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Research Paper

Floating renewables for sustainable Malaysian Islands: A 3E assessment

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ABSTRACT

Island communities in Malaysia remain highly dependent on fossil fuel–based electricity, necessitating reliable and economically viable renewable energy alternatives. This study presents a 3E (energy, economic, and environmental) assessment of 1 MW offshore floating solar photovoltaic (OFPV), floating offshore wind (FOW), and wave energy converter (WEC) systems' feasibility at Tioman, Langkawi, and Pangkor Islands of Malaysia. Energy performance results show that OFPV systems generate 1455.3–1553.3 MWh/year, achieving capacity factors of 17–18% and high-performance ratios of 0.84–0.86, with Langkawi exhibiting the most stable and favourable solar conditions. Floating offshore wind produces the annual energy output of 114.2 -853.58 MWh/year with an average capacity factor of 5 %. Among sites, Pangkor Island demonstrates limited wind potential, with capacity factors below 2 %. Wave energy systems have outputs of approximately 461–684 MWh/year, with capacity factors ranging from 5 % to 8 %, reflecting the low-to-moderate wave climate of Malaysian coastal waters, though Langkawi performs best during monsoon months. Economic analysis indicates that floating solar is the most cost-effective technology, exhibiting the lowest levelized cost of energy (LCOE) and the shortest payback period under an avoided electricity cost of RM 0.20/kWh. Floating offshore wind shows a moderate LCOE and longer payback period due to higher capital and maintenance costs, while wave energy remains economically uncompetitive, with payback periods exceeding the project lifetime. Environmentally, all systems contribute to emissions reduction by displacing diesel-based generation. Overall, the results identify Tioman as the most suitable site for wind energy deployment, Langkawi as optimal for floating solar and wave energy, and floating solar as the most viable near-term solution for sustainable island electrification in Malaysia.

1. Introduction

Climate change has emerged as one of the most critical environmental challenges in recent decades, driven largely by greenhouse gas (GHG) emissions from fossil fuel-based energy production [1,2] . Transitioning to renewable energy sources is essential for sustainable and scalable power generation [3]. Among renewable technologies, ocean-based energy systems, including floating solar, offshore wind, and wave energy converters, hold significant potential due to the vast and underutilized energy resources available at sea [4]. Europe's ocean energy sector has ambitious plans to install 100 gigawatts (GW) of capacity by 2050, targeting to meet roughly 10 % of the region's electricity demand, which translates to powering around 94 million households daily. This development aims to create a robust European industrial sector and generate up to 500,000 skilled jobs [5]. Key ocean energy sources include offshore wind farms that utilize strong and consistent winds over oceans, wave energy systems that capture the kinetic energy of surface waves, tidal energy technologies that convert predictable tidal flows, and floating solar platforms deployed on ocean surfaces. These technologies complement each other and help balance the energy mix while achieving significant carbon emission reductions [6]. Characterised by its long coastlines and advantageous tropical climate, Malaysia is pursuing the adoption of renewable energy systems to address its energy needs and environmental concerns [7]. The Malaysian

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government aims to cut greenhouse gas (GHG) emissions by 45 % by 2030, emphasizing integrating renewable energy as a key component of this plan [8]. The potential for renewable energy on Malaysian islands is particularly significant. These regions often face challenges related to traditional power distribution and depend heavily on polluting diesel generators [9]. Floating solar, offshore wind, and wave energy systems offer feasible solutions to provide reliable, low-carbon electricity in these locations. Floating solar PV systems are particularly suitable for tropical, land-constrained island environments. The cooling effect of water surfaces improves panel efficiency, mitigating heat-related performance losses that are common in tropical conditions [10]. High solar irradiation during the Southeast Monsoon (May–September) further enhances energy yield. The Malaysian government has launched several initiatives to promote renewable energy, particularly in island communities. The Smart Green Island Project (Pulau Tenaga Hijau) targets islands like Tioman, Langkawi, and Pangkor to pioneer the adoption of clean energy technologies. This initiative aims to implement diverse clean generation sources and energy-efficient technologies across these islands, to achieve net-zero emissions by 2040 [11]. Malaysia enjoys significant solar potential due to its location near the equator, with average solar irradiation levels among the highest in Southeast Asia. The Malaysia Renewable Energy Roadmap (MyRER) outlines a plan to increase solar capacity significantly, targeting 31 % - 40 % of total energy demand from renewables by 2025–2035 respectively [12,13]. Floating solar systems are particularly advantageous for islands where land is limited, allowing for efficient utilization of water surfaces [14]. Economic studies, such as the 10 MW floating PV installation at UMP Lake, demonstrate favourable LCOE (USD 0.052/kWh) and a payback period of 9.5 years, along with substantial carbon emission reductions (11, 135.2 tons annually) [15]. For smaller 1 MW systems, proportional benefits remain significant, offering both economic and environmental value to island communities. Wind energy potential in Malaysia varies considerably by location. The Northeast Monsoon (January–May) provides higher wind speeds on certain islands, making offshore wind turbines viable. However, wind speeds on Pangkor and other locations are relatively low (1–6 m/s), which limits capacity factors and energy production [16,17]. Successful deployment requires careful site selection, considering bathymetry, seasonal variability, and typhoon exposure. Offshore wind platforms can reduce dependence on diesel generators, providing both environmental benefits and enhanced energy security. Integrating small-scale wind turbines on offshore platforms has been shown to improve the reliability of island power systems while minimizing operational costs. Wave energy is an underexplored but promising resource for Malaysian waters. Technologies such as Oscillating Water Columns (OWCs) and point absorbers can harness wave heights of up to 2 m observed during windy seasons [18] . While most WEC designs target high-energy sites (>25 kW/m), optimally designed point absorbers can achieve capacity factors above 30 % even under Malaysia's moderate wave conditions [13,19,20]. Economic feasibility depends on capital costs, discount rates, and achievable capacity factors. LCOE values for wave energy range between 60 and 250 €/MWh, with payback periods varying from 3.8 to 10 years depending on site conditions and risk assumptions [13]. Wave energy offers environmental benefits by reducing reliance on fossil fuels, though ecological considerations such as marine habitats and noise impacts should be evaluated. Offshore wind in tropical regions faces unique challenges, including shallow bathymetry, typhoon risk, and fluctuating wind speeds, requiring careful site selection and technology adaptation [14,15]. Wave energy converters (WECs), particularly point absorbers, are well-suited for moderate wave climates like Malaysia, where energy capture efficiency depends on wave height, period, and device resonance. The research suggests that even in these moderate conditions, optimally selected converters can achieve capacity factors over 30 % [13]. The economic feasibility of wave energy projects is heavily changed by the Levelized Cost of Electricity (LCOE), which depends on discount rate-capital combinations. Research shows that average LCOE values fall between 150 and 250 €/MWh, with the minimum recorded value at 60 €/MWh. Investment recovery periods for offshore wave farms differ, with the most favorable cases achieving payback within approximately 3.8 years, while typical scenarios may extend up to 10 years. Projects with a higher risk discount rate of 10 % are considered viable only if the devices maintain capacity factors of at least 40 % [13].

1.2. Novelty and research contributions

This study offers a comprehensive evaluation of floating renewable energy systems on Malaysian islands, employing a multi-faceted approach that encompasses technical, economic, and environmental perspectives through a 3E framework. Island-Specific Analysis Across Multiple Technologies: Unlike earlier studies that typically concentrate on a single technology or geographical location, our research evaluates 1 MW floating solar, wind, and wave energy systems across three different Malaysian islands Tioman, Langkawi, and Pangkor. This comparative analysis enables us to assess the feasibility and performance of each technology in a site-specific context, yielding practical insights for tailored renewable energy planning on these islands. This study evaluates technology-specific connecting technological characteristics to the unique conditions:

- In the Floating Solar natural cooling effect provided by water enhances panel efficiency in Malaysia's tropical climate, effectively mitigating heat-induced performance losses.
- In wind, Floating Wind different strategies consider prevailing low-to-moderate wind speeds and susceptibility to typhoons, thus illuminating both challenges and potential opportunities specific to each site.
- In Wave Energy (Point Absorbers), optimally designed for the comparatively gentle wave conditions of Malaysian waters, this technology enables better energy capture in scenarios where traditional high-energy wave energy converters would underperform.
- Integrated 3E Framework evaluates energy yield, economic viability (including LCOE and payback period), and environmental impacts (such as CO_2 reduction and ecosystem considerations). This holistic approach provides a level of assessment that is seldom found in existing literature.
- Analyzing individual technologies and presenting quantitative outcomes, this study establishes a foundational dataset that can inform the design of hybrid renewable energy systems customized for the tropical island grids. This supports effective policy-making and strategic implementation efforts.

2. General description of floating solar, wind and wave technologies

Floating renewable energy technologies, including floating solar, wind, and wave energy systems, represent a transformative approach to harnessing clean energy from marine environments. Fig. 1 illustrates floating solar, floating wind, and wave energy technologies. Each renewable energy source is represented by its specific components: floating solar panels, offshore wind turbines on floating platforms, and a wave energy converter.

2.1. Floating solar

Floating solar photovoltaics (FSPV) involves mounting solar panels on buoyant platforms installed on water bodies such as reservoirs, lakes, and ponds. This technology offers several key advantages that are particularly relevant in tropical Malaysian conditions. Enhanced Efficiency from Water Cooling below the panels draws away heat, providing a cooling effect. In a hot and humid tropical climate similar to Malaysia, this effect is critical as it helps keep the panel temperature lower than a land-based installation. This temperature reduction significantly

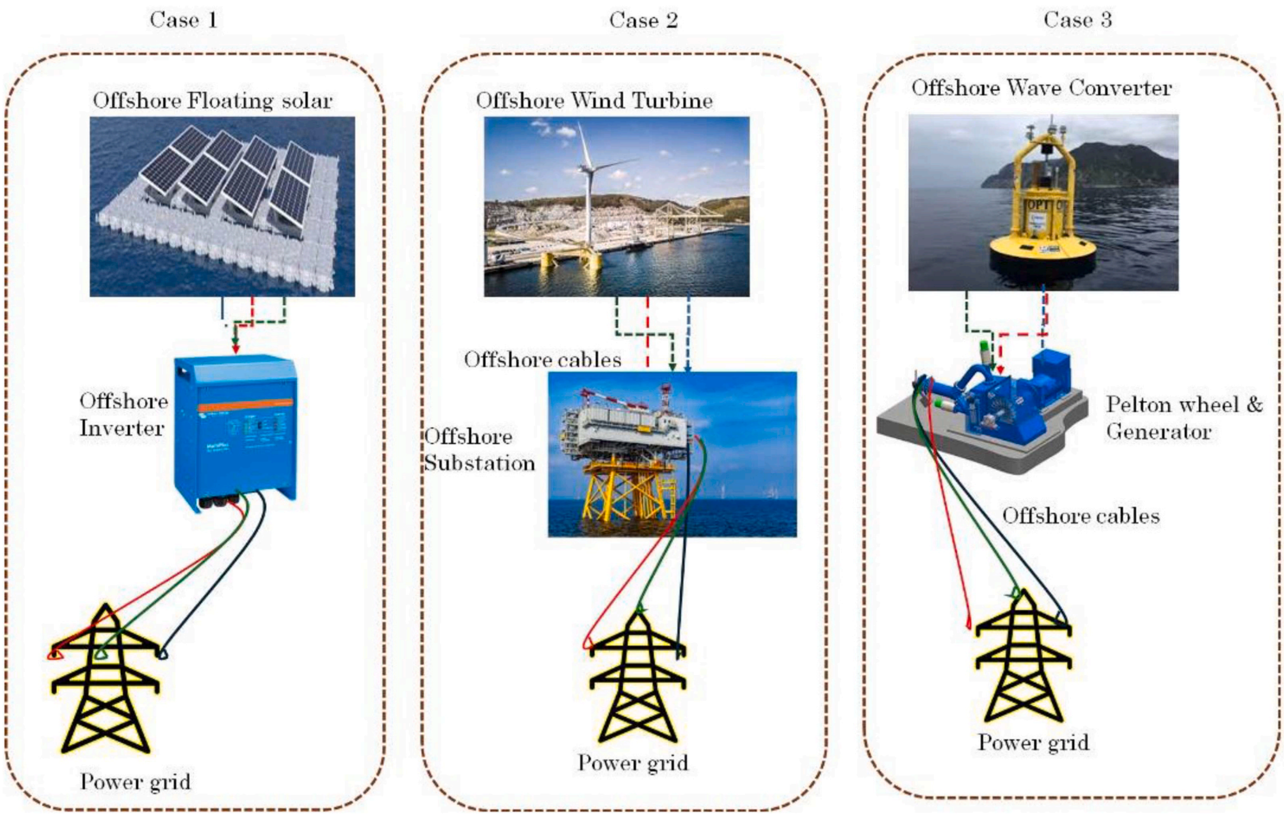

Fig. 1. Schematic of floating solar and floating wind and Wave energy systems.

mitigates the loss of efficiency that solar panels typically experience with increasing heat (a phenomenon known as the temperature derating effect), potentially boosting performance by up to 15 % compared to land-based systems [21,22]. The low-friction nature of the water surface facilitates the potential integration of single-axis tracking systems, which further enhances electricity generation by 12–15 % [23]. FSPV installations offer environmental benefits such as reducing water evaporation, mitigating algal blooms by blocking sunlight, and optimising already-utilised water surfaces, thus conserving valuable land resources [24]. These characteristics make FSPV particularly well-suited for land-constrained tropical countries aiming to combine renewable energy expansion with water resource management. Floating solar installations have grown significantly, with global capacity increasing from 3 GW in 2020 to 13 GW in 2022 [25].

2.2. Floating wind

Offshore floating wind turbines are cutting-edge renewable energy technologies designed to generate electricity in deep water regions where fixed-bottom foundations are not feasible [26]. his technology is highly relevant for Malaysia, as many of its offshore areas feature water depths exceeding 50 m, which is the general limit for fixed-bottom installations. Wind turbines are mounted on floating platforms, allowing deployment in areas with greater water depths and providing access to stronger and more consistent offshore winds compared to near-shore areas [27]. As of October 2024, floating wind turbines have a global operational capacity of 245 MW, with a substantial pipeline of 266 GW under development [28]. Most projects remain in the early phases, highlighting the technology's rapid growth and future potential. The operational capacity is currently in the North Sea and North Atlantic (more energetic, non-tropical climates), there is increasing interest in its deployment in Asian waters, including the Philippines, Taiwan, and Vietnam, which share similar tropical characteristics [23,29] . These important case studies for understanding performance and resilience in high-temperature, high-humidity, and potentially cyclonic environments. However, Malaysian wind speeds are generally lower and more variable than those in high-latitude regions where floating wind farms install [30] . The steep drop-offs in water depth in certain Malaysian waters (such as off the coasts of Sabah and Sarawak) are an opportunity for floating wind, as fixed foundations are impossible. Wave conditions in the South China Sea are generally less severe than in the North Atlantic, presenting a lower structural stress challenge for the floating platforms and mooring systems [31] . Additionally, local wave conditions are moderate, reducing extreme load risks but requiring platforms optimized for lower-energy seas. While direct typhoon hits are less frequent in Peninsular Malaysia, the waters off Sabah and Sarawak can be affected by the periphery of Pacific typhoons, posing a specific design challenge related to extreme wind and wave loading that requires robust and resilient mooring and platform designs. Seasonal monsoon-driven conditions must also be considered, though Malaysia .This reduces the design exposure to extreme cyclonic events but still necessitates robust mooring and station-keeping (substructure) systems to accommodate monsoonal waves and currents. Overall, Malaysia's bathymetry and environmental conditions suggest technical feasibility but require region-specific platform design and refined resource assessments. While direct typhoon hits are less frequent in Peninsular Malaysia, the waters off Sabah and Sarawak can be affected by the periphery of Pacific typhoons, posing a specific design challenge related to extreme wind and wave loading that requires robust and strong mooring and platform designs.

