal fluctuations and highlights periods of high and low water availability.

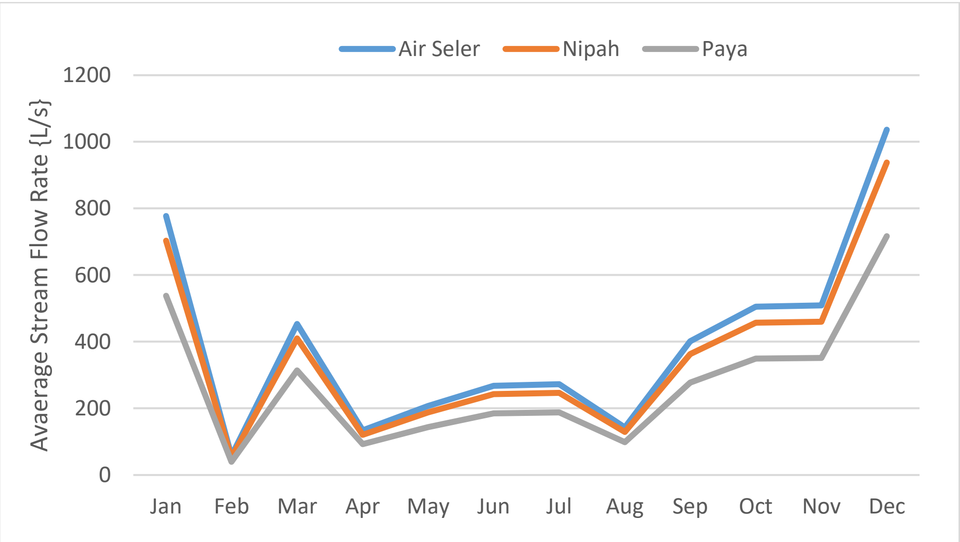


Figure 8.
Average monthly stream flow rate of river on Tioman Island.

The monthly flow rate data was collected for all three rivers, and a comparative analysis was conducted. Among them, Air Seler demonstrated the most favorable characteristics in terms of both flow consistency and peak discharge levels. The river maintained relatively high average flow rates across the year, with notable peaks in January (800 L/s) and December (1050 L/s), which coincide with the northeast monsoon season. Importantly, during the dry months of May to August, Air Seler maintained flow rates in the range of 200–300 L/s, outperforming the other two rivers and ensuring reliable year-round energy potential. This is critical for addressing seasonal load demands, especially during tourism peaks. Furthermore, the combination of higher base flow, greater hydrological stability, and the potential for minimal environmental disruption due to its accessible terrain, renders Air Seler the most technically and economically viable choice for mini-hydro deployment in this study. As such, it was selected as the representative hydropower input in the hybrid system modeling conducted using HOMER Pro.

2.1.3. Load Profile Analysis

Accurate load profile analysis is a fundamental component in the design and optimization of hybrid renewable energy systems, especially for remote or island communities. A well-defined load profile enables precise estimation of daily and seasonal energy consumption patterns, which in turn ensures optimal system size and reliability [30]. In off-grid contexts like Tioman and Perhentian Islands, where energy demand is influenced by both residential needs and fluctuating tourism activity, the development of realistic and location-specific load profiles is essential to ensure the techno-economic viability of the proposed energy. Moreover, incorporating variations in demand based on seasonal cycles and population dynamics improves system resilience and reduces the risk of under- or over-sizing renewable components [31, 32]. This section presents the methodology and assumptions used in constructing the hourly and monthly load profiles for the study sites, forming the basis for subsequent optimization using HOMER Pro.

The electrical load in the system corresponds to the energy consumption of appliances and facilities located on Pulau Perhentian. Figure 9 illustrates the average hourly load profiles across two distinct seasonal periods. A significant portion of the local population is engaged in tourism-related activities, often operating their own resorts, homestays, or chalets. Others are primarily involved in fisheries. The island’s fishing village includes key public infrastructure such as a police station, health clinic, jetty, and retail outlets. During the peak tourism season, which typically spans from February to October, the island’s electricity demand nearly doubles compared to the off-peak period from November to January.

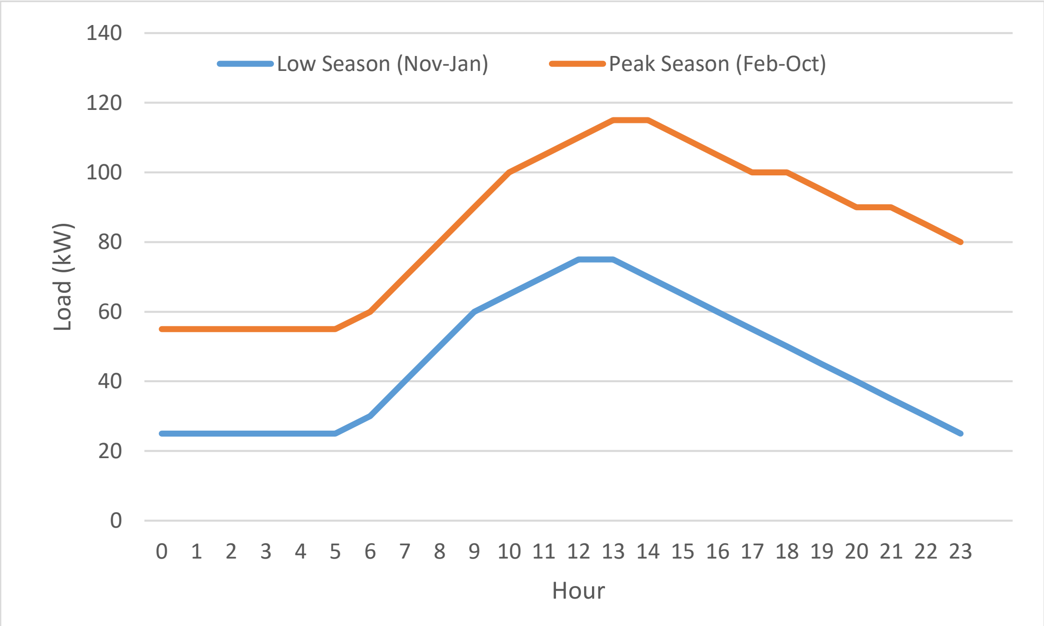


Figure 9.
Load Profile for Perhentian Island.

The electrical load demand on Tioman Island demonstrates significant seasonal variability, primarily influenced by fluctuations in tourist arrivals. The island’s climatic conditions are governed by four distinct seasonal phases: the low season, which is in November to February, and the peak season, which falls from March to October. During the low season, strong winds and heavy rainfall often deter tourists, resulting in reduced energy demand. Conversely, the peak season witnesses a substantial increase in tourism-related activities such as accommodation, transportation, and food services, which collectively contribute to higher electricity consumption. This seasonal load variation is clearly illustrated in Figure 10, where peak season load profiles exhibit a significantly higher magnitude compared to the low season.