2.3. Wave converter

Wave energy technologies harness the kinetic and potential energy of ocean waves to generate electricity, using systems such as oscillating water columns, point absorbers, and attenuators [32]. Wave conditions in the South China Sea, which borders much of Malaysia, are generally characterized by relatively modest wave heights and periods compared to the highly energetic wave climates found in regions [33]. For these more moderate wave conditions, Point Absorbers are particularly appropriate [34]. This technology typically consists of a buoy tethered to a fixed base or a submerged spar, enabling it to capture and convert the vertical heave motion of ocean waves into electricity . Point absorbers are generally less sensitive to wave direction and are efficient at converting energy even from smaller, less powerful waves [35]. Other WEC types, such as attenuators (which orient perpendicular to large, long waves) or oscillating water columns (which require high, energetic waves to compress air effectively), would likely be less effective in the typically lower energy wave climate of Malaysian waters [36,37]. As the buoy moves with the waves, the mechanical energy generated by this motion is transformed into electrical energy using specialized power take-off systems. While comprehensive data on wave energy systems remains limited, their potential contribution to renewable energy operational loads and structural demands.

3. Methodology

This study evaluates the most suitable location for installing a 1 MW floating solar, wind, and wave energy system across three Malaysian islands: Tioman Island, Langkawi Island, and Pangkor Island. The design method, key parameters, and technical specifications for a 1 MW floating solar, wind, and wave energy system for Malaysian islands have been outlined in this section. Fig. 2 illustrates the comprehensive method employed in this study, with further details elaborated upon in the following subsections.

3.1. Site selection and environment conditions

The site selection process was conducted through an integrated assessment of geographical, climatic, and economic parameters. Data for Tioman, Langkawi, and Pangkor Islands were compiled from peer-reviewed literature, government meteorological databases, and satellite-derived climate products. The site characteristics are summarized in Table 1, while Fig. 3 illustrates the spatial distribution of solar radiation across the selected islands. Because solar resource quality is a key driver of floating solar performance, solar irradiance data were obtained from satellite sources Such as (World Bank Global Solar Atlas, PVGIS). Satellite-derived irradiance is widely used in feasibility studies; however, in tropical regions such as Malaysia, frequent cloud formation and high atmospheric water vapor introduce additional uncertainty. The environmental data presented in Table 1 is sourced from two main categories:

Table 1
Site details and site-specific data.

Parameter	Tioman Island	Langkawi Island	Pangkor Island	Data source
Latitude, Longitude	2.7902° N, 104.1698° E	6.3782° N, 99.7902° E	4.2275° N, 100.5577° E	Geolocation [38]
Area (km²)	133.6	466.0	18.0	[39]
Population	3700	98,100	25,000	[39]
Average wind Speed (hight 10 m/s)	4.52	4.67	3.96	[40,41]
Solar Radiation (kWh/kWp/day)	3.42–3.87	3.922	4.030	[42]
Significant wave height (m)	1 -2.5	1.5–2.5	0.3–0.7	[40,43]
Temperature (°C)	27–30	28–31	27–30	[40]
Electricity Tariff (kWh/sen)or per unit (< 200 kWh) 2025	0.21.8	0.21.8	0.21.8	[44]
Climate zone	Tropical	Tropical	Tropical	

(a) **Solar Radiation Data:** The Global Horizontal Irradiation (GHI) values used in this study (detailed in Table 4) are derived from the Global Solar Atlas (GSA), which utilizes high-resolution satellite-derived estimates for the period 1991–2023. This is a standard and acceptable practice where ground station data is unavailable. This inherent uncertainty is factored into the interpretation of the final simulation results.While ground-based measurements are limited on these islands, the Global Solar Atlas datasets have been shown to align with Malaysian Met Department (MET Malaysia) ground observations within a typical uncertainty band of ±5–10 %. This uncertainty is acknowledged in the analysis, and sensitivity checks were performed during PVsyst simulations to account for potential variations.

(b) **Wind and Wave Data:** Table 1 represent long-term averages from published coastal climate studies and The wind speed and wave height values are based on monthly and annual averages derived from the ERA5 reanalysis dataset (European Centre for Medium-Range Weather Forecasts(2008–2017), Global Wind Atlas reports) for the period 2015–2024. Although offshore wind speeds in Malaysia are generally moderate (3–5 m/s), they are sufficient to induce surface cooling, reduce module temperatures, and improve FPV performance. Similarly, wave-height ranges

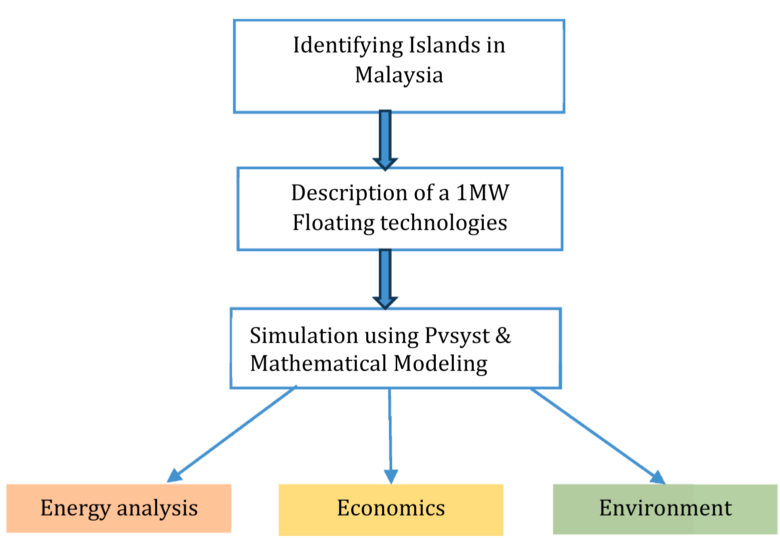

Fig. 2. Flow chart illustrating the simulation procedure for the analysis.

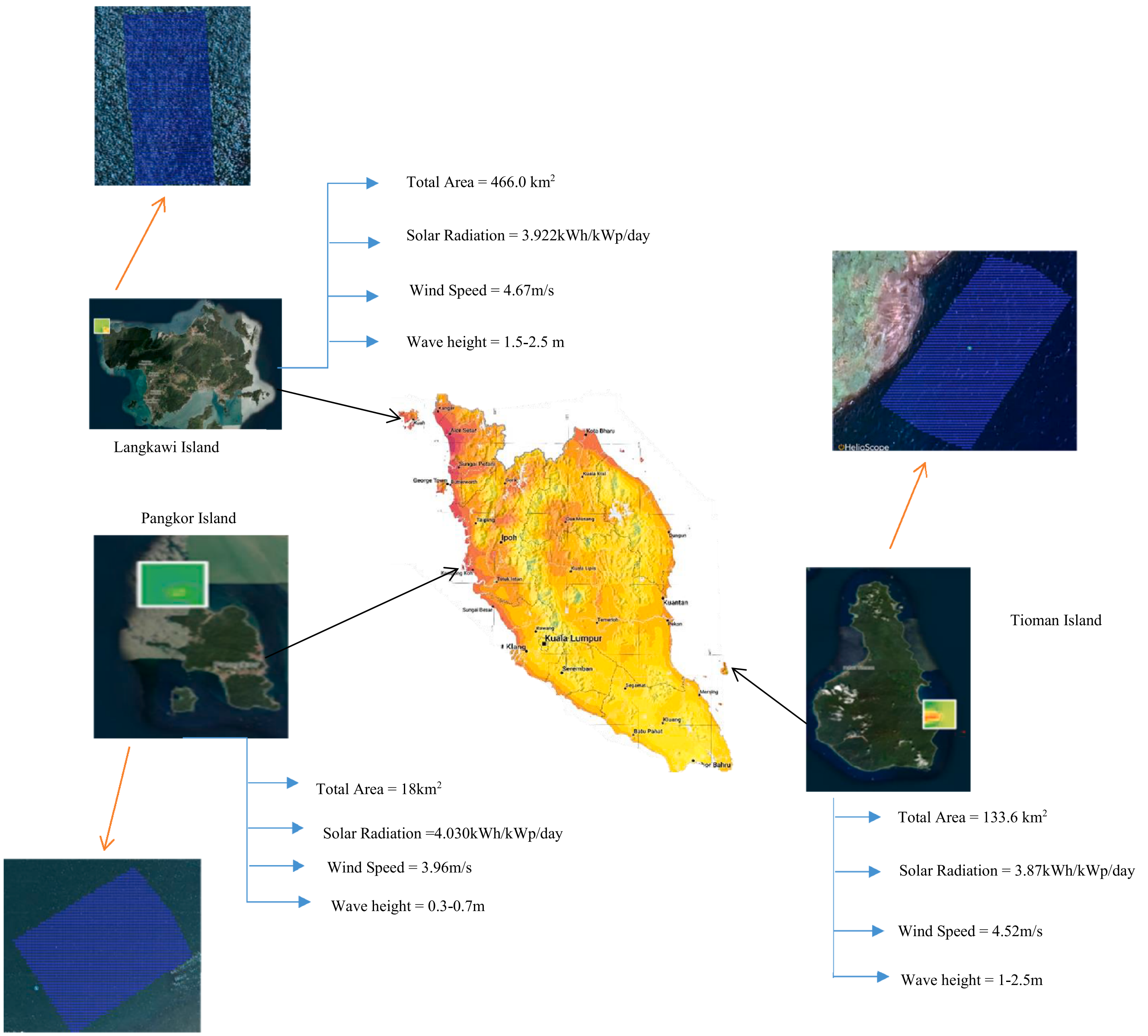

Fig. 3. Solar radiation map of Selected Island in Malaysia.

help determine pontoon stability and anchoring requirements but do not directly affect PV electrical output.

3.1.1. *Selection of offshore floating solar and its specifications*

The performance analysis for the 1 MW Floating Solar PV (FPV) systems was conducted using the PVsyst V7.2 simulation software, which is recognized as the industry standard for PV system design and energy yield assessment. All systems are configured with southward orientation and site-specific tilt angles (Table 2) were not chosen arbitrarily. These angles were optimized within PVsyst based on annual energy yield simulations using global horizontal irradiance (GHI) and diffuse radiation profiles. Given the islands' locations near the equator (2°–6° N), shallow tilts generally maximize annual energy production by balancing high diffuse radiation fractions and minimizing self-shading on floating platforms. The selected angles reflect the optimum positions for maximizing annual yield under tropical atmospheric conditions. PVsyst simulations were conducted using local irradiance, temperature, and weather variability, as well as typical offshore operational conditions. Satellite-derived data are an acceptable and often necessary source for remote or offshore locations where ground measurement stations are insufficient. However, their accuracy can be compromised in tropical regions due to frequent, localized cloud cover and high atmospheric water content. These conditions can cause the satellite model's cloud masking and atmospheric loss algorithms to either under- or over-estimate the actual GHI. The uncertainty associated with these values is typically in the range of +-5 %. While ground measurements would be preferred for validation, in their absence, the PVsyst model internal atmospheric and spectral correction functions were relied upon to mitigate potential errors. (Table 3) were determined

Table 2
Site selection Title angle data [45].

Title angle			
	Tioman Island	Langkawi Island	Pangkor Island
Average title angle	4.6°	8.5°	6.2°

Table 3
Site selection annual solar irradiation data [42,46].

GHI Irradiation			
Year	Tioman Island	Langkawi Island	Pangkor Island
January	135.4	166	158.8
February	152.2	165.3	156.8
March	176.2	185.3	172.5
April	177.1	169	162.7
May	169.4	158.5	155.3
June	161.5	145.6	145.8
July	143.2	150.3	154.1
August	158.6	144.2	149.3
September	152.9	138.9	144.7
October	146.8	139.6	139.6
November	125.2	133.4	136.9
December	116.8	141	138.4

through a sensitivity analysis within the PVsyst software to maximize the annual energy yield for each latitude.

3.1.2. PV system components and environmental factors

(a) **PV Modules and Inverters**: Monocrystalline PV modules were selected due to their higher efficiency (18 %–22 %) and better temperature performance relative to polycrystalline modules an important consideration given Malaysia's ambient temperature of 27–31 °C [47]. Each 1 MW FPV system uses 2000 units of 500 Wp modules, occupying approximately 4434 m^2 of water surface area (Table 4).

(b) **Environmental Loss Factors (Soiling and Degradation):** PVsyst's soiling loss parameter was adjusted to account for marine aerosol, salt spray, and high humidity. Typical monthly soiling losses of 1–2 % were applied based on literature for tropical maritime environments [48]. A degradation rate of 1.0 % per year was assumed for the crystalline silicon modules, which aligns with standard industry practice and accounts for performance drop due to factors. Temperature Effects: Module temperature modelling used site-specific ambient temperature and wind profiles, with FPV-related cooling effects incorporated through PVsyst's default water-cooling correction model.

3.2. Selection of floating offshore wind turbine and its specifications

The selection of a suitable Floating offshore wind turbine (FOW) for this study followed a structured methodology that integrates site-specific wind characteristics, turbine performance parameters, and engineering feasibility. The three selected sites Tioman, Langkawi, and Pangkor Islands were chosen based on their coastal exposure and focuse on 1 MW wind turbine.

Table 4
Specification of the selected panel and inverter.

Parameter	Value
Module type	Monocrystalline (High efficiency)
Model	AIKO-500
Dimensions (mm)	29 × 500 × 69
Nominal power(Wp)	500
No. of PV modules	2001 units
Total Nominal (STC) power (kWp)	1001
Nominal power PMPP (kWp)	936
Voltage at Pmax VMPP (V)	1010
Current at Pmax IMPP (A)	927
Efficiency range(manufacturer spec)	15 %–24 %
Module area	4434m^2
Cell area	3977m^2
Inverter	
Inverter model	Sinacon PV1000
Nominal power (kW_{AC})	1000
Operating voltage	802–1500V
No. of inverter	1 unit
Capacity	1000kW

(a) **Data Preparation**: The wind speed data used for the analysis, presented in Table 5, represents the monthly average wind speeds measured at a standard meteorological height of 10 above the sea surface.

(b) **Extrapolation to Hub Height**: The measured 10m/s wind speeds are not representative of turbine operation. They must be extrapolated to the assumed hub height of the selected 1 MW turbine, which is (60–80 m). This extrapolation is crucial for accurate power calculation, as power output is proportional to the cube of the wind speed *(V^3)*.

(a) **Floating Wind Turbine**: The analysis focuses on a conceptual Floating Semi-Submersible Platform supporting a 1 MW horizontal-axis monopile-supported offshore wind turbine (HAWT) with fixed structure (Table 6) . This system is designed for water depths greater than 30 m, making them suitable for Malaysian coastal conditions. The evaluation process incorporates aerodynamic performance, efficiency losses, and energy yield calculations using Eqs. (1)–(8) .

(a) **Wind Power Calculations:**

Swept Area of the Turbine

The first step is estimating the rotor swept area, which determines the amount of wind captured by the turbine. For a Horizontal-Axis Wind Turbine (HAWT), the swept area A is given by:

$$A = \pi \times L^2 = \frac{\pi (D)^2}{2} \tag{1}$$

Where, L= length of the turbine blades.