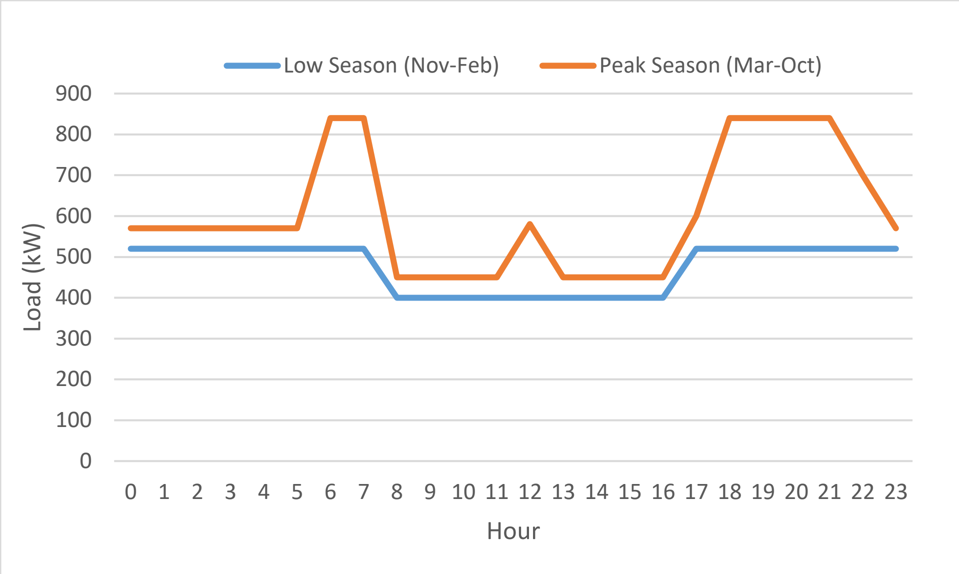


Figure 10.
Load Profile for Tioman Island.

To ensure a realistic yet manageable modeling framework in HOMER Pro, several key assumptions were applied in this study. It is assumed that the daily load shape remains consistent within each season, reflecting typical user behavior across tourism-related facilities. No demand-side management or active load shifting strategies are considered; thus, the load profile remains passive throughout the simulation. The analysis is conducted using a static load profile, without accounting for future population growth or increased tourist influx. Occupancy in homestays, resorts, and chalets is presumed to follow seasonal trends, with significantly higher usage during the peak tourism months. Additionally, backup generators are assumed to operate only when renewable sources and battery storage fail to meet demand, particularly during extended cloudy or windless periods. Constant base load is modeled for essential public services such as police stations, health clinics, and jetty operations throughout the year, regardless of seasonal changes. Although weather conditions influence tourism activity, direct temperature-driven load variations (e.g., air-conditioning spikes) are not explicitly modeled. Lastly, the island's electricity demand is assumed to be driven solely by residential, commercial, and tourism-related activities, with no industrial loads present. These assumptions provide a structured foundation for the HOMER Pro simulation, ensuring that the hybrid energy system design aligns closely with the operational realities and socio-economic context of Tioman Island.

2.2. Hybrid System Modelling
2.2.1. Photovoltaic Cell (PV) Modelling

HOMER Pro computes the out of the PV array by using the following equation [33].

$$P_{out,PV} = Y_{rated} D_f \left(\frac{G'}{G'_{stc}}\right) [1 + \alpha_P (T_{cell} - T_{stc})] \quad (1)$$

Here, the PV cell temperature represents the surface temperature of the PV array. During nighttime, it matches the ambient temperature, whereas in full sunlight, it can rise to 30 ◦C or higher. The following equation illustrates how HOMER Pro computes the cell temperature by considering both the ambient temperature and the radiation incident on the array.

$$\tau\alpha R_T = \eta_{con} R_t + H(T_{cell} - T_{amb}) \quad (2)$$

By solving Equation 2 for cell temperature, the following equation is derived.

$$T_{cell} = T_{amb} + R_T \left(\frac{\tau\alpha}{H}\right)\left(1 - \frac{\eta_{con}}{\tau\alpha}\right) \quad (3)$$

Since directly measuring the value of $\left(\frac{\tau\alpha}{H}\right)$ is challenging, manufacturers typically report the nominal operating cell temperature (NOCT) instead. NOCT is achieved under specific conditions: 800 W/m2 solar irradiation, 20 ◦C ambient temperature, and a no-load condition (i.e. η_{con} =0). Consequently, Equation 3 can be rewritten as follows:

$$\left(\frac{\tau\alpha}{H}\right) = \frac{T_{cell,NOCT} - T_{amb,NOCT}}{R_{T,NOCT}} \quad (4)$$

With τα estimated to be around 0.9, the PV cell temperature can be derived using Equation 5.

$$T_{cell} = T_{amb} + R_T \frac{T_{cell,NOCT} - T_{amb,NOCT}}{R_{T,NOCT}} \left(1 - \frac{\eta_{con}}{0.9}\right) \quad (5)$$

2.2.2. Wind Turbine Modelling

HOMER computes the wind speed at a specific hub height using the following equation [33].

$$V_{hub} = V_{anem} \times \frac{\ln(H_{hub}/H)}{\ln(H_{anem}/H)} \quad (6)$$

If the power law is chosen to apply, HOMER calculates the hub height wind speed using the following equation:

$V_{hub} = V_{anem} \times \left(\frac{H_{hub}}{H_{anem}}\right)^{\beta}$ (7)

Where β is the power law exponent.

Power curves generally illustrate the performance of wind turbines under standard temperature and pressure (STP) conditions. To accommodate actual conditions, HOMER Pro modifies the power value estimated by the power curve as illustrated in Figure 11 [34] by the air density ratio, as per the following equation:

$$P_{out,wtg} = \left(\frac{\rho_{actual}}{\rho_{stp}}\right) \times \rho_{stp} \quad (8)$$

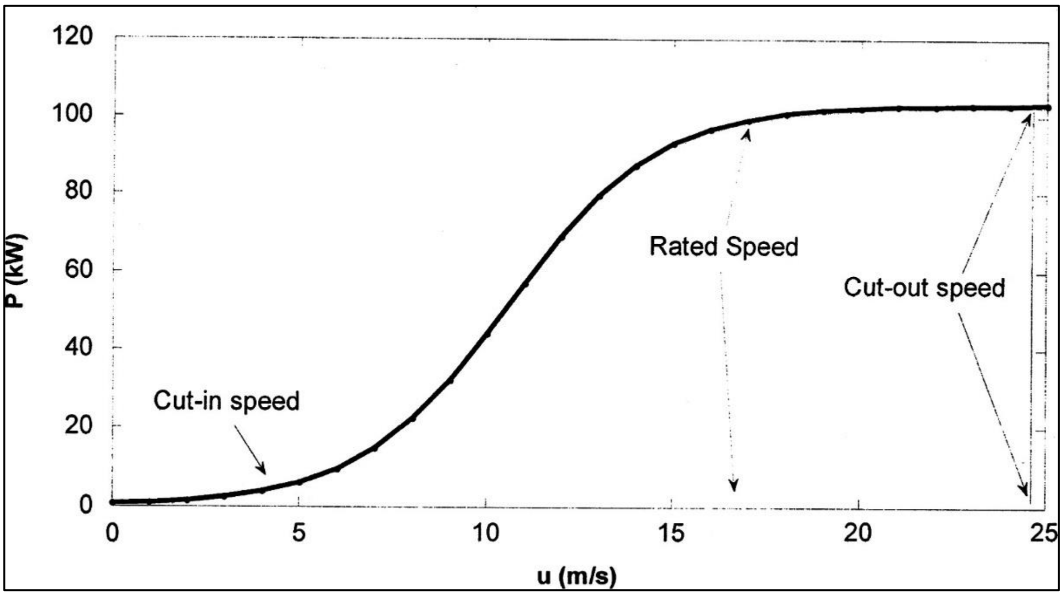


Figure 11.
Typical Output Power vs Wind Speed Curve of a Wind Turbine.

2.2.3. Mini-Hyrdo Modelling

HOMER Pro applies a simplified steady-state model to estimate the electrical output of a hydro turbine using key hydraulic parameters such as flow rate, head, and turbine efficiency. The equation is derived from the basic principles of fluid mechanics [33].

The potential energy of water at a given height is given by:

$E_p = mgh$ (9)

Since mass flow rate, $\dot{m}$, can be expressed as:

$\dot{m} = \rho Q$ (10)

The hydraulic power available at the turbine shaft is given by:

$P_{hydraulic} = \rho g Q H$ (11)

Considering the efficiency of the turbine ,η, the actual electrical power output is:

$P = \eta \rho g Q H$ (12)

Where η is typically 0.9.

In HOMER Pro, this equation is used as a time-step simulation input, where QQQ and HHH may vary monthly or seasonally depending on the hydrological data provided. The model assumes steady-state operation and does not account for transient effects or dynamic control of turbine operation. Furthermore, HOMER allows users to specify minimum flow thresholds below which the hydro turbine ceases operation, representing dry season or ecological flow constraints.

2.2.4. Energy Storage System Modelling

During each time step, HOMER calculates the highest amount of electricity that the storage bank is capable of absorbing [33]. This maximum charging power is utilized to determine whether the storage bank can take in all the excess renewable power available or how much extra power a cyclic charging generator should produce. The subsequent equation outlines the maximum quantity of electricity that the two-tank system can absorb.

$$P_{max,battery} = \frac{zQ_a e^{-zT_L} + Q_a zs(1-e^{-zT_L})}{1-e^{-zT_L} + s(zT_L - 1 + e^{-zT_L})} \quad (13)$$

The following equation represents the storage charging power that corresponds to the maximum charging rate.

$$P'_{max,battery} = \frac{(1-e^{-\beta T_L})(Q_m - Q_b)}{T_L} \quad (14)$$

The subsequent equation delineates the maximum power for charging the storage bank, aligned with this maximum charging current.

$P^{\eta}_{max,battery} = \frac{NIV}{1000}$ (15)

HOMER Pro establishes the maximum storage charging power as equivalent to the smallest value under the assumption that each factor applies post charging losses. From that,

$$P_{max} = \frac{MIN(P_{max,battery}, P'_{max,battery}, P^{\eta}_{max,battery})}{\eta_s} \quad (16)$$

The subsequent expression establishes the maximum power that the storage bank can discharge over a certain period:

$$P_{max,battery} = \frac{-zQ_m + zQ_a e^{-zT_L} + Q_b zs(1-e^{-zT_L})}{1-e^{-zT_L} + s(zT_L - 1 + e^{-zT_L})} \quad (17)$$

The maximum discharging power of the storage bank is determined by the following equation:

$$P_{max} = \eta_d P_{max,discharge} \quad (18)$$

2.2.5. Bidirectional Converter Modelling

Since solar PV and energy storage unit generate DC power while the requirement is for AC power, a bidirectional converter is utilized. HOMER Pro utilizes the subsequent equation to determine the converter's size according to the energy flow between the buses [33].

$$P_{max} = \eta P_{in,con} \quad (19)$$

2.2.6. Grid Integration

During electricity shortages, the grid supplies the required energy. HOMER calculates the cumulative yearly energy charge using the following equation [33].

$$C_{AEC} = \sum_{x}^{rates} \sum_{y}^{12} E_{gp,x,y} P_{power,x} - \sum_{x}^{rates} \sum_{y}^{12} E_{gs,x,y} P_{sellback,x} \quad (20)$$

HOMER utilizes the following equation to determine the total annual grid demand charge:

$$C_{gd} = \sum_{x}^{rates} \sum_{y}^{12} P_{pgd,x,y} D_x \quad (21)$$

2.3. Technical and Economic Specification of System Components

The primary components of the proposed hybrid renewable energy system are summarized in Table 2. Each component has been evaluated based on its technical specifications and associated financial parameters, including capital, replacement, and operational and maintenance (O&M) costs. The values used in the simulation are based on manufacturer data, local market pricing (adjusted for island logistics), and relevant literature. The system comprises solar PV modules, wind turbines, mini-hydro turbines, diesel generators, energy storage systems, and inverters where all are integrated within the HOMER Pro simulation environment to determine optimal performance under techno-economic constraints.

Table 2.
Technical and Economic Specifications of the Required Components for System Modeling.

Component	Rated Capacity	Lifetime	Capital Cost	Replacement Cost	O&M Cost/year	Efficiency/Notable Specs
PV Module	1/100/ 680 kW	25 years	RM145.66 / kW	Same as capital	RM2.91–1,981	13% Vmp: 37V 72 poly cells Derating: 85%
Wind Turbine	1 kW	20 years	RM31,141.67	Same as capital	RM622.83	Start wind: 3 m/s, Max output: 1.3 kW, 24 VDC
Mini-Hydro	532.518 kW	30 years	RM4,256,000	Same as capital	RM85,120	Head: 20 m Flow rate: 4300 L/s, Efficiency: 63%
Diesel Generator	Auto-sized	15,000 hours	RM500 / kW	Same as capital	RM2	Min load: 25% Fuel use: 109 + 0.236·P L/hr
Energy Storage System	1 MW / 4,220 kWh	15 years	RM500,000	Same as capital	RM5,000	Round trip efficiency: 90% 7,030 Ah 600 V
Inverter	100 kW	15 years	RM11,639.14	Same as capital	RM232.78	DC-AC efficiency: 96% DC input: 105 kW AC output: 100 kW

2.4. Software Modelling

2.4.1 Homer Pro

Over the years, a wide array of computational tools has been developed to assess the technical, economic, and environmental viability of hybrid renewable energy systems (HRES), particularly in off-grid and remote contexts. Among these, the Hybrid Optimization of Multiple Energy Resources (HOMER) software has emerged as one of the most widely adopted platforms for modeling and optimization of microgrids.

HOMER Pro allows users to input various system parameters, including renewable resource profiles, load demand patterns, technology specifications, and economic indicators, to simulate and evaluate thousands of possible configurations. The tool utilizes an optimization-simulation hybrid approach, comparing system performance based on present net cost (NPC), levelized cost of energy (LCOE), renewable energy fraction, excess electricity, unmet load, and other key metrics to determine the most cost-effective and technically feasible solution [35]. Notably, HOMER Pro models systems using component-level simulation coupled with an economic modeling framework, ensuring both the operational and financial sustainability of proposed microgrid architectures over their entire lifecycle.

One of HOMER’s defining strengths lies in its flexibility where it supports both grid-connected and stand-alone systems, and allows users to apply multiple dispatch strategies, such as load following, cycle charging, or generator order, based on the control logic required by the user [36]. Despite the steep learning curve associated with mastering its full set of features, the software is highly regarded for its speed, reliability, and robust optimization capabilities, making it particularly suitable for pre-feasibility studies and policy-level decision-making in energy planning.

Given these capabilities, HOMER Pro was selected as the simulation and optimization tool for this study to evaluate the techno-economic feasibility of deploying a hybrid energy system tailored to the resource availability and load demand of the selected island locations. This decision was further reinforced by HOMER’s ability to balance trade-offs between capital investment, energy reliability, and environmental impact, which is critical for sustainable energy deployment in remote areas.

A comprehensive understanding of how HOMER Pro operates is essential to appreciate its role in the optimization process. Figure 12 illustrates the general simulation and optimization workflow within the HOMER Pro environment. As shown, the process begins with inputting system parameters such as load profiles, renewable resource availability, technical specifications of system components, economic indicators, and constraints. HOMER Pro then performs a multi-layered analysis consisting of simulation, optimization, and sensitivity evaluation. Through this iterative process, the software generates a wide array of feasible system configurations and ranks them based on performance indicators like Net Present Cost (NPC), Levelized Cost of Energy (LCOE), renewable fraction, unmet load, and excess energy. This visualization effectively demonstrates the integrative nature of HOMER’s modeling approach and supports the rationale for its adoption in this study.