D= rotor diameter (m)

Available Wind Power

The theoretical power available in the wind is calculated as:

$$P_{wind} = 0.5\rho \times A \times v^3 \tag{2}$$

'ρ' = air density (assumed to be 1.225 kg/m^3),

'v' = wind speed (with a typical usable range of 3–25 m/s),

Real Efficiency and Power Coefficient ('μ' and 'C_p')

The net output power is calculated using the overall system efficiency,'μ'.

$$\mu = (1-k_m) \times (1-k_e) \times \left(1-k_{e,t}\right) \times (1-k_t) \times (1-k_w) \times C_p \tag{3}$$

A value of $C_p = 0.40$ is used. This is selected as a realistic, yet slightly optimistic, value for a well-designed turbine operating in low to moderate wind speeds, aiming to capture the maximum energy from a

Table 5
Site selection annual wind speed data [41].

Wind Speed(m/s) 10m(fixed reference heights above ground/sea level)			
Year	Tioman Island	Langkawi Island	Pangkor Island
January	5.3	3.1	1.7
February	5.6	3.5	1.7
March	3.8	2.3	1.9
April	3.0	2.0	1.5
May	2.4	1.8	2.1
June	3.4	1.9	2.2
July	3.3	1.8	2.4
August	3.9	2.1	2.4–3.1
September	3.6	2.3	2.2
October	3.3	2.9	1.9
November	2.9	3.3	1.7
December	4.5	2.8	2.1–3.0

Table 6
Specification of the 1 MW Wind turbine [49].

Parameter	Value
Foundation Type	Semi-Submersible Platform
Structure	Monopile
Material	Steel
Rated capacity	1MW
Pipeline diameter	3.5–6m
Hub height	60–80 m
Average water depth	0–30m
Sweep area	2827m^3
Rotor diameter	60m
Blade length	30m
Capacity	1–2MW
Cut-in wind speed	2.5–3.5m/s
Cut-out wind speed	20–25m/s

Table 7
Site selection annual wave height.

Month	Tioman (Hs)	Langkawi (Hs)	Pangkor (Hs)	Assumed Average Period in sec (Ts)
January	1.75	1.85	1.2	4
February	1.5	1.85	1.1	4
March	1.25	1.85	1.3	4
April	1.05	1.25	1	4
May	0.75	1.05	0.9	4
June	0.75	1	1.5	4
July	0.75	1	1.4	4
August	0.75	1	1.6	4
September	0.75	0.8	1.3	4
October	1.05	1.25	1.2	4
November	1.75	1.85	1.4	4
December	1.5	1.85	1.5	4

marginal site. This justifies moving away from the conservative 30–40 % range.

C_p = (Power coefficient) (typically 0.30–0.40, below Betz limit of 0.593)

k_m= (Mechanical losses) (0–0.3 %)

k_e= (Electrical losses) (1–1.5 %)

$k_{e,t}$= (Transmission losses) (3–10 %)

k_t= (Downtime/maintenance losses) (2–3 %)

k_w= (Wake losses) (3–10 %)

Output Power

The actual power output of the turbine is:

$$P_{output} = \mu \times P_{Wind} \tag{4}$$

Revenue Estimation

Energy revenue for each site is calculated using the local electricity tariff:

$$Revenue = tariff \times P_{output} \tag{5}$$

where, tariff = RM 0.21.8/kWh.

Torque Calculation (τ)

The mechanical torque acting on the turbine shaft is calculated as:

$$\tau = \frac{P_{\mathrm{output}}}{\omega} \tag{6}$$

$$\omega = 2\pi \times \; RPM/60 = \text{angular velocity (rad / s)}$$

The turbine rotational speed is estimated using the tip speed ratio (TSR):

$$RPM = \frac{60vTSR}{2\pi \mathrm{L}} \tag{7}$$

Overall Power Production

The general expression for wind turbine power output is:

$$Power(W) = 0.5 \times \rho \times \pi r^2 \times Cp \times CF \times v^3 \tag{8}$$

Where, Cp = power coefficient

CF =capacity factor.

$$F = \frac{\text{Actual energy produced over a period}}{\text{Energy if turbine ran at rated power for the entire period}} \tag{9}$$

3.3. Selection of wave converter and its specifications

Wave power generation is largely influenced by two key factors, the significant wave height (H^2s) and the wave period (T). This research evaluates the operational efficiency of a 1 MW floating wave energy converter (WEC) system across three purposefully selected coastal islands sites: Tioman Island, Langkawi, and Pangkor Island. The selection of these sites was based on their favourable wave climate, with monthly significant wave height (H_S) data shows in Table 7. For Tioman Island, annual wave heights generally range from 0.2 to 1.7 m, with wave periods varying between 4 and 7 s, as established by recent weather forecasts. Notably, in the monsoon season, wave heights may occasionally increase to between 1–2 m, slightly extended wave periods nearing 9 s. On Pangkor Island, while specific average data is less available, a similar trend of moderate wave heights and periods continues, with typical heights remaining under 1 m and periods scattered across a few seconds. Langkawi Island is characterized by relatively calm to moderate wave conditions. Here, wave heights typically remain below 1–2 m Specific average wave heights and periods are not frequently provided in daily forecasts; however, they are generally consistent with those observed in adjacent coastal regions of Malaysia. Given that the wave resource in the South China Sea primarily consists of short-period wind waves, rather than long-period swells, it is reasonable to assume an average wave period of $T = 4.0$ s for all three investigated sites. This assumption will serve as the basis for subsequent power generation calculations and analyses. Crucial assumption acknowledges the data limitation and allows for the calculation of group velocity.

3.3.1. Wave power calculation

The standard industry formula for gross wave power per unit crest width (P_{wave}), which is typically measured in (kW/m).Since the proposed WEC implementation is in moderately assume deep offshore waters, the deep water approximation is used [50]. The gross wave power density is calculated (Eqs. (10) and (11)):

$$P_{wave} = 0.5xH_S^2T_e(kW/m) \tag{10}$$

Were,

P = Gross wave power in kW/s

H_S = Significant wave height (m)

T_e= the wave period (s)

$$P_{\mathrm{wave}} = \frac{\rho g^2}{64\pi} \; \times \; H^2 S_e \tag{11}$$

ρ = Density of seawater (1025 kg/m^3)

g = Acceleration due to gravity (9.81 m/s^2)

Power Captured by the WEC

$$P_{\mathrm{captured}} = Pwave \; \times \; CWR \tag{12}$$

CWR (Capture Width Ratio)= 0.5

3.3.2. Point absorber specifications and system configuration

A Point Absorber–type specifications for the 1 MW installation (specifications in Table 8) reflect realistic dimensions for a commercial-scale Point Absorber and to justify the system configuration. Point Absorbers are compact, axisymmetric devices capable of extracting energy from waves arriving from multiple directions, making them suitable for Malaysia’s moderately energetic nearshore environment. A commercial

Table 8
Specification of the 1 MW Wave converter [51,52].

Parameter	Value	Justification
WEC Type	Point Absorber	Better performance in low/moderate wave conditions typical of Malaysian waters
Rated capacity per unit	100 kW	Representative of commercial-scale devices
Number of units	10	Achieves total installed capacity of 1 MW
Total installed capacity	1 MW	Wave energy array
Structure	Buoyant Floating	
Buoy diameter	8–10 m	Typical for 100 kW Point Absorbers
Power Take Off (PTO system)	Hydraulic–electric	Industry standard

100 kW Point Absorber typically has a diameter of several meters. Their efficiency depends on the dynamic interaction between the buoy motion and incoming waves, which determines how much mechanical energy is transferred to the power take-off (PTO) system. The primary performance indicator of a Point Absorber is its absorbed wave power, which reflects the portion of the available wave energy converted into usable mechanical or electrical power. The output power depends on the local wave resource, buoy geometry, capture width ratio, and PTO efficiency. Therefore, we base our analysis on a realistic commercial specification:

3.4. System performance

3.4.1. Annual energy yield

The annual energy yield of a 1 MW hybrid system comprising floating solar panels, wind turbines, and wave energy converters can be evaluated on a daily, monthly, or yearly basis. This assessment is influenced by the specific module specifications and the environmental conditions at the installation site, including solar irradiation, wind speed, and wave height. In locations such as Tioman Island, Langkawi, and Pangkor Island, these factors play a crucial role in determining the system's overall power production and efficiency.

3.4.2. Capacity factor

The capacity utilization factor (CUF) is a key metric used to evaluate the efficiency and performance of a renewable energy system. It represents the actual energy output of a system over a specific period compared to its theoretical maximum output if it operated at full capacity all the time [53].

$$CUF = Plantoutputpower/Installedcapacityx365daysx24hr \tag{13}$$

3.4.3. Performance ratio (PR)

The Performance Ratio (PR) is the ratio of a system's actual or forecasted energy output under typical operating conditions to its theoretical energy output, which is assumed based on the local climate conditions of the islands.

$$PR\% = E_{actual}/E_{theoretical} \times 100 \tag{14}$$

3.5. Economic analysis

The economic assessment of the 1 MW Floating Renewable Energy Systems (Floating Solar, Floating Wind, and Wave Converters) using a 3E analytical framework Energy, Economics, and Environment a widely adopted evaluation structure in international renewable energy studies such as hydrogen/battery storage assessments, island decarbonization analyses, and thermal power plant optimization and project lifespan of 21 years. The analysis is grounded in specific cost assumptions and utilizes a discounted cash flow approach to reflect the Economics (E) component of the comprehensive 3E framework [54].

3.5.1. Levelized cost of energy L_{COE}

The LCOE represents the average cost per unit of energy (kWh) required for the project to break even over its entire lifespan. This is the most crucial metric for comparing the cost-effectiveness of different generation technologies.

$$LCOE = \frac{\sum_{N}^{t=0} \frac{CAPEX_t + OPEX_t}{(1+r)^t}}{\sum_{N}^{t=1} \frac{AEP^t}{(1+r)^t}} \tag{15}$$

Where,
$CAPEX_t$= Capital Expenditures (initial investment) in year 't'.
$OPEX_t$ = Operating Expenditures (maintenance, etc.) in year 't'
AEP= Annual Energy Production (kWh) in year
r= Discount Rate (reflecting the cost of capital).
N= Project lifetime, set at 21 years for this analysis.

3.5.2. Payback period (PBP)

The Payback Period estimates the time required to recover the initial investment:

$$\text{PaybackPeriod(PBP)} = \frac{\text{InitialInvestmentCAPEX)}}{\text{AnnualSavings(NetCashflow}} \tag{16}$$

The Annual Savings must be calculated based on the annual energy generated and the avoided cost of grid electricity (the tariff)

$$Annual\ Savings = Annual\ Energy\ Production\ (AEP\ in\ kWh)\ x\ TariffRate\ (RM/kWh) \tag{17}$$

Key Economic Assumptions: To ensure transparency and comparability, the following cost assumptions are adopted based on Malaysian market conditions, international literature, and recent island-based renewable energy studies [55,56]:

3.5.3. Capital cost breakdown and operating & maintenance costs

The capital expenditure (CAPEX) of the 1 MW floating renewable energy systems is a major cost component to support transparent and

Table 9
Key Economic assumptions for 1 MW floating renewable energy systems in Malaysia.

Parameter	Floating Solar (FPV)	Floating Wind (FOW)	Wave Converter (WEC)	Justification
Project lifetime (years)	21	21	21	Aligned with Malaysian project financing and FIT contracts
Discount rate (%)	7	7	7	Typical cost of capital for emerging Asian renewable projects
Total CAPEX (RM million/ MW)	5–7	8–10	18–22	FPV: Malaysian projects; FOW/ WEC: early-stage offshore technologies
CAPEX (RM/kW)	5000–7000	8000–10,000	18,000–22,000	Converted from total CAPEX
Annual OPEX (% of CAPEX)	1.0 %	3.0 %	5.0 %	Offshore access and mechanical complexity
Electricity tariff / avoided cost (RM/ kWh)	0.20	0.20	0.20	Malaysian reference electricity tariff

consistent economic evaluation. Tables 9 **and** 10 summarise the Assumptions, CAPEX breakdown for Floating Photovoltaics (FPV), Floating Offshore Wind (FOW), and Wave Energy Converter (WEC) systems, including equipment cost, floating structures and mooring, power electronics and cabling, installation and marine works, development and permitting, etc.

3.6. Environmental analysis

The environmental (E) performance of floating renewable energy systems floating solar PV, offshore wind turbines, and wave energy converters was assessed using a cradle-to-grave Life Cycle Assessment (LCA) framework approach, calculating the total Greenhouse Gas (GHG) emissions (expressed as kg Co_2 equivalents per kWhof electricity generated) for each technology. The grid emission factor for Malaysia and the life-cycle emission factors for each technology used in this study are summarized in Table 11.

Net Co_2 reduction via LCA

The net Co_2 reduction achieved by replacing grid electricity with floating renewable energy is calculated as:

$$Net\ CO_2\ Reduction = CO_2\ Emissions\ avoided - Total\ Lifecycle\ CO_2\ Emissions \tag{18}$$

Co_2 Emissions Avoided (Mitigation)

This represents the emissions mitigated by displacing the energy that would otherwise be generated by Malaysia's fossil-fuel-intensive grid. This is the benefit of the renewable energy project

$$CO_2\ Emission\ mitigation\ by\ FPV\ plant = Annual\ energy\ production(kWh) \times Grid\ emission\ factor \tag{19}$$

Total life cycle Co2 emissions (LCA)

Eq. (18) represents the total environmental cost of the renewable energy project across its 21-year lifespan. This figure is normalized by the total energy produced over that lifespan (AEP x 21 years) to give an LCA-based emission factor (in kg Co_2 per kWh). The detailed LCA stages and their descriptions used in the emission factor estimation are presented in Table 12.

$$Total\ LCA\ Emissions = GHGM + GHGTI + GHGOM + GHGDD \tag{20}$$

Final net Co_2Reduction calculation

The total net reduction for each technology is calculated:

$$Net\ CO_2\ Reduction\ (Life\ Cycle\ ) = (AEP\ x\ 0.758) - (\ AEP\ x\ Life\ Cycle\ Emission\ Factor) \tag{21}$$

Table 10
CAPEX beakdown for 1 MW floating renewable systems.

Cost Component	FPV (RM million/MW)	FOW (RM million/MW)	WEC (RM million/MW)
Generation equipment	2.0	2.5	6.0
Floating structure & mooring	1.2	2.0	4.0
Power electronics & cabling	0.6	1.0	2.0
Installation & marine works	0.8	1.5	3.0
Development & permitting	0.4	0.5	1.5
Contingency (10–15 %)	0.6	1.0	2.5
Total CAPEX	5.6	8.5	22.0

Table 11
LCA Carbon emission factor in Malaysia [57,58].

Parameter	Value/Unit
Grid emission factor (Malaysia)	0.758 kg CO_2/kWh
Technology	Emission Factor (kg CO2/kWh)
Floating Solar (FPV)	0.040 kg CO2/kWh
Floating Wind (FOW)	0.015 kg CO2/kWh
Wave Converters (WEC)	0.025 kg CO2/kWh

Table 12
Life-cycle stages considered in emission factor estimates [57].

LCA Stage	Abbreviation	Description
Manufacturing	GHGM	Emissions from material extraction, processing, and component production (e.g., PV panels, steel for turbines, buoyancy platforms).
Transport & Installation	GHGTI	Emissions from transporting components to the site and installation via marine vessels.
Operation & Maintenance	GHGOM	Emissions primarily from maintenance vessel trips and minor material replacements.
Decommissioning & Disposal	GHGDD	Emissions from dismantling the system and disposal/recycling of materials at the end of the 21-year lifespan.

4. Results

The feasibility of a 1 MW floating solar, wind turbine, and wave energy project is evaluated individually based on technical, economic, and environmental performance. Critical factors such as global horizontal irradiance, irradiance on the tilted plane, wind speed, wave height, system output, and energy yield are analysed to assess the viability of each technology at different locations. Furthermore, average yearly values of specific yield, performance ratio (PR), energy price, and CO_2 emissions are observed and discussed for different islands, offering insights into the potential of each system.