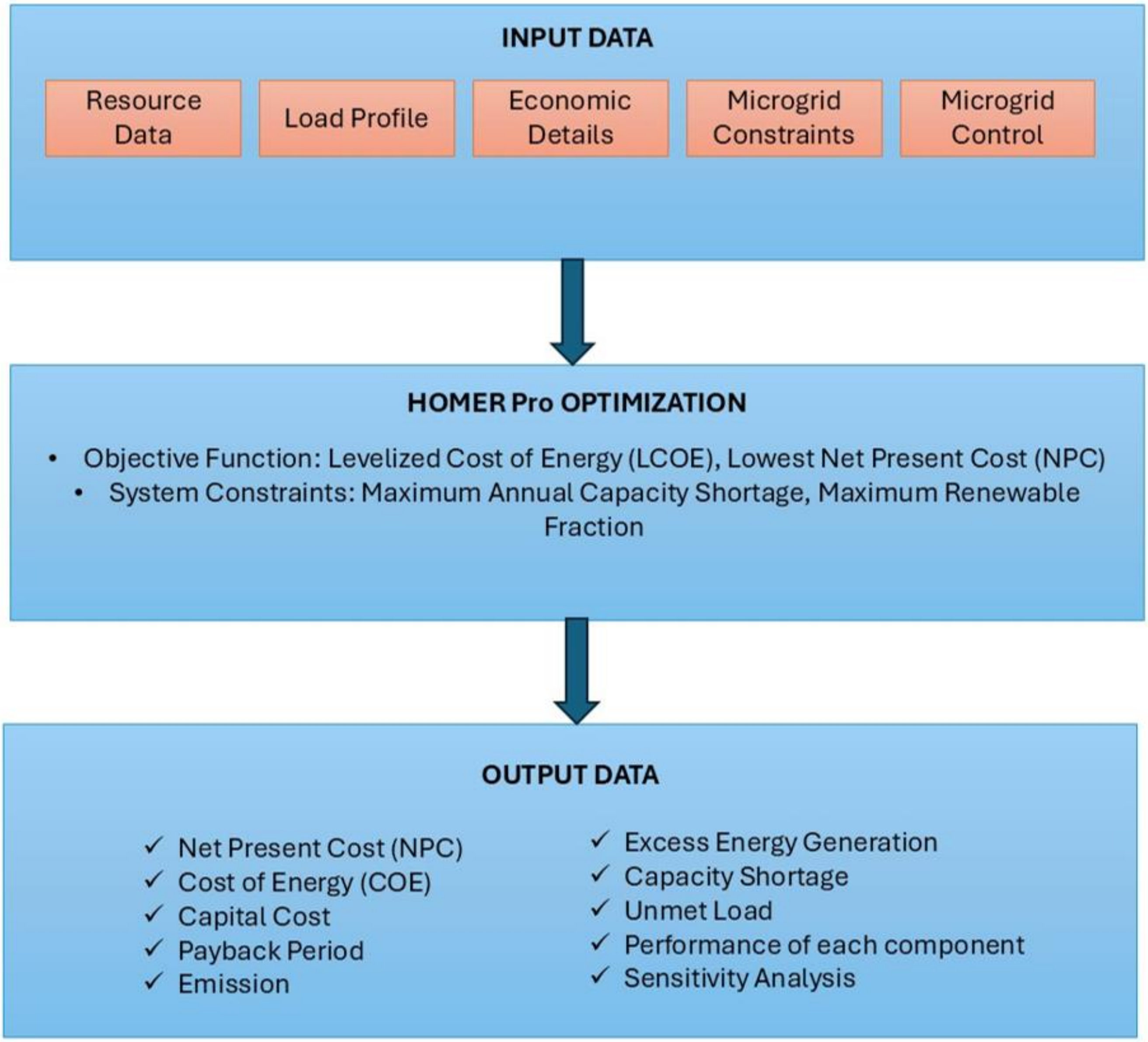


Figure 12.
General Simulation and Optimization Workflow of HOMER.

2.4.2. Levelized Cost of Energy

The optimal sizing is established by considering the lowest LCOE. HOMER computes the LCOE utilizing Equation 23 [33].

$$LCOE = \frac{C_C + C_R + C_{OM} + C_f - S}{E_Y} \quad (23)$$

2.4.3. Net Present Cost

The NPC is computed using Equation 24, where CRF(p,q)represents the capital recovery factor, determined by Equation 25 and 26 [33].

$$NPC = \frac{C_C + C_R + C_{OM} + C_f - S}{CRF\ (p,q)} \quad (24)$$

$$CRF\ (p,q) = \frac{p(1+p)^N}{p(1+p)^N - 1} \quad (25)$$

$$P = \frac{p' - s}{p' + s} \quad (26)$$

2.4.4. Renewable Fraction

The renewable fraction is a key performance indicator used in HOMER Pro to assess the contribution of renewable energy sources to the total electricity demand of a hybrid energy system. This parameter is crucial in evaluating the sustainability and environmental impact of the proposed system configuration. HOMER defines the renewable fraction as the ratio of the total electrical energy supplied to the load from renewable sources such as solar photovoltaic (PV), wind turbines, and hydropower to the total electrical energy supplied to the load from all sources, including both renewable and non-renewable components (e.g., diesel generators) over the entire simulation period [33]. The renewable fraction (RF) is expressed as:

$$RF = \frac{E_{renewable}}{E_{total}} \quad (27)$$

The computation of the renewable fraction allows for comparative assessments between different system configurations and guides the decision-making process in achieving an optimal balance between economic feasibility and environmental sustainability. It also plays a pivotal role in policy compliance for renewable energy integration, carbon footprint reduction, and long-term energy planning in off-grid or hybrid energy systems.

3. Results and Discussion

3.1. Proposed System Architecture for Perhentian and Tioman Islands

The proposed hybrid renewable energy system configurations aim to enhance energy access and reliability for remote island communities, while simultaneously minimizing dependence on fossil fuel sources and reducing greenhouse gas emissions. By integrating solar photovoltaic (PV), wind turbines (WT), mini-hydropower (MH), and energy storage systems (ESS), these microgrid configurations are designed to leverage the islands' locally available renewable energy resources for sustainable and resilient electricity generation. The system architecture incorporates both alternating current (AC) and direct current (DC) subsystems, managed through bidirectional inverters to ensure seamless energy flow and real-time load balancing.

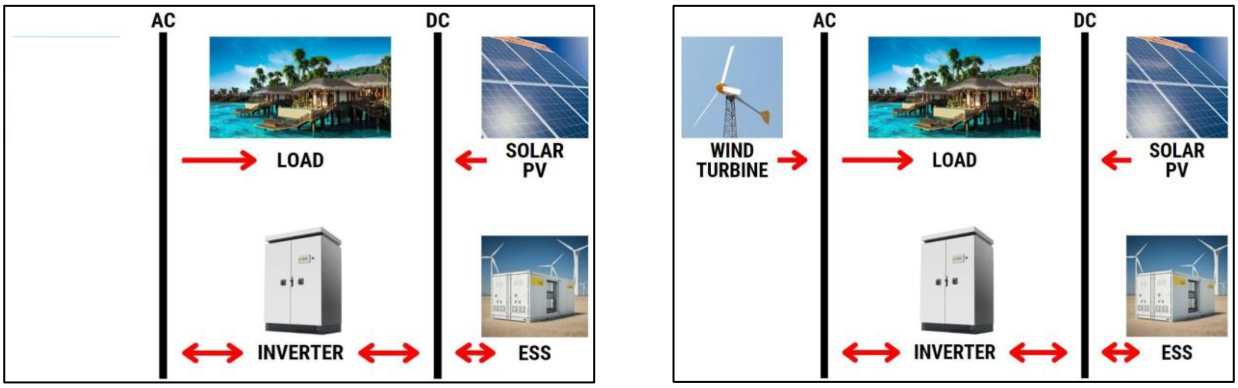
3.1.1. Hybrid Configuration for Perhentian Island

Figure 13 illustrates two hybrid configurations proposed for Perhentian Island, which is characterized by high solar irradiance and moderate coastal wind speeds. Both configurations are designed to operate autonomously and are particularly tailored to serve the island's load, which fluctuates significantly due to seasonal tourism demand.