4.1. Floating solar energy analysis

Fig. 4 presents the monthly Global Horizontal Irradiation (GHI) for Tioman, Langkawi, and Pangkor Islands. Clear seasonal variations are observed, with GHI peaking in March across all sites and declining during November–December due to the Northeast Monsoon. Langkawi consistently records higher GHI throughout the year, indicating inherently stronger solar resource availability compared to Tioman and Pangkor. Tioman shows lower GHI toward the end of the year, suggesting reduced energy potential during the monsoon season. The daily and monthly energy yields of the 1 MW FPV systems (Fig. 5) reflect these irradiation trends. Langkawi produces the highest monthly output, approaching 160 MWh in March–April, consistent with its higher GHI. Tioman and Pangkor demonstrate strong performance from February to July, with Tioman peaking during June–July and Pangkor peaking in March. Significant reductions in energy yield for all sites during October–December correspond to increased cloud cover and rainfall associated with monsoon activity. The simulated annual energy yields 1533.7 MWh for Tioman, 1550.4 MWh for Pangkor, and 1553.3 MWh for Langkawi result in capacity factors of approximately 17–18 %, which align with typical values reported for tropical Southeast Asia. This confirms the internal consistency between irradiance data, monthly energy outputs, and annual performance. Fig. 6 shows the Performance Ratio (PR) for the three islands, with values ranging between 0.80 and 0.85 throughout the year. These are strong performance levels for floating solar installations. PVsyst simulations explicitly included realistic soiling and degradation factors tailored for a tropical marine environment. Soiling Loss based on literature for tropical maritime

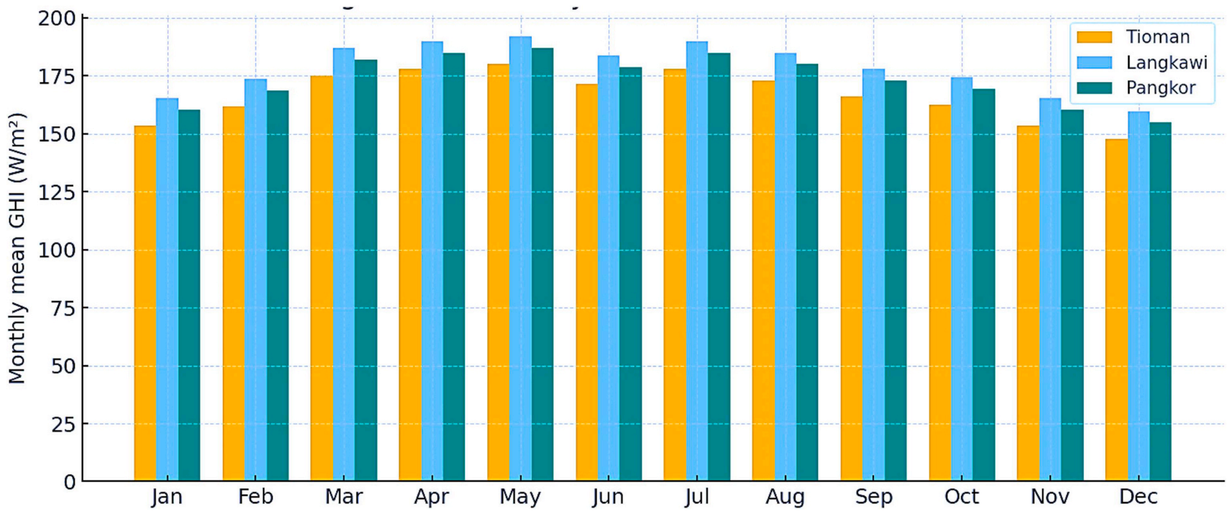

Fig. 4. Monthly variation of GHI irradiation for three islands.

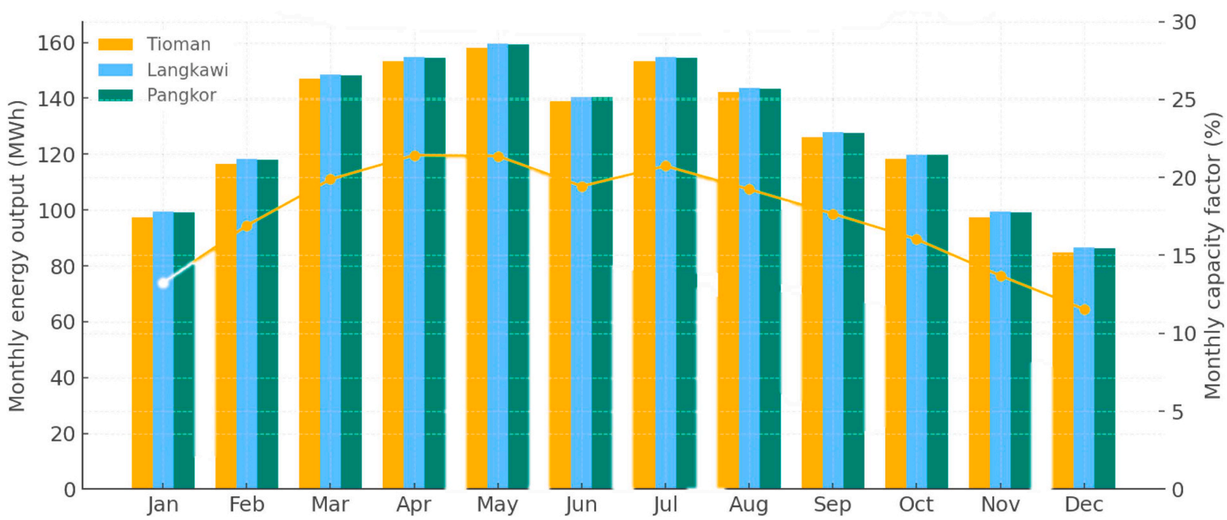

Fig. 5. Monthly variation of floating solar energy yield for three islands.

environments, we applied a monthly soiling loss of 1 % to 2 % in the PVsyst simulations to account for marine aerosol, salt spray, and high humidity (as detailed in Section 3.1.3 (b) of the methodology). A standard annual degradation rate of 1.0 % was applied to the monocrystalline silicon modules. The consistently high PR across all islands suggests that FPV installations can maintain reliable operational efficiency under tropical maritime conditions. The high PR is also partially attributed to the water-cooling effect inherent to floating solar systems, which improves module efficiency by maintaining lower operating temperatures relative to ground-mounted systems. Among the three sites, Langkawi shows slightly more stable PR values which, combined with its higher GHI, makes it the most favorable location for offshore FPV deployment. Tioman and Pangkor also demonstrate strong performance but with slightly greater seasonal variability.

4.2. Floating wind energy analysis

1MW wind turbine comparative analysis of the monthly wind speeds for Tioman Island, Langkawi Island, and Pangkor Island . Fig. 7 and Table 13 presents the monthly variation of wind speed at the turbine hub height (70 m) for Tioman Island, Langkawi Island, and Pangkor Island. The wind speeds shown in this figure were extrapolated from measured 10 m data using the power-law method with a shear exponent of 0.14 to better represent actual turbine operating conditions. Among the three sites, Tioman Island consistently exhibits the highest hub-height wind speeds throughout the year, reaching peak values of approximately 7.0–7.4 m/s during January and February. Wind speeds at Tioman decrease during the inter-monsoon period, with minimum values of around 3.1 m/s in May, before increasing again towards the end of the year. Langkawi Island experiences moderate wind conditions, with hub-height wind speeds generally ranging between 2.3 and 4.6 m/s, showing slightly stronger winds during February and November. Pangkor Island records the lowest wind speeds among the three sites, with hub-height values mostly below 2 m/s, indicating comparatively weaker wind resources.

Fig. 8 illustrates the monthly wind energy output of a 1 MW floating offshore wind turbine at each site, expressed in megawatt-hours (MWh) over a 12-month period. The energy output was calculated based on the extrapolated hub-height wind speeds, turbine swept area, power coefficient, and was limited by the rated capacity of the turbine. Tioman consistently exhibits the highest monthly energy output across most months compared to Langkawi and Pangkor. Its peak generation occurs in January and February, reaching approximately 175 MWh, indicating favourable seasonal conditions for renewable energy generation, likely solar-dominated. Langkawi demonstrates moderate energy output, with monthly values generally ranging between 5 and 45 MWh. Notably,

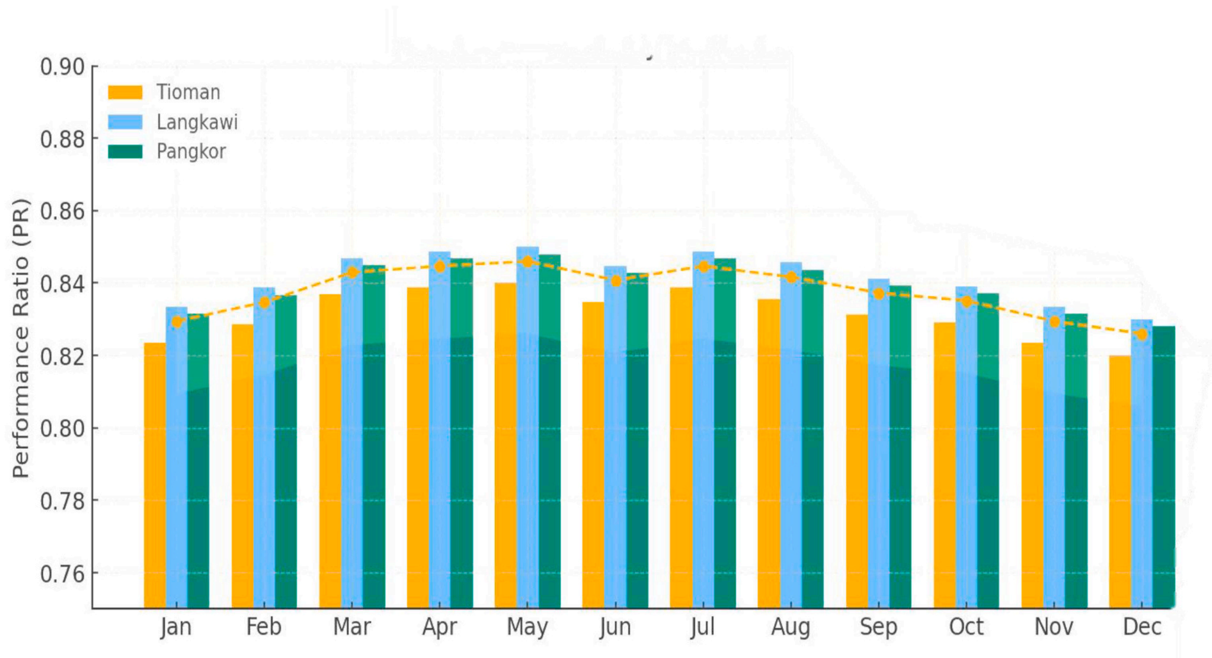

Fig. 6. Monthly variation of floating solar Performance ratio for three islands.

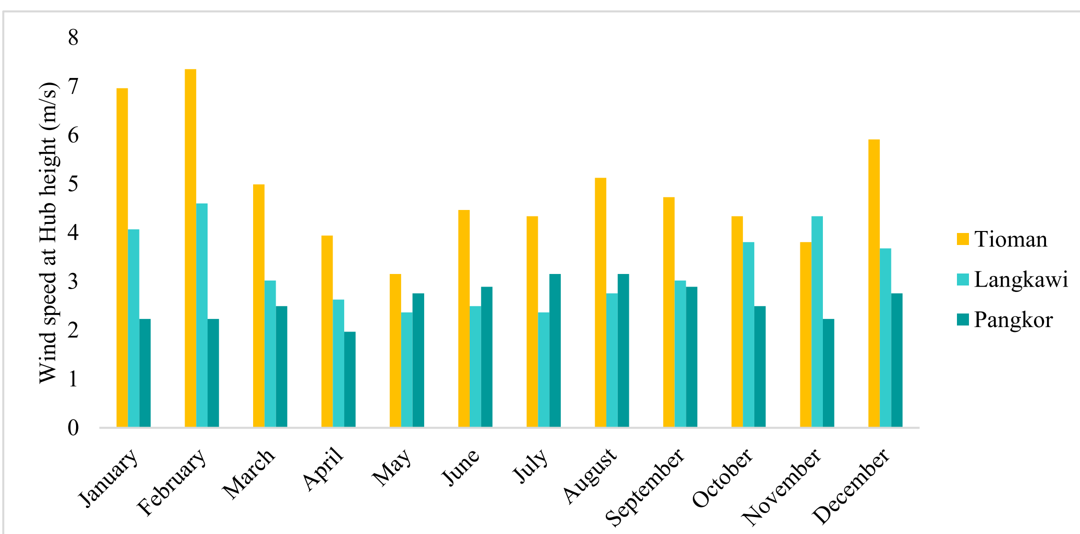

Fig. 7. Monthly Variation of wind speed at the hub height for three Islands.

Table 13
Assumptions and justification of wind turbine.

Parameter	Value
Reference height	10 m
Hub height	70 m
Wind shear exponent (α)	0.14
Air density (ρ)	1.225 kg/m^3
Rotor diameter	60 m
Swept area	2827 m^2
Power coefficient (Cp)	0.40
Rated power	1 MW
Losses	Included implicitly via Cp

higher outputs are observed in October and November, suggesting a seasonal increase in wind or wave resource availability. Pangkor has the lowest monthly energy output overall, consistently below Langkawi and Tioman. Monthly values remain below 15 MWh for most months, highlighting limited renewable energy potential at this site or less favourable environmental conditions. Seasonal variations are evident for all islands. Tioman shows a clear peak in early-year months (January–February), followed by lower production mid-year (May–July). Langkawi and Pangkor show smaller fluctuations, with slight increases during the later months (October–December). Pangkor Island shows the lowest wind energy output, with most monthly values remaining below, highlighting the limited viability of wind energy as a standalone power source at this location.

Fig. 9 presents the monthly capacity factor (CF %) of the renewable energy system for Tioman, Langkawi, and Pangkor Islands over a full annual cycle. The results reveal pronounced seasonal and spatial variability, highlighting the strong influence of local meteorological conditions on system performance. Tioman Island consistently exhibits the highest capacity factor throughout the year, with peak values observed

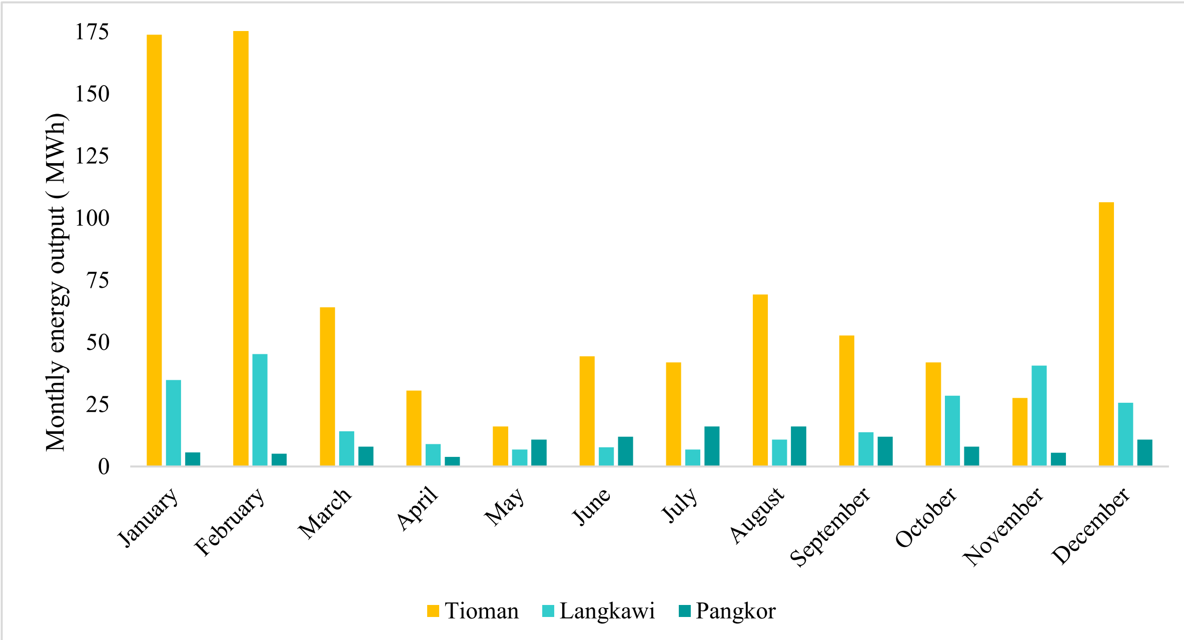

Fig. 8. Monthly variation of 1 MW wind turbine output for three Islands.