Configuration 1 in Figure 13(a) comprises a solar PV array, energy storage system, and a bidirectional inverter. The PV panels generate DC power that is either used directly, stored in the ESS, or converted to AC via the inverter to supply the local grid. Meanwhile Configuration 2 in Figure 13(b) expands upon this setup by integrating a wind turbine alongside the PV system. The turbine supplies power directly to the AC load or through the inverter, complementing solar generation and improving system resilience during periods of low irradiance.

The DC subsystem is composed of PV panels and the ESS, which collectively ensure energy availability during nighttime or low-generation periods. The AC subsystem consists primarily of the wind turbine and load centers, where the inverter facilitates bidirectional energy exchange between AC and DC domains.

This configuration is deemed suitable for Perhentian Island due to the high consistency of solar radiation throughout the year and moderate wind activity, particularly during the inter-monsoon and southwest monsoon seasons. The combination of solar and wind, supported by battery storage, forms a decentralized, low-emission solution capable of meeting variable load demand while reducing reliance on diesel generators.



(a) Configuration 1 **(b) Configuration 2**

Figure 13.
Schematic representation of system design for Perhentian Island with (a) Solar-Energy Storage System-Inverter and (b) Wind Turbine-Solar-Energy Storage System-Inverter.

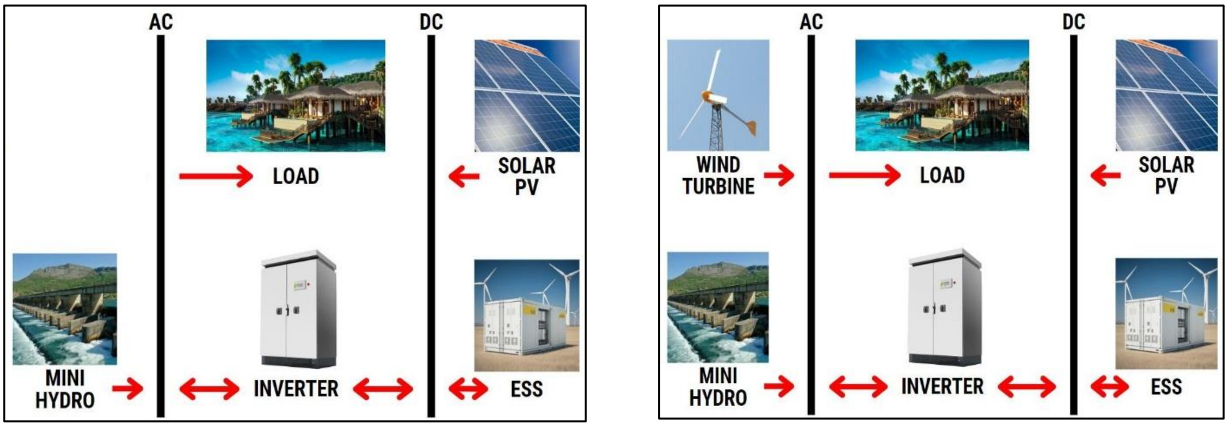
3.1.2. Hybrid Configuration for Tioman Island

In comparison, Tioman Island benefits from diverse renewable energy resources, including river systems suitable for small-scale hydroelectric applications. As such, Figure 14 presents two extended hybrid configurations that include a mini-hydro generator, in addition to solar and wind systems.

Configuration 1 in Figure 14(a) integrates mini-hydro (MH), solar PV, ESS, and an inverter. The MH generator contributes a stable source of base-load electricity, complementing the intermittent nature of solar power. On the other hand, Configuration 2 in Figure 14(b) further enhances the system by adding a wind turbine. In this configuration, all three renewable sources (MH, WT, PV) supply power either directly to the load or via the bidirectional inverter, while the ESS ensures grid stability.

The AC subsystem is strengthened by the inclusion of MH, which is especially advantageous during extended cloudy or low-wind periods. The DC subsystem continues to consist of PV generation and ESS components. The bidirectional inverter acts as the central power interface, coordinating supply and demand dynamics across both current types.

This configuration aligns with Tioman Island's topographical advantages and hydrological profiles, particularly the flow characteristics of the Air Seler River. The inclusion of mini-hydro not only provides a reliable and consistent generation source but also reduces the operational burden on the ESS, thereby extending battery lifespan and improving system economics.



(a) Configuration 1 **(b) Configuration 2**

Figure 14.
Schematic representation of system design for Tioman Island with (a) Solar-Energy-Mini Hydro-Storage System-Inverter and (b) Wind Turbine-Mini Hydro-Solar-Energy Storage System-Inverter.

Both proposed configurations present technically and environmentally sound solutions for powering remote islands through hybrid renewable energy systems. The configuration for Perhentian Island is optimized for locations with strong solar and wind potential but limited hydro resources. In contrast, the Tioman Island configuration integrates an additional hydropower source, enhancing base-load supply and system reliability. The use of bidirectional inverters and energy storage systems in both models ensures operational flexibility and supports real-time energy balancing.

3.1.3. Comparative Analysis and System Suitability

The two proposed configurations for each island represent context-specific energy strategies that leverage distinct renewable profiles. Perhentian Island's configuration prioritizes solar and wind energy sources due to the absence of adequate hydropower resources. In contrast, Tioman Island's configuration benefits from an additional renewable energy pathway through mini-hydro, enhancing its capacity to support higher base-load requirements and ensuring improved system stability.

Both systems incorporate bidirectional inverters and energy storage, which are critical for maintaining power quality and balancing supply-demand mismatches in island microgrids. The modularity of the system design also allows for future scalability, ensuring compatibility with evolving energy demands and technological advancements.

These proposed hybrid architectures offer technically sound and environmentally beneficial alternatives to conventional diesel-based energy systems. Their implementation can significantly contribute to decarbonization, energy security, and long-term sustainability for remote island communities in Malaysia and similar geographies worldwide.

3.2. Techno-Economic Evaluation of Optimized Hybrid Energy Configurations

3.2.1. Perhentian Island

Table 3 presents the optimized simulation results for two hybrid renewable energy configurations proposed for Perhentian Island. Both configurations incorporate a mix of solar PV, wind turbines, and energy storage systems (ESS), optimized using HOMER Pro based on technical, economic, and reliability criteria. The results are analyzed in terms of Net Present Cost (NPC), Levelized Cost of Energy (LCOE), Operating Cost (OC), Initial Capital (IC), and Renewable Fraction (RF).

Table 3.
Optimized Results for Perhentian Island.

Config.	SP (kW)	WT	ESS	I (kW)	NPC (RM)	LCOE (RM/kWh)	OC (RM)	IC (RM)	RF
1	177,240		23	9,030	51.1M	0.0839	986,744	38.4M	100
2	167,504	18	25	13,236	52.4M	0.086	1.04M	39.0M	100

SP = Solar Panel, WT = Wind Turbine, ESS = Energy Storage System, I = Inverter, NPC = Net Present Cost, COE = Cost of Energy, OC = Operating Cost, IC = Initial Capital

Configuration 1 consists of 177,240 kW of installed solar PV capacity, 23 units of ESS, and a 9,030 kW inverter, while Configuration 2 has a slightly lower solar PV capacity (167,504 kW) but compensates with a higher inverter capacity (13,236 kW) and more storage units (25 ESS units). Both configurations include wind turbines, with Configuration 1 deploying 23 turbines, and Configuration 2 using 18 units.

The variation in component sizing reflects HOMER's sensitivity-based optimization strategy, which seeks to balance energy generation, reliability, and cost under fluctuating load and renewable resource profiles. The higher inverter and ESS capacities in Configuration 2 suggest an approach geared toward enhanced storage and dispatch flexibility, particularly valuable during periods of low renewable generation or peak demand.

From an economic perspective, Configuration 1 achieves a lower Net Present Cost (RM 51.1 million) and LCOE of RM 0.0839/kWh, indicating a more cost-effective solution over the system's lifespan compared to Configuration 2, which records an NPC of RM 52.4 million and an LCOE of RM 0.086/kWh. These figures are consistent with other island-based renewable energy studies, which highlight the cost advantage of systems optimized for solar dominance and minimal storage overhead [37-39].

The operating cost of Configuration 1 is also marginally lower (RM 986,744/year) than Configuration 2 (RM 1.04 million/year), likely due to the smaller inverter size and fewer storage units, both of which incur routine maintenance and replacement costs over time. However, initial capital investments are almost comparable where RM 38.4 million for Configuration 1 and RM 39.0 million for Configuration 2 which implyies similar upfront funding requirements.

Notably, both configurations achieved a 100% Renewable Fraction (RF), indicating complete reliance on renewable energy sources without auxiliary support from diesel generators or the national grid. This reflects the feasibility of establishing fully renewable microgrids on Perhentian Island under optimal sizing and control strategies. Such high RF values contribute significantly to energy security, environmental sustainability, and operational independence, especially crucial for isolated island communities that experience logistical constraints in fuel transportation and generator maintenance [40-43].

While both configurations are technically viable and environmentally sustainable, Configuration 1 emerges as the preferred solution due to its lower overall cost, improved LCOE, and slightly reduced maintenance burden. However, with its higher storage and inverter capacity, Configuration 2 may provide better operational flexibility and load-shifting capability, particularly under variable load profiles or resource intermittency. As such, decision-makers may consider Configuration 2 under scenarios prioritizing load management, whereas Configuration 1 is optimal for cost minimization.

3.2.2. Tioman Island

Table 4 presents the techno-economic performance of two optimized hybrid renewable energy system configurations for Tioman Island. Both configurations integrate solar photovoltaic (SP), mini-hydro (MH), energy storage systems (ESS), inverters (I), and in the second configuration, wind turbines (WT). A constant mini-hydro capacity of 533 kW is maintained in both cases, capitalizing on Tioman Island's favorable hydrological resources and terrain characteristics.

Table 4.
Optimized Results for Tioman Island.

Config.	MH	SP (kW)	WT	ESS	I (kW)	NPC (RM)	LCOE (RM/kWh)	OC (RM)	IC (RM)	RF
1	533	1,187,800		293	65,618	451M	0.0803	9.26M	331M	100
2	533	1,062,360	24	337	71,638	463M	0.0824	9.75M	337M	100

SP = Solar Panel, MH=Mini Hydro, WT = Wind Turbine, ESS = Energy Storage System, I = Inverter, NPC = Net Present Cost, COE = Cost of Energy, OC = Operating Cost, IC = Initial Capital

Configuration 1 excludes wind turbines and instead relies on a larger solar PV capacity of 1,187,800 kW. The system also includes 293 units of energy storage and a 65,618 kW inverter system. This configuration yields the lowest Net Present Cost (NPC) of RM 451 million, Levelized Cost of Energy (LCOE) of RM 0.0803/kWh, operating cost of RM 9.26 million, and initial capital cost of RM 331 million. The absence of wind turbines simplifies the system while leveraging the stable output from solar and mini-hydro sources. The renewable fraction (RF) of 100% indicates complete reliance on renewable sources.

Configuration 2 introduces 24 wind turbines and correspondingly reduces the solar PV capacity to 1,062,360 kW. This configuration requires a higher number of ESS units (337) and inverter capacity (71,638 kW) to manage the increased system complexity and variable wind output. Consequently, it incurs a higher NPC of RM 463 million, LCOE of RM 0.0824/kWh, operating cost of RM 9.75 million, and initial capital cost of RM 337 million. Despite its more diversified generation mix, this configuration results in slightly higher system costs, likely due to the capital and operational expenses associated with wind turbine integration.

Both configurations demonstrate 100% renewable energy penetration, ensuring zero fossil fuel dependency. However, Configuration 1 emerges as the more cost-effective solution for Tioman Island, achieving a lower LCOE and total investment despite its heavier reliance on solar energy. This is consistent with prior studies which found that solar–hydro systems offer economic advantages and stable generation profiles, especially in locations with dependable solar radiation and hydrological conditions [44].

The inclusion of wind energy in Configuration 2 provides an alternative energy stream but may not significantly improve economic outcomes unless the island's wind potential is consistently strong. As such, Configuration 1 is recommended for its simpler design, lower cost, and dependable energy generation potential, aligning with HOMER Pro's optimization objectives to minimize cost while maximizing renewable utilization [45-47].

The deployment of high-capacity ESS and inverter systems in both configurations ensures effective power balancing, especially during peak load periods or when renewable generation fluctuates. Furthermore, both systems are scalable and designed with operational robustness, allowing for future energy demand growth and integration of additional renewable components. The findings also confirm that the optimal hybrid design for Tioman Island is one that strategically balances cost, reliability, and the available natural resources.

3.3. Electricity Generation Analysis

Figure 15 presents the monthly electricity production pattern for Perhentian Island generated by the proposed hybrid renewable energy system (Configuration 1). The system demonstrates a highly consistent energy yield, with monthly production ranging from approximately 13,500 MWh in December to over 22,500 MWh in March, reflecting the influence of seasonal solar and wind resource availability.