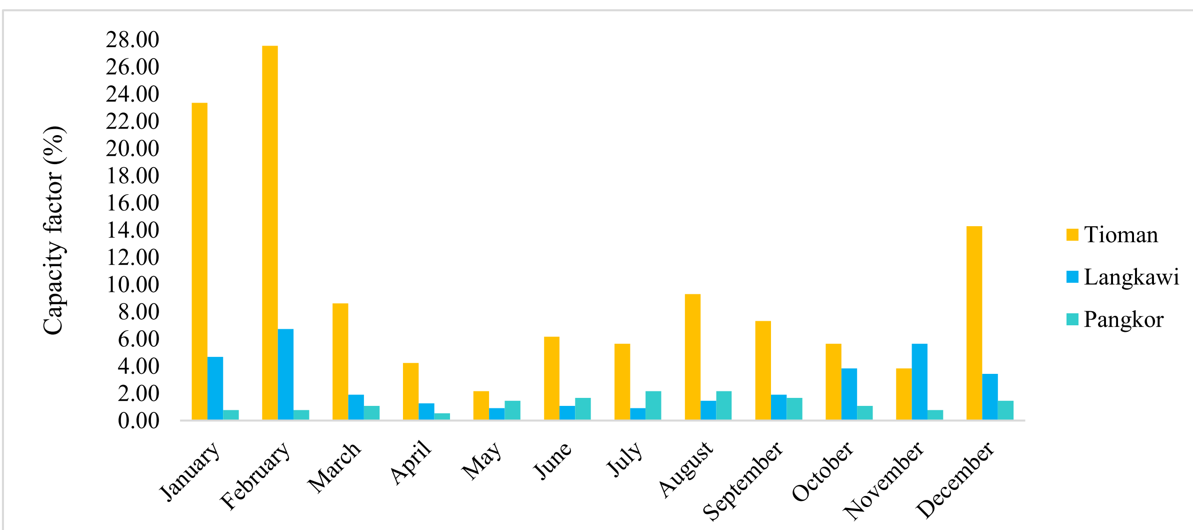

Fig. 9. Monthly capacity factor of Wind turbine in three Islands.

during January–February and December, reaching approximately 24–28 %. These elevated values correspond to periods of favourable climatic conditions, including higher solar irradiance and stronger wind regimes associated with the northeast monsoon. A moderate decline is observed during the inter-monsoon months (April–May), followed by partial recovery in August–September. Langkawi Island demonstrates moderate capacity factors, generally ranging between 2 % and 7 %. Seasonal fluctuations are evident, with higher performance during February, October, and November, while lower values occur during mid-year months. Compared to Tioman, Langkawi's reduced capacity factor reflects comparatively weaker and more variable renewable energy resources. Pangkor Island records the lowest capacity factor among the three sites, remaining mostly below 3 % throughout the year. Minor increases are observed during July–August, but overall performance remains limited, indicating weaker resource availability and less favourable operational conditions for energy generation.

4.3. Wave energy analysis

Fig. 10 presents the monthly variation of significant wave height (Hs) for Tioman, Langkawi, and Pangkor Islands over an annual cycle. Across all three sites, the wave climate is characterized by low to moderate wave heights, consistent with the sheltered and semi-enclosed conditions of Malaysian coastal waters. Langkawi Island consistently records the highest wave heights, with Hs values ranging from approximately 1.0 to 1.9 m. Peak conditions occur during January–March and again in November–December, corresponding to the northeast monsoon period, which enhances wind-driven wave generation in the northern Strait of Malacca. Even during the mid-year months, Langkawi maintains relatively elevated wave heights, indicating more stable wave energy availability. Tioman Island exhibits moderate wave conditions, with Hs values generally between 0.7 and 1.8 m. Higher wave heights are observed during January–February and November, while reduced

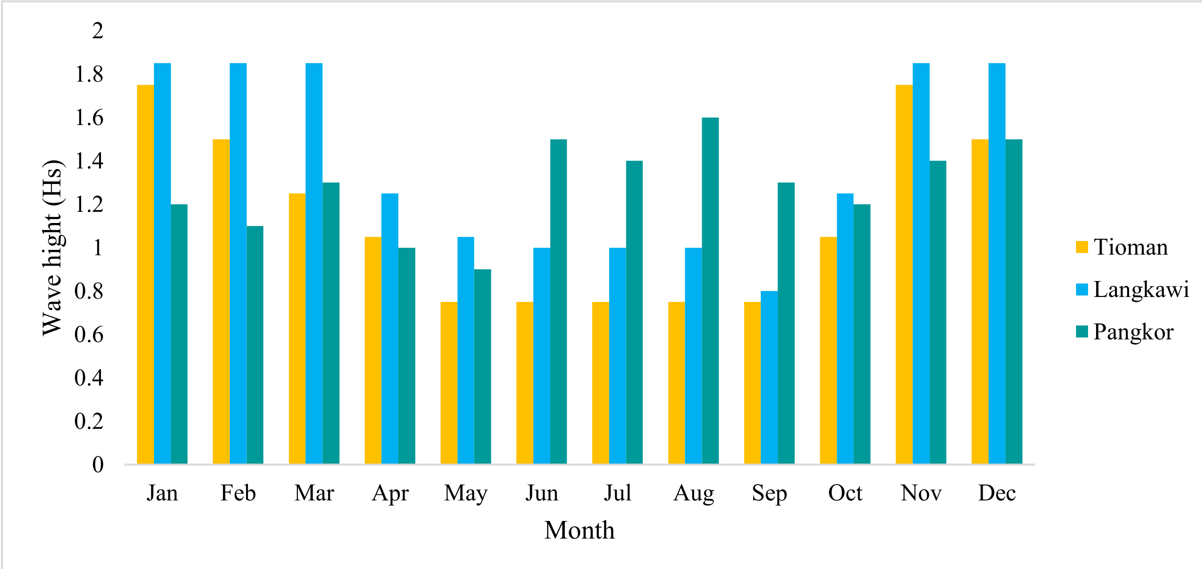

Fig. 10. Monthly Wave height Characteristics for three islands.

values occur during the inter-monsoon and southwest monsoon periods (May–September). This seasonal pattern suggests that wave energy potential at Tioman is more intermittent compared to Langkawi but remains significant during monsoon-dominated months. Pangkor Island shows distinct mid-year enhancement, with wave heights peaking at approximately 1.4–1.6 m during June–August. Lower values (around 1.0–1.2 m) are observed at the beginning and end of the year. This behaviours reflects Pangkor's exposure to southwest monsoon winds and local bathymetric effects, which amplify wave activity during mid-year months. .

Fig. 11 illustrates the monthly energy output (MWh) from floating solar PV systems at three Malaysian island locations—Tioman, Langkawi, and Pangkor—over a one-year period. Clear seasonal and site-specific variations in energy generation are observed. Langkawi consistently records the highest energy output among the three sites, particularly during January–March and November–December, with peak values of approximately 94–95 MWh. This indicates stronger and more stable solar resource availability during the early and late parts of the year. A noticeable decline occurs between April and September, reaching a minimum of around 17 MWh in September, which can be attributed to increased cloud cover and monsoonal influences.Tioman shows a similar seasonal trend but with lower overall generation compared to Langkawi. The highest outputs are observed in January and November (around 82 MWh), while the lowest generation occurs from May to September, dropping to approximately 15 MWh. This suggests higher sensitivity of Tioman's solar output to seasonal weather

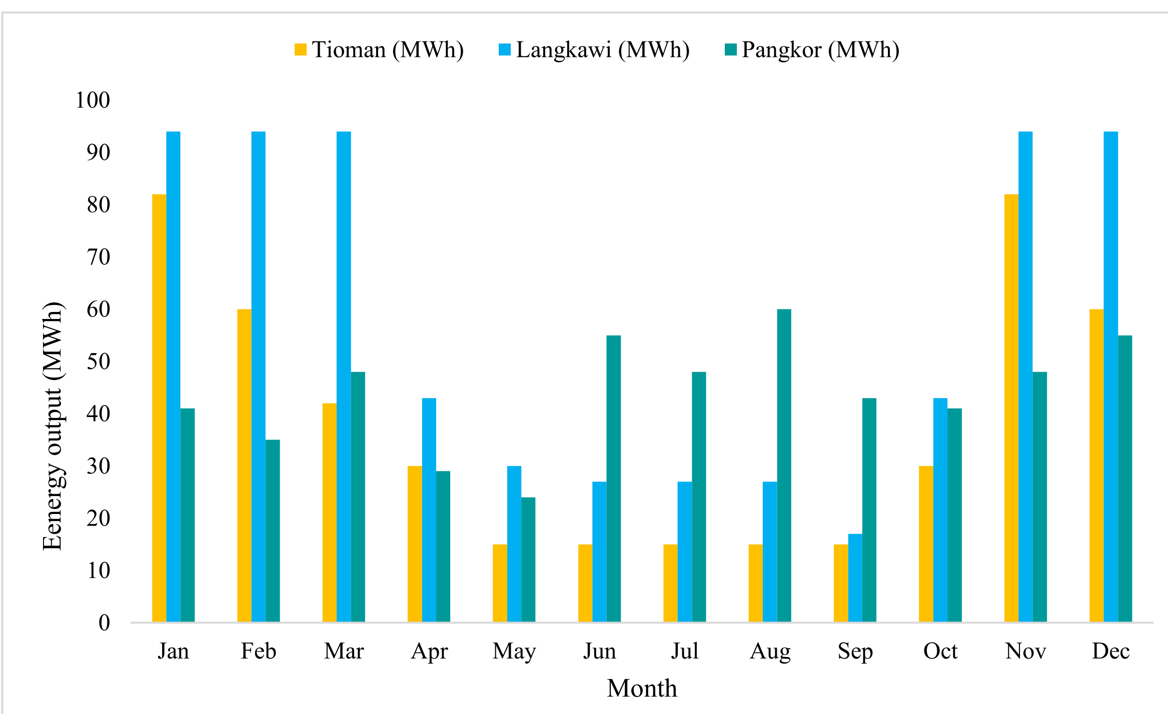

Fig. 11. Monthly variation of Wave Power output for three islands.

variations, particularly during the southwest monsoon period. In contrast, Pangkor exhibits a different pattern, with relatively higher energy production during the mid-year months (June–August), peaking at about 60 MWh in August. Although its output during the early months (January–February) is moderate (35–41 MWh), Pangkor demonstrates better performance during periods when Tioman and Langkawi experience reduced generation. This complementary actions highlights Pangkor's comparatively strong solar resource during mid-year conditions.

Fig. 12 presents the monthly capacity factor (%) of the floating solar PV systems at Tioman, Langkawi, and Pangkor. Capacity factor is defined as the ratio of the actual electrical energy generated over a given period to the maximum possible energy that could be produced if the system operated continuously at its rated capacity during the same period. Langkawi exhibits the highest capacity factor overall, particularly during the beginning and end of the year. Peak values of approximately 12–13 % are observed from January to March and again in November–December, indicating favorable solar irradiance and system utilization during these periods. A substantial reduction is evident between May and September, with the lowest value of around 2–4 %, reflecting the impact of increased cloud cover and monsoonal weather conditions. Tioman follows a similar seasonal pattern but with comparatively lower capacity factors throughout the year. The highest values occur in January and November (around 11–11.5 %), while the minimum capacity factor, approximately 2 %, is recorded from May to September. This pronounced drop suggests that Tioman's floating solar performance is more strongly affected by seasonal climatic variations. In contrast, Pangkor demonstrates a more balanced mid-year performance. Although its capacity factor in the early months (January–February) is moderate (about 5–6 %), Pangkor shows relatively higher values during the southwest monsoon period, peaking at approximately 8 % in August. This indicates greater resilience of solar generation during mid-year months compared to Tioman and Langkawi.

4.4. Economic performance results

4.4.1. Annual energy production

Table 14 summarizes the annual energy production (AEP) and capacity factors for the three floating renewable energy technologies across the studied island sites. Floating solar produces moderate annual energy output, influenced by solar irradiance availability and system performance ratio, while wave energy converters deliver the lowest annual energy production because of the moderate wave climate typical of Malaysian coastal waters. Floating solar demonstrates stable and predictable energy output with limited seasonal variability, making it suitable for island-scale applications. Wind energy output exhibits greater variability but benefits from higher energy capture during monsoon periods. In contrast, wave energy output remains constrained by low significant wave heights and short-wave periods, which limit the extractable power from point absorber systems.

Table 14
Annual Energy Production and Capacity Factor for 1 MW Systems.

Island	Technology	Capacity Factor(%)	(MWh)
Tioman	Solar (FPV)	17–18	1455.3
	Wind (FOW)	5	853.5
	Wave (WEC)	5–8	461
Langkawi	Solar (FPV)	**17–18**	1553.3
	Wind (FOW)	5	243.7
	Wave (WEC)	5–8	684
Pangkor	Solar (FPV)	**17–18**	1550.4
	Wind (FOW)	5	114.2
	Wave (WEC)	5–8	527

4.4.2. Levelized cost of energy

Fig. 13 compares the LCOE of the three floating renewable energy systems. Floating solar exhibits the lowest LCOE, reflecting its relatively low capital spending and minimum operation and maintenance requirements. Floating offshore wind shows a moderately higher LCOE, driven by increased capital costs associated with offshore structures and higher maintenance complexity. Wave energy converters present a substantially higher LCOE compared to both floating solar and wind systems. This result is primarily attributed to high capital investment costs, elevated operation and maintenance expenses, and comparatively low annual energy production. Under the assumed economic parameters, wave energy remains economically uncompetitive for island-based electricity generation. Simple payback period calculated using the avoided electricity cost of RM 0.20/kWh. Floating solar achieves the shortest payback period, indicating rapid capital recovery within the project lifetime. Floating offshore wind demonstrates a longer payback period, approaching the assumed project lifespan, due to higher upfront costs despite greater energy generation. The wave energy system exhibits a payback period far exceeding the project lifetime. This outcome results from the low revenue generated relative to the high capital cost

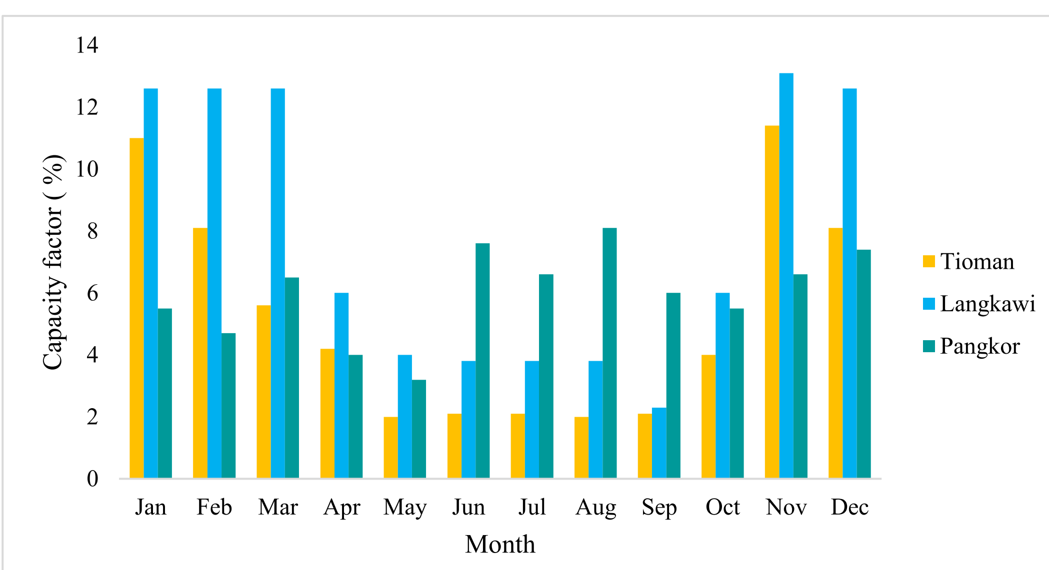

Fig. 12. Monthly variation of Capacity factor of wave power for three islands.