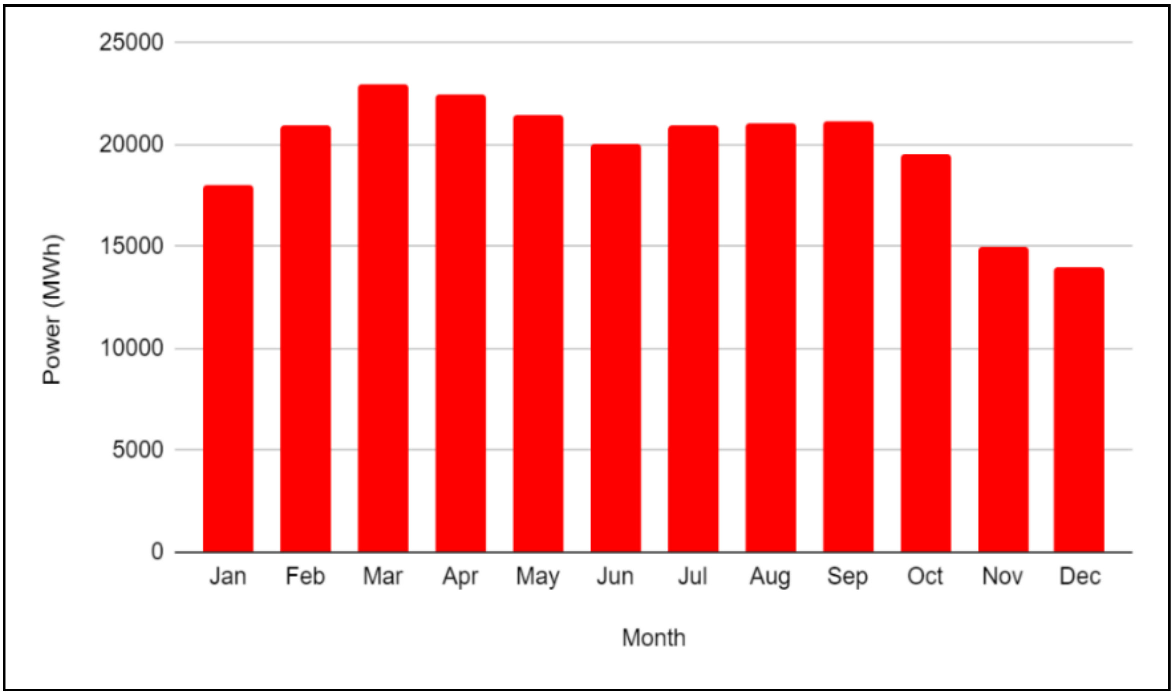


Figure 15.
Monthly Electricity Production for Perhentian Island.

From March to September, the energy output remains relatively stable, maintaining levels above 20,000 MWh. This aligns with the Southwest Monsoon (SWM) season (May–August) and both Inter-Monsoon periods (March–April and September–October), during which Perhentian Island experiences high solar irradiance and relatively stable wind patterns. This period coincides with peak tourist activity, thereby ensuring the system's ability to meet elevated electricity demand associated with tourism infrastructure, hospitality operations, and increased domestic load.

Conversely, a notable decline is observed during November through January, which corresponds to the Northeast Monsoon (NEM) season characterized by heavy rainfall, cloud cover, and stronger but less consistent wind profiles. Nevertheless, even in these low-generation months, the system maintains production above 13,000 MWh, confirming its reliability and resilience under varying meteorological conditions. The energy storage system (ESS) integrated into the microgrid effectively mitigates supply intermittency by balancing daily and monthly variations in renewable resource availability.

Additionally, the production profile supports sustainable tourism and low-emission energy goals of Malaysia's National Renewable Energy Policy (NREP), which emphasizes green solutions for rural and island electrification. The system's capability to generate and sustain high energy outputs throughout the year without fossil fuel backup highlights its technical feasibility, environmental soundness, and alignment with national development frameworks.

Figure 16 illustrates the monthly electricity production for Perhentian Island, showing a clear seasonal trend influenced by climatic and environmental factors. The energy output ranges from approximately 9,000 MWh in December to a peak of around 18,000 MWh in March, with noticeable reductions towards the end of the year. The highest generation is observed during the months of March and April, while the lowest occurs in December, indicating a strong correlation with the island's seasonal weather patterns and tourist influx.

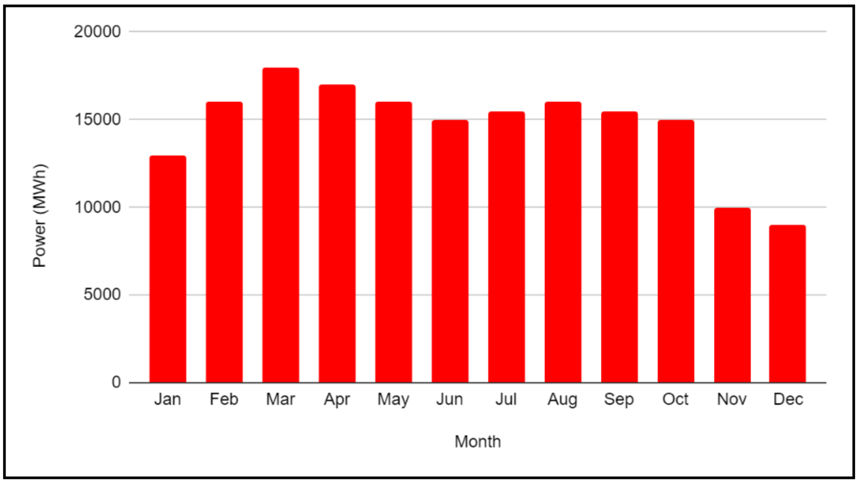


Figure 16.
Monthly Electricity Production for Perhentian Island.

Electricity production is relatively higher between February and September, which coincides with Malaysia's dry season and the island's peak tourist season. During this period, solar irradiance and wind availability are typically higher, contributing to increased power output, especially if renewable energy sources such as solar photovoltaic (PV) and wind turbines are integrated into the system [48]. The increase in tourist activity also raises energy demand, necessitating more consistent and higher electricity generation.

In contrast, electricity production significantly drops from October to December, correlating with the Northeast Monsoon (November–March), characterized by frequent rainfall and reduced solar radiation. The decline in output may also be attributed to lower system efficiency during overcast periods and potential curtailment due to adverse weather conditions. This finding aligns with the observations in reference [49-51] who emphasized that hybrid renewable systems in coastal and island regions often suffer from seasonal variability, particularly during monsoon periods.

Interestingly, despite the reduction in solar energy availability in June and July, production remains relatively stable, possibly due to the compensation from other renewable sources such as wind or energy storage systems (ESS). Incorporating a hybrid energy approach with adequate storage can significantly improve the reliability and stability of electricity supply on island microgrids [52, 53].

Since data suggests seasonal fluctuations likely due to dependence on solar-based generation, this opens a case for considering hybridization with biomass, wind, or small hydro sources to flatten the variability curve. Wind resources, often complementary to solar during monsoon months, could enhance generation during periods when solar is weak. As noted by research in reference [54] multi-source hybrid systems offer improved reliability and energy security in islanded contexts.

The dip in production during the monsoon may also indicate insufficient energy storage to buffer intermittent supply. Advanced battery systems (e.g., lithium-ion or flow batteries) or even hydrogen-based storage could be modeled to bridge the shortfall and maintain grid resilience [55, 56]. ESS also provides ancillary benefits such as frequency regulation and peak shaving, essential for islands with limited grid stability [56].

Islands often operate on microgrids with limited interconnection to mainland power infrastructure. Seasonal drops in production could expose the system to blackouts or voltage instability if not managed properly. The current trend highlights the importance of grid automation, real-time monitoring, and predictive maintenance algorithms to ensure system robustness, especially during the rainy season [57].

The seasonal pattern emphasizes the need for energy policy frameworks that account for seasonal forecasting, flexible tariffs, and incentives for diversified RE integration. Government and utility stakeholders could introduce performance-based incentives for hybrid systems that ensure minimum monthly supply thresholds, ensuring both economic and energy security goals are met [58].

Lastly, climate change is likely to exacerbate monsoon variability and extreme weather events, potentially increasing production volatility. Planning for climate-resilient energy systems that incorporate redundancy, real-time meteorological forecasting, and climate-adaptive infrastructure is essential to secure long-term sustainability [59].

These results highlight the importance of optimizing the configuration and operation of microgrid systems according to seasonal load profiles and renewable energy potential. Strategies such as demand-side management, energy storage integration, and predictive energy scheduling could mitigate the impact of seasonal variability and ensure a resilient power supply throughout the year.

3.4. Environmental and Socioeconomic Implications of the Proposed Hybrid Renewable Energy System

The integration of hybrid renewable energy systems (HRES) on Perhentian and Tioman Islands offers substantial environmental advantages by minimizing dependency on fossil fuels and mitigating greenhouse gas (GHG) emissions. Currently, these islands rely heavily on diesel generators, which are associated with high carbon dioxide (CO_2), nitrogen oxides (NO_x), and particulate matter emissions [60]. Transitioning to a solar-wind-hydro integrated system can significantly reduce these pollutants. Based on simulation results from HOMER Pro, both proposed configurations achieve a 100% renewable fraction, effectively eliminating diesel consumption. This transition not only reduces the carbon footprint but also minimizes the risks of fuel spills and contamination of the islands' fragile marine ecosystems. Moreover, the use of clean energy aligns with Malaysia's national renewable energy targets and climate action commitments under the Paris Agreement [61]. Furthermore, reducing diesel dependence mitigates the logistical challenges and environmental risks associated with transporting fuel to remote island communities, which often involve marine vessels prone to leakage and spills.

From a social standpoint, the proposed systems enhance energy security and access for communities and the tourism sector. Stable and sustainable electricity supply reduces outages and supports critical services, such as healthcare, education, and communication infrastructure, which are essential for long-term human development on the islands [62, 63]. The tourism industry, which is a major economic driver for Perhentian and Tioman Islands, benefits from the perception of environmental sustainability. Eco-conscious travelers are increasingly favoring destinations with low environmental impact and renewable energy initiatives [64]. Deploying HRES enhances the islands' branding as eco-tourism hubs, potentially leading to increased tourist arrivals and income generation. Additionally, the project can generate local employment during the construction, operation, and maintenance phases. Community engagement and training programs can foster technical skills, improve local capacity, and empower residents to manage and sustain the energy infrastructure, contributing to inclusive development [65].

Energy resilience is another critical benefit, particularly in the face of climate-related events that may disrupt fuel transport. Renewable energy systems with integrated storage enhance the islands' ability to withstand and recover from such disruptions. This is crucial for climate adaptation and disaster preparedness in remote regions. The implementation of hybrid renewable energy systems (HRES) on islands such as Perhentian and Tioman not only addresses technical and economic challenges associated with rural electrification but also directly contributes to the following advancement of multiple United Nations Sustainable Development Goals (SDGs).

i) SDG 7: Affordable and Clean Energy

HRES systems ensure universal access to affordable, reliable, sustainable, and modern energy [66]. By replacing diesel generators with locally available solar, wind, and mini-hydro resources, communities can reduce the levelized cost of electricity (LCOE) and minimize supply interruptions. HOMER-based simulations typically show a lower Net Present Cost (NPC) and higher renewable fraction, thereby offering both economic and environmental sustainability [67]. Moreover, remote locations that are traditionally underserved by national grids benefit from decentralized energy solutions that promote energy justice and equity.

ii) SDG 13: Climate Action

The deployment of renewable energy directly supports climate mitigation efforts by reducing dependence on fossil fuels, particularly diesel, which is a major source of greenhouse gas (GHG) emissions on isolated islands [60]. According to the IPCC Report of 2022 [68] transitioning to renewables is one of the most effective pathways to limit global warming to below 2°C. The HOMER results for both Perhentian and Tioman Islands show that systems with high renewable penetration drastically reduce CO_2 emissions and particulate pollutants.

iii) SDG 11: Sustainable Cities and Communities

Islands such as Perhentian and Tioman are not only tourist destinations but also home to small communities whose livelihoods depend on reliable energy access. By deploying HRES, the resilience and livability of these communities are enhanced through reliable energy for schools, clinics, small businesses, and public infrastructure. This supports the creation of inclusive, safe, resilient, and sustainable communities [66]. Moreover, island communities can serve as demonstration sites for sustainable off-grid energy systems that could be replicated across similar contexts.

iv) SDG 8 – Decent Work and Economic Growth

The renewable energy transition presents new economic opportunities, especially for local employment in installation, operation, and maintenance of clean energy systems. Community-based renewable energy projects have been shown to enhance skills development and create jobs in remote regions [47]. Furthermore, clean and reliable energy access enhances productivity and enterprise development, particularly in tourism-centric economies like those of Perhentian and Tioman Islands.

4. Conclusion

This study presented a comprehensive techno-economic and environmental assessment of hybrid renewable energy systems (HRES) tailored for Perhentian and Tioman Islands in Malaysia. By integrating solar photovoltaic (PV), wind turbines (WT), mini-hydro, and energy storage systems (ESS), optimized configurations were simulated using the HOMER Pro software. These configurations were designed to reduce reliance on diesel generators, improve energy access, and align with Malaysia's national sustainability targets. For Perhentian Island, configurations incorporating solar and wind energy with energy storage demonstrated high renewable fractions and low net present costs, capitalizing on the island's high solar irradiance and moderate wind resources. In contrast, Tioman Island's favorable hydrological and topographical conditions allowed for the effective inclusion of mini-hydro systems, resulting in higher base load stability, enhanced system reliability, and significant reductions in emissions.

The optimization results showed that hybrid systems are not only technically viable but also economically and environmentally advantageous. HOMER's simulations confirmed the potential for substantial reductions in fuel consumption, carbon emissions, and operating costs. Moreover, the proposed systems demonstrated resilience against seasonal variations in load demand and renewable resource availability. Beyond technical feasibility, this research highlights the broader implications of HRES deployment, including alignment with the United Nations Sustainable Development Goals (SDGs), particularly those related to clean energy (SDG 7), climate action (SDG 13), and sustainable communities (SDG 11). These systems also offer long-term socio-economic benefits by improving energy access, enhancing community resilience, and creating new avenues for local employment.

Despite the comprehensive simulation and analysis conducted in this study, several limitations must be acknowledged. First, the analysis relied heavily on secondary meteorological and load profile data due to limited availability of real-time measurements on the islands. While HOMER Pro allows for sensitivity analysis, incorporating actual measured data could enhance the accuracy of system sizing and operational predictions. Second, seasonal tourism-driven load fluctuations were modeled based on assumptions and extrapolations from existing literature and field surveys. However, detailed hour-by-hour demand-side modeling, particularly accounting for behavioral and economic factors (e.g., tourist inflow, fuel delivery delays, generator maintenance), could provide more robust and adaptive system configurations. Third, the study did not include detailed environmental impact assessments such as land use implications of PV installations, ecological disturbances from mini-hydro systems, or waste management of batteries. Incorporating Life Cycle Assessment (LCA) and Environmental Impact Assessment (EIA) methodologies would offer a more holistic sustainability evaluation. Fourth, the financial modeling assumed fixed component prices and uniform replacement costs. In practice, fluctuations in fuel prices, policy incentives, technology costs, and local tariffs can significantly influence system feasibility. Future work should consider a stochastic economic analysis or Monte Carlo simulations to assess long-term investment risks.

For future research, the following directions are suggested:

- Integration of real-time IoT-based monitoring systems to continuously update renewable energy performance and load demands.
- Development of machine learning-based predictive control algorithms for optimal dispatch and energy management in microgrids.
- Evaluation of community participation models and socio-economic impacts, including willingness-to-pay, acceptance, and local ownership structures.
- Simulation of grid-interactive microgrids to explore grid-support functions such as demand response, frequency regulation, and export revenue from surplus generation.
- Exploration of alternative bioenergy or hydrogen-based storage options to diversify energy storage and reduce environmental burden.

By addressing these limitations and expanding the scope of analysis, future research can contribute to more resilient, inclusive, and technically adaptive hybrid energy systems for island and remote communities. In conclusion, the successful implementation of hybrid renewable energy systems on Malaysian islands can serve as a model for sustainable rural electrification in remote and off-grid communities. Future studies are recommended to incorporate real-time monitoring data, dynamic load profiles, and life cycle environmental assessments to further refine system performance and sustainability outcomes.

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