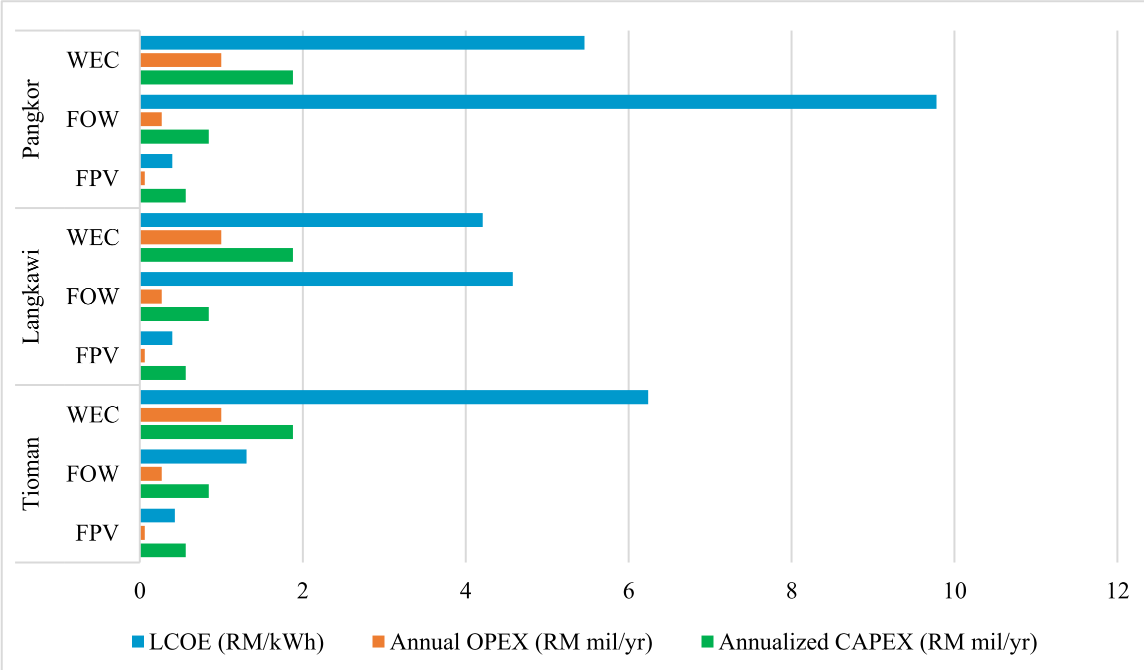

Fig. 13. Economics analysis of 1MW floating solar, wind, and wave power.

of deploying a 1 MW wave energy array composed of multiple point absorber units. The extended payback period indicates that wave energy is not financially viable under current Malaysian market conditions. Annualized cost breakdown for each technology, separating capital recovery costs and annual operation and maintenance expenses. Floating solar shows the lowest total annual cost, with operation and maintenance representing a minor portion of the overall expenditure. Floating offshore wind displays higher annualized costs, driven by both increased capital recovery and higher maintenance requirements associated with offshore operation. Wave energy converters incur the highest total annual costs, with both capital and maintenance expenses significantly exceeding those of the other technologies. The harsh marine environment, mechanical complexity, and lower technological maturity of wave energy systems contribute to these elevated costs.

In contrast, floating offshore wind systems exhibit significantly values, particularly at Pangkor, where wind resources are relatively weak. Tioman shows comparatively better wind performance; however, its energy output remains substantially lower than that of FPV. Wave energy converters produce moderate AEP across all locations, with Langkawi showing slightly higher wave energy potential than Tioman and Pangkor. From an economic perspective, FPV requires higher upfront CAPEX compared to wind at Pangkor and wave energy at some

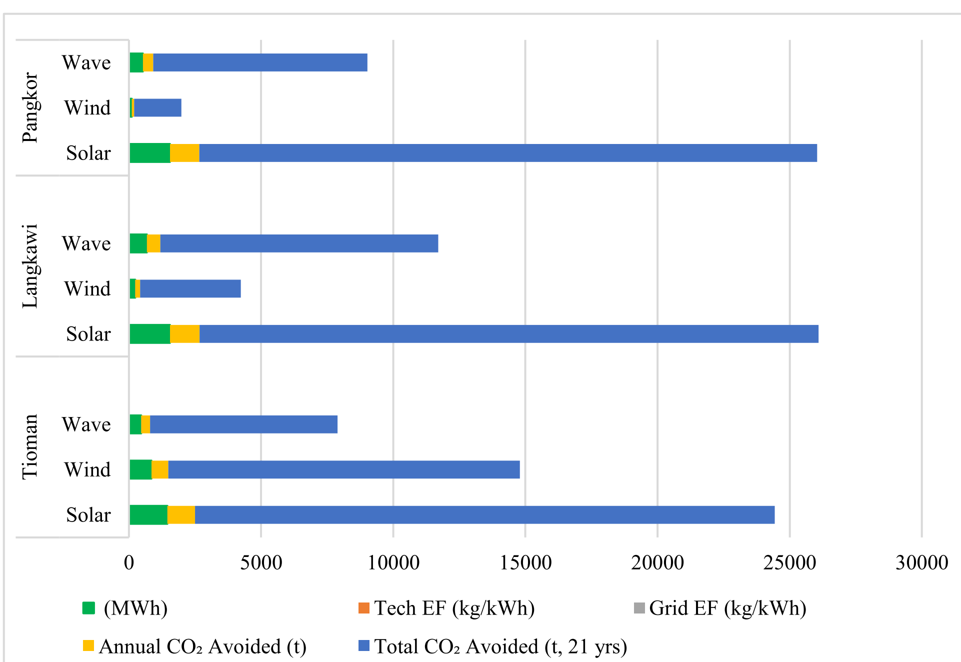

Fig. 14. CO_2 emission reduction.

sites, but it remains competitive when considering its much higher energy yield. WEC systems are associated with relatively high CAPEX and OPEX, reflecting the technological complexity and maintenance demands of wave energy harvesting in offshore environments. Floating offshore wind generally exhibits lower CAPEX than wave energy but still delivers limited energy output, which negatively affects its overall techno-economic attractiveness at these locations.

4.5. Broader environmental impacts of offshore renewable energy systems

4.5.1. CO_2 emission reduction performance

The environmental performance of the proposed floating renewable energy technologies was evaluated based on their potential to reduce carbon dioxide (CO_2) emissions through displacement of grid electricity, while accounting for life-cycle emissions associated with each system.

Fig. 14 presents the annual electricity generation (MWh) and the corresponding CO_2 emission reductions (tonnes) achieved by solar, wind, and wave energy systems across Tioman, Langkawi, and Pangkor Islands. The CO_2 mitigation results are shown both as annual avoided emissions (t CO_2 yr^{-1}) and total avoided emissions over a 21-year project lifetime (tCO_2).The annual electricity generated by the floating renewable energy systems results in considerable avoided CO_2 emissions when compared with electricity supplied by the Malaysian grid. Using an average grid emission factor of 0.758 kg CO_2/kWh, floating offshore wind achieves the highest avoided emissions at approximately 1.66 kt CO_2 per year. Across all three islands, solar energy produces the highest electricity output, exceeding 24,000–26,000 MWh over 21 years, which results in the largest CO_2 emission reductions. The annual CO_2 avoidance from solar ranges from approximately 1100 to 1300 t`CO_2 yr^{-1}, leading to a cumulative reduction of about 24,000–27,000 t CO_2 over the project lifetime. This confirms solar PV as the most effective technology in terms of both energy generation (MWh) and carbon mitigation (tonnes).The results clearly indicate that higher electricity generation in MWh directly translates into higher CO_2 savings in tonnes, due to the significant difference between the grid emission factor and the renewable technology emission factors. Replacing grid electricity with renewable generation therefore delivers substantial carbon benefits, particularly for high-yield technologies such as solar PV. In conclusion, the figure demonstrates that solar energy offers the greatest potential for CO_2 mitigation (t CO_2) per unit of electricity generated (MWh) across all three islands, followed by wind energy in resource-rich locations and wave energy as a supplementary option. These findings support prioritizing solar-dominated renewable systems to maximize long-term emission reductions on small islands.

4.5.2. Impact of offshore ambient conditions

Offshore hybrid renewable energy systems, such as those combining wind, tidal, and solar power, are increasingly crucial for reducing greenhouse gas emissions and enhancing energy security. However, these systems are exposed to harsh ambient conditions that can affect their performance and environmental impact, such as biological and physical impacts. Offshore ambient conditions significantly impact the performance and longevity of hybrid renewable energy systems. Offshore renewable energy installations can positively and negatively affect marine ecosystems.

(a) **Negative impacts.**

Negative impacts include habitat disturbance, noise pollution, and electromagnetic field emissions, affecting biodiversity and marine dynamics. Climate change can alter marine renewable energy resources, such as wind patterns and tidal currents, potentially impacting the efficiency and reliability of these systems. Physical stressors are extreme weather conditions like high winds, waves, and corrosion, common in offshore environments. These conditions can stress equipment and infrastructure, requiring robust design and maintenance strategies. High winds and waves can increase wear and tear on equipment, while extreme temperatures can affect the efficiency of solar panels and other components [59,60]. Corrosion in saltwater environments accelerates corrosion, necessitating protective coatings and materials for equipment longevity. Variability in tidal currents can impact the performance of tidal energy converters, while strong currents can affect the stability of installations [61,62]. While these conditions pose challenges, they also offer opportunities for harnessing abundant renewable energy resources. The environmental interactions of wave energy devices can vary based on their design and location, potentially altering habitats and affecting marine species. The deployment of FPV systems in marine environments poses unique challenges due to wind and wave loads, which differ significantly from onshore conditions [63-65]· Additionally, the environmental implications of FPV systems, such as impacts on water quality and marine life, require thorough investigation through pilot projects and monitoring. However, the ecological implications of such complex integrated systems are not yet fully understood, and further research is needed to assess their effects on marine ecosystems, including potential habitat alterations and changes in water quality [59].

(a) **Positive impacts**

Positive impacts include the creation of artificial reefs around installation structures (Fig. 15). These installations can create artificial habitats for aquatic organisms, enhancing biodiversity in ocean water bodies. The underwater structures of floating solar platforms can provide new habitats for marine organisms, effectively creating artificial reefs. This can increase biodiversity and provide shelter and breeding grounds for fish and other marine life, there is potential for synergies between floating farms and aquaculture operations [66]. The shade could give a more suitable environment for some aquaculture species, and the platforms could potentially be used to support aquaculture infrastructure. By producing clean, renewable energy, offshore floating systems can help reduce greenhouse gas emissions, contributing to climate change and ocean acidification.

Developing these systems should proceed with careful consideration of environmental protection and sustainability. The ecological impacts must be carefully managed through mitigation strategies and best practices.

5. Governmental initiatives and renewable energy framework

Island governments in Malaysia have recognized the strategic importance of renewable energy for achieving sustainability essential to consider the policies and initiatives established by the [70] (particularly for island administration) to support and promote renewable energy (RE) installation. National goals such as Malaysian government, under the Ministry of Energy Transition and Water Transformation (PETRA, formerly KeTSA/MESTECC), has set an ambitious target to achieve 70 % renewable energy capacity mix by 2050 . Projects focusing on islands align directly with this national mandate [71] .

a) **Net Energy Metering (NEM) Program**: While primarily focused on distributed rooftop solar, the NEM program demonstrates a regulatory mechanism for crediting RE generation to the grid, setting a precedent for similar large-scale projects, including floating solar which may be considered under various grid integration schemes [72].
b) **Green Technology Financing Scheme (GTFS):** This scheme provides financial assistance through loan guarantees and interest subsidies for projects deemed "green technology," which would encompass the FOWT and WEC systems investigated in this study, thereby improving their economic viability [73].
c) **Large Scale Solar (LSS) Program:** The LSS tender program has successfully brought down the cost of utility-scale solar. This model

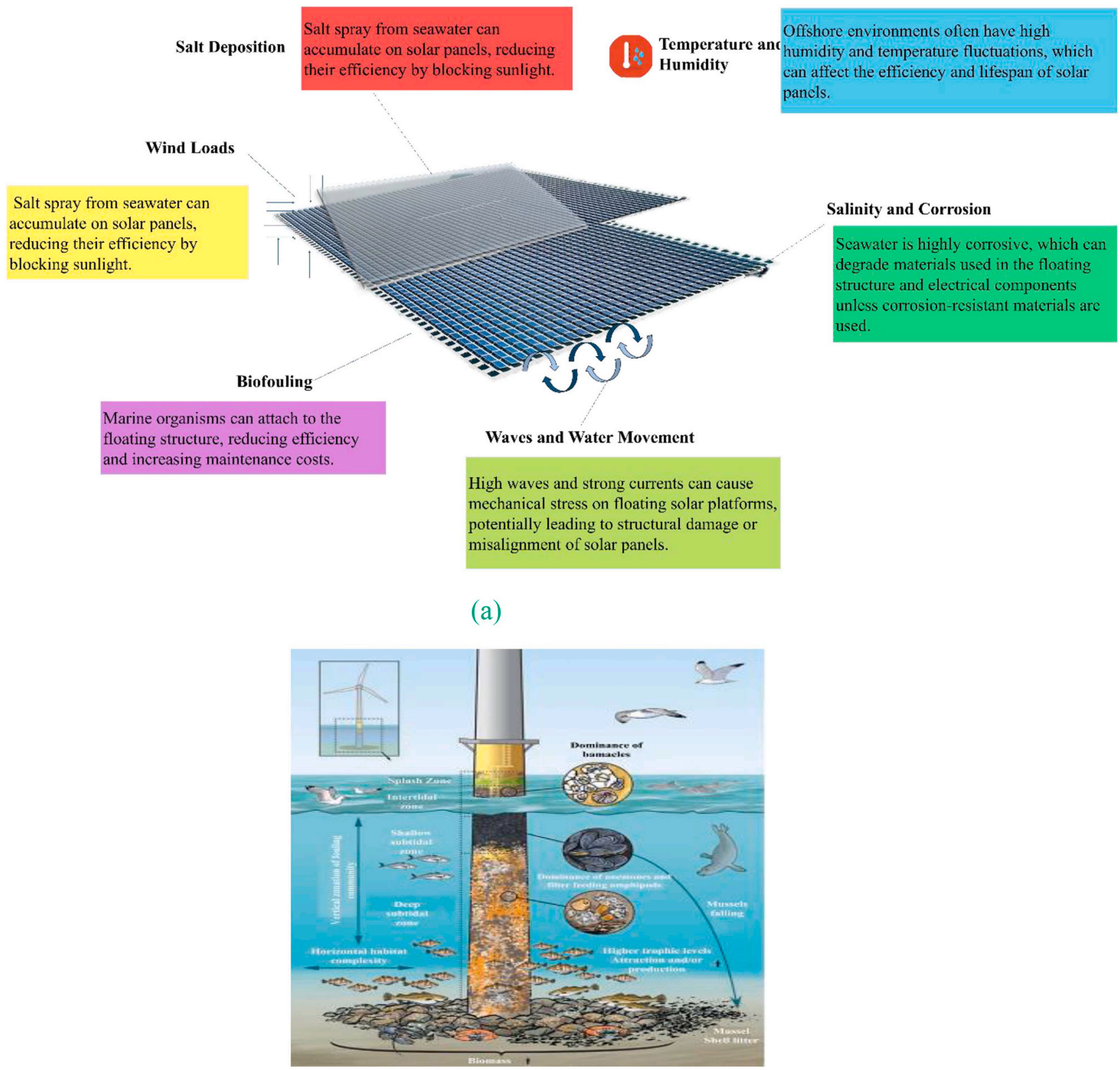

Fig. 15. Impact of Offshore Ambient Conditions on (a) Floating Solar Systems and (b) Wind Systems [67] (c) wave systems (d) Hybrid (floating solar, wind and wave) technology impact [68,69].

can be adapted to structure tenders for floating solar and potentially floating wind projects, providing a clear procurement pathway for the 1 MW systems assessed [74].

d) **Langkawi (Kedah)**: As a designated duty-free and premier tourist destination, Langkawi often receives special development grants. The establishment of any large-scale, high visibility RE project here (like a floating solar array) could be promoted as a component of sustainable ecotourism, gaining strong political and economic support from the state government and relevant agencies like the Langkawi Development Authority (LADA).

e) **Tioman (Pahang) and Pangkor (Perak):** Both islands operate under local development boards focused on environmental preservation and sustainable tourism. Projects like these would likely require expedited approval processes due to their alignment with Low Carbon Island or Green Island initiatives, potentially offering streamlined permitting for the floating structures in coastal waters.

f) **Research & Development (R&D) Collaboration**: State governments, in partnership with local universities, may offer sites or funding for pilot/demonstration projects for novel technologies like WECs, leveraging the unique wave resources off these islands for technological advancement and capacity building.

6. Critical discussion: renewable energy options for malaysian islands

6.1. Comparison with existing studies

The comparative analysis of 1 MW renewable energy systems (floating solar, wind, and wave energy) on Tioman, Langkawi, and Pangkor Islands reveals significant insights into the potential of these technologies to support sustainable energy generation. Each technology was evaluated in terms of energy yield, performance ratios (PR), levelized cost of energy (LCOE), and CO_2 emission reductions, providing a

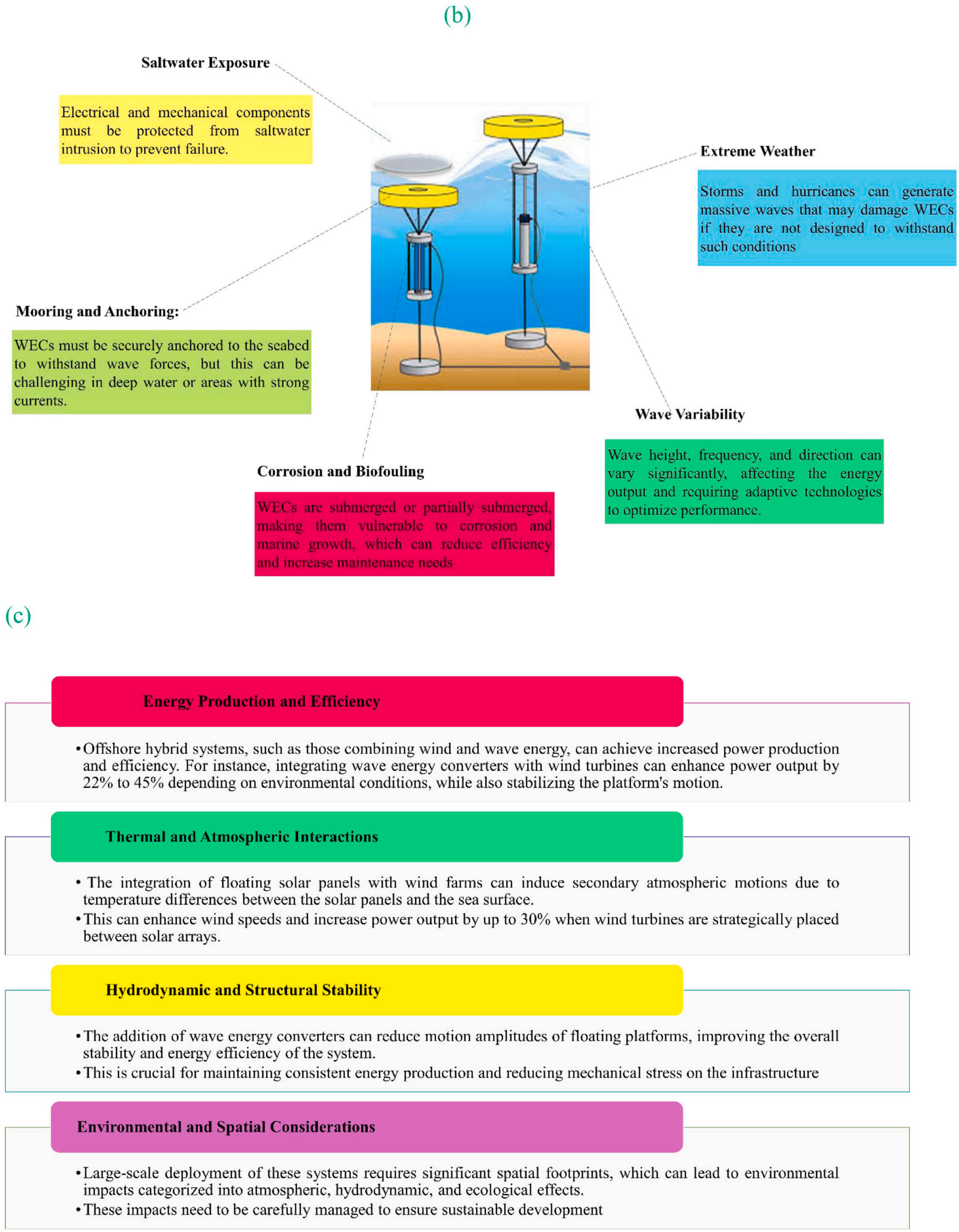

Fig. 15. (*continued*).

comprehensive understanding of their technical, economic, and environmental shown in Table 15.

6.2. *implications of hybrid system integration and logistical challenges*

A critical insight emerging from this study is that no single renewable energy technology can fully meet island electricity demand in a reliable and cost-effective manner when deployed in isolation. While the results identify the most suitable technology for each island based on resource availability and performance indicators, real-world island energy systems typically require hybrid configurations to address the variability of renewable resources and ensure supply reliability. For Tioman Island,

Table 15
Summary of the energy, economic, and environmental parameters.

Parameters	Floating Solar PV	Floating Wind Turbine	Wave Energy	Hybrid Synergy / Policy Implication
Energy Yield	High during dry season (Feb–Aug); peak ~160 MWh/month	Moderate year-round; peak ~45–75 MWh/month at Tioman	Moderate, especially during monsoon; potential for baseload	Combining resources flattens overall generation; hybrid systems reduce intermittency
Capacity Factor	17–18 % annual	10–11 % (Tioman); 4–6 % (Langkawi); <3 % (Pangkor)	Variable; depends on wave climate	Complementary CF patterns reduce storage requirements and enhance reliability
Seasonal Variability	Lower in dry season, drops during monsoon	Modest variability but low overall	Higher during monsoon, lower in dry season	Hybrid systems exploit seasonal complementarity for smoother output
Infrastructure / CAPEX	Moderate CAPEX; platform maintenance required; risk of corrosion/biofouling	High CAPEX; offshore installation and maintenance challenging	High CAPEX; less mature technology; maintenance uncertain	Shared infrastructure for hybrid systems reduces cost per MW and improves efficiency
Environmental Impact	Water surface occupation, potential biofouling	Marine habitat impact, visual/aesthetic concerns	Possible marine ecological impacts, wave interference	Policy required to regulate marine impacts while encouraging renewable deployment
Grid / Storage Implications	Requires minimal storage during dry season	Supports complementary generation; reduces peak load stress	Can provide continuous generation during low solar/wind months	Hybrid systems reduce storage needs and improve microgrid stability
Policy / Regulatory Considerations	Tariffs and incentives to support solar PV adoption	Site prioritization (Tioman) for offshore wind; regulatory guidelines for installation	Incentives for technology development; environmental permitting required	Hybrid microgrid policies can maximize renewable penetration, improve energy security, and optimize tariff structures

the seasonal complementarity between wind and solar resources is particularly notable. Stronger wind resources during the early months of the year coincide with periods of lower solar output, while mid-year conditions favor higher solar generation. A hybrid FPV–FOW system could therefore smooth seasonal variability and improve overall system capacity utilization. Wave energy, although contributing lower annual output, could provide additional diversification and enhance system resilience during periods of reduced wind or solar availability. In Langkawi and Pangkor, where tourism-driven electricity demand is relatively stable throughout the year, floating solar systems could serve as a baseline renewable source, supplemented by offshore wind during high-wind periods. Integrating energy storage systems, such as battery energy storage, would be essential to manage short-term variability, provide nighttime supply, and increase the effective capacity factor of the overall system. Although detailed hybrid optimization is beyond the scope of this study, the results clearly indicate that hybrid renewable systems combined with storage represent the most practical pathway for island decarbonization. Beyond technical performance, the implementation of floating renewable energy systems on Malaysian islands presents several practical challenges. Offshore and floating installations require regulatory approvals related to maritime zoning, environmental impact assessments, and grid interconnection, which may involve multiple agencies. Compared to onshore systems, permitting processes for offshore renewable energy in Malaysia are still evolving, potentially introducing project delays and uncertainty. Logistical constraints are particularly relevant for islands. Transporting large offshore wind components, such as turbine blades and floating platforms, to remote islands requires suitable port infrastructure and specialized vessels. Fabrication of floating platforms may need to occur on the mainland, followed by marine transport and offshore assembly. Seasonal weather conditions, including monsoon periods, could further constrain installation and maintenance windows. Operation and maintenance capabilities also represent a challenge. Islands may lack local expertise for maintaining offshore wind or wave energy systems, necessitating external support and increasing operational costs. These factors highlight the importance of phased deployment, starting with less complex technologies such as floating solar, before scaling up more capital-intensive systems.

6.3. Social, community policy and planning implications

Malaysia's existing renewable energy policy framework, including feed-in tariffs, net energy metering, and the Green Investment Tax Allowance, has primarily been designed for onshore and rooftop solar systems. The findings of this study suggest that policy mechanisms tailored specifically to offshore and floating renewable energy technologies may be required to accelerate deployment on islands. The Smart Green Island Project provides an important opportunity to pilot integrated floating renewable energy systems. The results of this study can inform technology selection under this initiative by identifying suitable combinations of solar, wind, and wave energy based on island-specific resource profiles. Differentiated support mechanisms may be necessary, given the varying cost structures and maturity levels of each technology, particularly for wave energy, which remains at an early development stage. Social acceptance plays a critical role in the success of renewable energy projects on islands, where communities are closely connected to their natural environment. Offshore renewable installations may raise concerns related to visual impacts, fishing activities, and tourism. However, experiences from other island regions suggest that early community engagement, transparent communication, and local participation can significantly improve acceptance. For tourism-oriented islands such as Langkawi and Pangkor, floating renewable energy installations could be positioned as symbols of environmental stewardship and sustainability, potentially enhancing the island's green image. Opportunities for local employment in system operation, maintenance, and monitoring could further strengthen community support and create local economic benefits.

6.4. Study limitations

This study has several limitations that should be acknowledged. First, the analysis relies on modelled and satellite-based resource data rather than extensive long-term ground measurements, which may introduce uncertainty in estimated energy yields. Second, the assessment evaluates individual renewable technologies independently and does not perform a detailed optimization of hybrid systems or energy storage sizing. Third, the environmental analysis focuses primarily on CO_2 emissions and qualitative impacts, without conducting a full quantitative life cycle or ecological assessment. Fourth, the economic analysis is based on generalized cost assumptions rather than detailed site-specific cost data. Finally, the results have not been validated against operating floating renewable energy systems under similar climatic conditions. Recognizing these limitations provides important context for interpreting the findings and highlights opportunities for future research, particularly in hybrid system optimization, detailed environmental assessment, and pilot-scale validation.

7. Conclusion

- This study provides a comprehensive evaluation of 1 MW floating solar (FPV), floating offshore wind (FOW), and wave energy (WEC) systems across three Malaysian islands—Langkawi, Tioman, and

Pangkor—based on technical, economic, and environmental performance. The findings reveal clear differences in resource availability, energy generation potential, cost-effectiveness, and CO_2 mitigation, highlighting opportunities for targeted renewable energy utilization in Malaysia climates.

- Floating Solar PV: Langkawi consistently demonstrates the highest solar irradiance and energy yield, producing approximately 1553 MWh annually per MW with a performance ratio of 0.82–0.85. The corresponding LCOE of ~5–6 cents/kWh and cumulative CO_2 avoidance of ~27,000 t over 21 years indicate that FPV is both economically and environmentally competitive with diesel generation. Tioman and Pangkor also show strong FPV potential, though with slightly lower annual outputs (~1533–1550 MWh). Seasonal variations are modest for Langkawi, while Pangkor exhibits complementary mid-year generation patterns, suggesting potential for hybrid system integration.
- Floating Offshore Wind: Tioman offers the most favorable wind resource, achieving monthly energy outputs up to 175 MWh and capacity factors of 24–28 %. However, Langkawi and Pangkor experience significantly lower wind speeds and energy yields (capacity factors <7 %), limiting standalone FOW feasibility at these locations. The higher LCOE relative to FPV and the variable resource availability suggest that offshore wind is best suited for islands with strong monsoonal winds, with Tioman prioritized for near-term deployment.
- Wave Energy: All three islands exhibit moderate wave climates, with Langkawi slightly higher (Hs 1.0–1.9 m). WEC systems generate low annual energy (~6.4 % capacity factor) and carry the highest LCOE, making them economically uncompetitive under current conditions. Wave energy may serve as a supplementary resource for hybrid microgrids, but substantial technological advancements are required to improve efficiency, reduce CAPEX, and enhance survivability in tropical offshore environments.

Policy and Development Implications:

- Island Prioritization: Langkawi should be prioritized for floating solar projects due to its high irradiance, stable performance, and competitive economics. Tioman represents the best near-term candidate for offshore wind deployment, while wave energy remains suitable only for experimental or demonstration projects at Langkawi or Tioman.
- Hybrid and Complementary Systems: Combining FPV, FOW, and WEC in hybrid microgrids can reduce seasonal intermittency, improve capacity factors, and optimize energy storage requirements. For example, Pangkor's mid-year FPV peak complements Langkawi's early-year solar peak, demonstrating potential for regional renewable energy integration.
- Demonstration Projects: Pilot-scale installations of FPV in Langkawi and FOW in Tioman would provide practical insights into operational performance, marine environmental impacts, and community engagement, supporting future large-scale deployment. Wave energy pilot projects can test technological solutions to reduce LCOE and improve resilience in tropical offshore environments. Research Recommendations: Future studies should focus on:
- Optimizing FPV system design under tropical marine conditions to further improve PR and reduce maintenance costs.
- Developing low-cost, corrosion-resistant floating wind turbine platforms suitable for moderate wind regimes like those in Tioman.
- Advancing wave energy converter efficiency and survivability to make WEC economically viable.However, it must be acknowledged that the monthly average wind speeds at Pangkor Island are close to or below the cut-in range for much of the year, resulting in a low-capacity factor and limited annual energy production. As such, while the selected turbine could operate intermittently, the overall economic viability is marginal. Given this context, alternative solutions may be more suitable for Pangkor Island, including:
- Hybrid energy systems combining small-scale wind turbines with solar PV, taking advantage of consistently high solar irradiance in Malaysia.
- Micro or low-wind-speed turbines, specifically designed for sites with average wind speeds below 3 m/s, which can provide more reliable energy generation.
- Battery storage integration to buffer the intermittent wind generation and improve overall energy reliability.
- The hybrid use of floating solar, wind, and wave energy systems across these islands can substantially contribute to the region's sustainable energy goals while reducing carbon emissions. Proper system optimization and strategic planning are essential for maximizing energy output and minimizing environmental impact. Future research should focus on improving technologies to mitigate marine ecosystem impacts, developing adaptive control systems to enhance performance under variable conditions, and conducting detailed cost-benefit analyses to inform decision-making and policy development. This study demonstrates the potential of individual renewable energy systems to provide sustainable energy for Malaysian islands, setting a precedent for renewable energy adoption in similar coastal regions worldwide.

Declaration of competing interest

No conflict of interest exists.

We wish to confirm that there are **no known conflicts of interest** associated with this publication and there has been no significant financial support for this work that could have influenced its outcome.

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References

[1] M. Bilgili, S. Tumse, S. Nar, Arab. J. Sci. Eng. 49 (11) (2024) 14503–14531, https://doi.org/10.1007/s13369-024-09390-y.
[2] D. Guven, Appl. Energy 377 (2025) 124768, https://doi.org/10.1016/j.apenergy.2024.124768. PD.
[3] V. Mahadevan, S.R. S, M.A. Rusho, S. Yishak, Results Eng. 26 (June) (2025), https://doi.org/10.1016/j.rineng.2025.105589.
[4] B. Yang, et al., J. Energy Storage 98 (June) (2024), https://doi.org/10.1016/j.est.2024.113031.
[5] H. Jeffrey, S. Pennock, J.L. Villate, P. Ruiz-Minguela, D. Cagney, and Lotta. Pirttimaa, "A European Ocean Energy Industry – the €140bn Economic Opportunity," no. 826033, pp. 1–28, 2022.
[6] Rémi Collombet and Donagh Cagney, "Last Stop to 2025 - A 2022 Action Plan to deliver on the Offshore Strategy's Ocean Energy Target," no. June 2022, 2022.
[7] "Malaysia's response and strategies towards climate change _ World Review of Entrepreneurship, Management and Sustainable Development refer8." (2019).
[8] S. Norasyiqin, et al., Energ. (Basel) 14 (2200) (2021) 1–26.
[9] A.G.M.B. Mustayen, M.G. Rasul, X. Wang, M. Negnevitsky, J.M. Hamilton, Energy Convers. Manage 260 (April) (2022) 115614, https://doi.org/10.1016/j.enconman.2022.115614.
[10] S.N. Chenoli, P.R. Jayakrishnan, A.A. Samah, O.S. Hai, M.Y. Ahmad Mazuki, C. H. Lim, J. Atmos. Sol. Terr. Phys. 179 (June) (2018) 81–93, https://doi.org/10.1016/j.jastp.2018.06.017.
[11] Green Energy - Tenaga Nasional Berhad, 2025 [Online]. Available, https://www.tnb.com.my/smart-grid/green-energy.
[12] SEDA MALAYSIA, MyRER – Renewable Energy Malaysia, 2021 [Online]. Available, https://www.seda.gov.my/reportal/.
[13] G. Lavidas, K. Blok, Renew. Energy 170 (2021) 1143–1155, https://doi.org/10.1016/j.renene.2021.02.041.
[14] E. Solomin, E. Sirotkin, E. Cuce, S.P. Selvanathan, S. Kumarasamy, Energ. (Basel) 14 (10) (2021) 1–25, https://doi.org/10.3390/en14102751.
[15] M.I. Islam, et al., Energ. (Basel) 16 (10) (May 2023), https://doi.org/10.3390/en16104034.
[16] L.W. Ho, Renew. Sustain. Energy Rev. 53 (2016) 279–295, https://doi.org/10.1016/j.rser.2015.08.054.

[17] J.O. Petinrin, M. Shaaban, Renew. Sustain. Energy Rev. 50 (2015) 967–981, https://doi.org/10.1016/j.rser.2015.04.146.
[18] M. Li, et al., Renew. Sustain. Energy Rev. 162 (March) (2022) 112404, https://doi.org/10.1016/j.rser.2022.112404.
[19] F. Alsebai, H.S. Kang, O. Yaakob, M.N.A.W.M. Yazid, J. Adv. Res. Appl. Sci. Eng. Technol. 30 (3) (2023) 127–149, https://doi.org/10.37934/araset.30.3.127149.
[20] N.H. Samrat, N. Bin Ahmad, I.A. Choudhury, Z. Taha, Prospect of wave energy in Malaysia, in: Proceedings of the 2014 IEEE 8th International Power Engineering and Optimization Conference, PEOCO 2014, 2014, pp. 127–132, https://doi.org/10.1109/PEOCO.2014.6814412.
[21] "Floating Solar Panel: understanding Advantages & Trends. (2024), [Online]. Available: https://www.muifatt.com.my/blog/floating-solar-panel-fpv/.
[22] M.S. Azam, et al., Energy 289 (December 2023) (2024) 129989, https://doi.org/10.1016/j.energy.2023.129989.
[23] T.A. Mooney, M. Andersson, J. Stanley, Oceanography 33 (4) (2020) 82–95.
[24] G. Kakoulaki, et al., Renew. Sustain. Energy Rev. 171 (October 2022) (2023) 112989, https://doi.org/10.1016/j.rser.2022.112989.
[25] G. Kakoulaki, et al., Renew. Sustain. Energy Rev. 171 (October 2022) (2023) 112989, https://doi.org/10.1016/j.rser.2022.112989.
[26] M. Barooni, T. Ashuri, D. Velioglu Sogut, S. Wood, S. Ghaderpour Taleghani, Energ. (Basel) 16 (1) (2023) 1–28, https://doi.org/10.3390/en16010002.
[27] IRENA, Future of wind: Deployment, investment, technology, Grid Integration and Socio-Economic Aspects, 2019.
[28] "Global Floating Offshore Wind Pipeline Grows to 266 GW - Report _ Offshore Wind." (2025). [Online]. Available: https://www.offshorewind.biz/2024/10/08/global-floating-offshore-wind-pipeline-grows-to-266-gw-report/.
[29] A. Mccoy et al., "Offshore Wind Market Report : 2024 Edition Table of Contents," no. August, 2024.
[30] Norman Mariun, Global Scenario and Way Forward For Malaysia, 2011 [Online]. Available, http://www.penerbit.upm.edu.my.
[31] Z. Zhang, X. Wang, X. Zhang, C. Zhou, X. Wang, Eng. Struct. 301 (December 2023) (2024) 117334, https://doi.org/10.1016/j.engstruct.2023.117334.
[32] T. Orekan and P. Zhang, "Design and Modeling of a Smart Wave Energy Converter," pp. 19–33, 2019, doi:10.1007/978-3-030-02562-5_2.
[33] L. Rusu, E. Rusu, Energ. (Basel) 14 (2) (2021), https://doi.org/10.3390/en14020394.
[34] F. Alsebai, H.S. Kang, O. Yaakob, M.N.A.W.M. Yazid, J. Adv. Res. Appl. Sci. Eng. Technol. 30 (3) (2023) 127–149, https://doi.org/10.37934/araset.30.3.127149.
[35] E. Petracca, E. Faraggiana, A. Ghigo, M. Sirigu, G. Bracco, G. Mattiazzo, Energ. (Basel) 15 (8) (Apr. 2022), https://doi.org/10.3390/en15082739.
[36] SEDA MALAYSIA, MyRER – Renewable Energy Malaysia, 2021 [Online]. Available, https://www.seda.gov.my/reportal/myrer/#1630302447960-89cc071a-f8ac.
[37] "Malaysia Targets 35% Renewable Energy By 2030 - BusinessToday." (2025). [Online]. Available: https://www.businesstoday.com.my/2025/11/12/malaysia-targets-35-renewable-energy-by-2030/.
[38] Lat Long, Where is Selangor, Malaysia on Map Lat Long Coordinates, 2022 [Online]. Available, https://www.latlong.net/place/selangor-malaysia-2719.html.
[39] D. of S. Malaysia, Langkawi (District, Malaysia) - Population Statistics, Charts, Map and Location [Online]. Available, https://www.citypopulation.de/php/malaysia-mukim-admin.php?adm1id=0207%0Ahttps://www.citypopulation.de/en/malaysia/admin/kedah/0207__langkawi/, 2010.
[40] "METMalaysia - Marine Weather Forecast - Melaka." (2025).[Online]. Available: https://www.met.gov.my/en/forecast/marine/shipping/Sh003/.
[41] World Bank and DTU Wind Energy, Global Wind Atlas, 2018 [Online]. Available, https://globalwindatlas.info/.
[42] "Global Solar Atlas." (2025). [Online]. Available: https://globalsolaratlas.info/map?c=11.647529,7.937622,10&s=11.997682,7.646484&m=site.
[43] Surf-Forcast.com, Malaysia Surf Map - Wind and Wave Forecasts [Online]. Available, https://www.surf-forecast.com/weather_maps/Malaysia, 2022.
[44] Tenaga National Berhad, Welcome to myTNB Portal - Bill Calculator, 2021.
[45] sun solar tilt, Tilt angle calculator [Online]. Available, https://sunsolartilt.com/pages/calculator, 2022.
[46] N.A. Kadir, A.Z. Abdullah, N.N. Mohd Hussin, J. Phys. Conf. Ser. 2550 (1) (2023) 0–9, https://doi.org/10.1088/1742-6596/2550/1/012005.
[47] M. Benghanem, et al., Sustainability. 15 (20) (2023) 14831 [Online]. Available, https://www.mdpi.com/2071-1050/15/20/14831.
[48] "Soiling loss - PVsyst documentation." (2017). [Online]. Available: https://www.pvsyst.com/help/project-design/array-and-system-losses/soiling-loss.html#:~:text=The%20soiling%20losses%20are%20strongly,for%20as%20an%20irradiance%20loss.
[49] R.M. Dorrell, et al., Front. Mar. Sci. 9 (March) (2022) 1–25, https://doi.org/10.3389/fmars.2022.830927.
[50] "WECs_ Calculating Power Output Using Wave Characteristics - Technical Articles." (2024). [Online]. Available: https://eepower.com/technical-articles/wecs-calculating-power-output-using-wave-characteristics/.
[51] M.M. Abaei, et al., Ocean Eng. 317 (November 2024) (2025) 119983, https://doi.org/10.1016/j.oceaneng.2024.119983.
[52] "WECs: calculating Power Output Using Wave Characteristics. (2024) [Online]. Available: https://eepower.com/technical-articles/category/renewable-energy/tidal/.
[53] S. Khan, K. Sudhakar, M. Hazwan Bin Yusof, Math. Probl. Eng. 2022 (2022), https://doi.org/10.1155/2022/7186009.
[54] N. Kaur, N.P. Hariram, K.B. Mekha, M.R. Mohamed, S.S. Priya, K. Sudhakar, Energy Convers. Manag.: X 28 (May) (2025), https://doi.org/10.1016/j.ecmx.2025.101234.
[55] Suruhanjaya Tenaga, Grid Emission Factor (GEF) in Malaysia, 2024, pp. 4–7 [Online]. Available, https://myenergystats.st.gov.my/en/pdf-viewer?pdf=/documents/d/guest/grid-emission-factor-gef-in-malaysia#flipbook-flipbookContainer/1/.
[56] Solaris Renewables, What Is the Carbon Footprint of Solar Panel Manufacturing?, 2025.
[57] A. Ghigo, E. Faraggiana, M. Sirigu, G. Mattiazzo, G. Bracco, Energ. (Basel) 15 (23) (2022), https://doi.org/10.3390/en15238804.
[58] A.C.R. Gonçalves, X. Costoya, R. Nieto, M.L.R. Liberato, Sustain. Energy Res. 11 (1) (2024), https://doi.org/10.1186/s40807-023-00097-6.
[59] S. Oliveira-pinto, "Marine floating solar plants : an overview of potential, challenges and feasibility," vol. 173, pp. 120–135, 2020.
[60] Marine floating solar plants_ an overview of potential, challenges and feasibility _, Proceedings of the Institution of Civil Engineers - Maritime Engineering. (2020).
[61] H. Attar, A. Alahmer, G. Borowski, and S. Alsaqoor, "Comprehensive review of advancements, challenges, design, and environmental impact in floating photovoltaic systems," vol. 26, no. 2, pp. 301–322, 2025.
[62] S. Gorjian, H. Sharon, H. Ebadi, K. Kant, F.B. Scavo, G.M. Tina, J. Clean. Prod. 278 (2021) 124285, https://doi.org/10.1016/j.jclepro.2020.124285.
[63] H.M. Pouran, M. Padilha Campos Lopes, T. Nogueira, D. Alves Castelo Branco, Y. Sheng, iScience 25 (11) (2022) 105253, https://doi.org/10.1016/j.isci.2022.105253.
[64] S.K. Afridi, et al., IEEe Access. 12 (April) (2024) 66147–66166, https://doi.org/10.1109/ACCESS.2024.3397243.
[65] S.K. Afridi, et al., IEEe Access. 12 (April) (2024) 66147–66166, https://doi.org/10.1109/ACCESS.2024.3397243.
[66] H. Yousuf, et al., Curr. Photovolt. Res. 8 (3) (2020) 67–78, https://doi.org/10.21218/CPR.2020.8.3.067.
[67] S. Oliveira-Pinto, J. Stokkermans, Energy Convers. Manage 211 (March) (2020) 112747, https://doi.org/10.1016/j.enconman.2020.112747.
[68] M.J.B. Kabeyi, O.A. Olanrewaju, Front. Energy Res. 9 (March) (2022) 1–45, https://doi.org/10.3389/fenrg.2021.743114.
[69] Y. Jin, et al., Nat. Sustain. 6 (7) (2023) 865–874, https://doi.org/10.1038/s41893-023-01089-6.
[70] "Malaysia schemes." (2021), [Online]. Available: https://www.malaysia.gov.my/portal/content/30704.
[71] "Incentives – Green Technology Financing Scheme (GTFS) – MSFI." (2020), [Online]. Available: https://www.msfi.com.my/incentives-green-technology-financing-scheme-gtfs/.
[72] "Guidelines – Renewable Energy Malaysia." (2025) [Online]. Available: https://www.seda.gov.my/reportal/nem/guidelines/.
[73] Incentives – Green Technology Financing Scheme (GTFS) [Online]. (2023) Available: https://www.msfi.com.my/incentives-green-technology-financing-scheme-gtfs/.
[74] Large Scale Solar (LSS) Malaysia: Development, EPC & Investments." [Online]. (2025) . https://www.seda.gov.my/reportal/large-scale-solar/.