



A GIS-based framework for hybrid offshore wind and floating solar power plants in Australia

Fida Ali ^{a,b}, Rodney A. Stewart ^{a,c}, Mohammad J. Sanjari ^{a,d}, Jennifer A. Hayward ^e, Robert C. Nicholson ^f, Amir Etemad-Shahidi ^{a,d,*}

^a School of Engineering and Built Environment, Griffith University, Southport, QLD 4222, Australia

^b Blue Economy Cooperative Research Centre, Australia

^c Australian Rivers Institute (ARI), Griffith University, Southport, QLD 4222 Australia

^d GIHER, Griffith University, Southport, QLD 4222, Australia

^e Commonwealth Scientific and Industrial Research Organisation, Energy Newcastle, NSW 2300, Australia

^f Pitt and Sherry, New South Wales, Australia

ARTICLE INFO

Keywords:

Co-location
Floating solar
Geographic information system
Offshore wind
Resource assessment

ABSTRACT

Co-locating offshore wind and floating solar energy represents a promising approach to enhancing renewable energy generation while optimising the use of marine space. This study develops a suitability index (*SI*) to identify and map suitable areas for hybrid offshore wind–floating solar farms within Australia's Exclusive Economic Zone. The index incorporates 11 years of hourly data on wind speed, solar irradiance, and significant wave height (Bureau of Meteorology Atmospheric High-resolution Regional Reanalysis for Australia (BARRA) and the Centre for Australian Weather and Climate Research (CAWCR), alongside indicators of resource magnitude, temporal variability, and wind–solar complementarity. The index also considers factors such as bathymetry, wave climate, marine protected areas, and operational thresholds. In addition, a wind–solar synergy index (*WSSI*) was created to quantify the proportion of time that at least one of the resources is available, to determine the measure of operational measure of hybrid reliability. Three planning scenarios, wind-dominant, balanced, and solar-dominant, were analysed to assess how shifting resource priorities affect spatial suitability. The findings reveal a northward shift in optimal sites under solar-dominant weighting, with the Northern Territory, northern Western Australia, and Queensland emerging as prime locations due to their stronger irradiance, favourable complementarity, and calmer seas. Beyond mapping efforts, the study estimates annual energy production (AEP) for the shortlisted sites, thereby linking suitability directly to practical energy yields. Collectively, the developed *SI*, scenario-based suitability maps, and AEP estimates provide a reproducible decision-support framework for planning co-located offshore wind–floating solar projects that can support the growth of the blue economy.

Nomenclature

A	Panel area (m ²)	AEP	Annual Energy Production
BARRA-R	Bureau of Meteorology Atmospheric High-resolution Regional Reanalysis for Australia	CAWCR	Centre for Australian Weather and Climate Research
CAPAD	Collaborative Australian Protected Areas Database	CF	Capacity Factor

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CoV	Coefficient of variation	EEG	Electrical Generation Threshold
CRC	Cooperative Research Centre		
DCCEEW	Department of Climate Change, Energy, the Environment and Water (Australia)		
EEZ	Exclusive Economic Zone	FPV	Floating Photovoltaics
ERA5	Fifth-generation ECMWF atmospheric reanalysis		

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* Corresponding author. School of Engineering and Built Environment, Griffith University, Southport, QLD 4222, Australia.

E-mail addresses: fida.ali@griffithuni.edu.au (F. Ali), r.stewart@griffith.edu.au (R.A. Stewart), m.sanjari@griffith.edu.au (M.J. Sanjari), Jenny.Hayward@csiro.au (J.A. Hayward), rnicholson@pittsh.com.au (R.C. Nicholson), a.etemadshahidi@griffith.edu.au (A. Etemad-Shahidi).

<https://doi.org/10.1016/j.ocecoaman.2026.108199>

Received 7 October 2025; Received in revised form 8 February 2026; Accepted 29 March 2026

Available online 3 April 2026

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G	Mean Solar Irradiance	GIS	Geographic Information System
GW	Gigawatts	H_s	Significant Wave Height
H_{smax}	Maximum Significant Wave Height	JCV	Joint Coefficient of Variation
LCOE	Levelised Cost of Energy		
MPA	Marine Protected Area	OWT	Offshore Wind Turbine
P_{rated}	Rated Power of Turbine	PR	Performance Ratio
PV	Photovoltaic	P_{solar}	Solar Power
P_{wind}	Wind Power	RCoV	Robust Coefficient of Variation
RSDS	Surface Downwelling Shortwave Radiation	SI	Suitability Index
SI_w	Wave-constrained Suitability Index	V	Wind speed (m/s)
WPD	Wind Power Density	WSSI	Wind-Solar Synergy Index
μ	Mean value	ρ	Air density
σ	Standard Deviation	τ	Kendall's Correlation Coefficient
η	Efficiency of Solar PV Panel		

1. Introduction

The accelerating impacts of climate change have intensified the global transition toward low-carbon energy systems, reinforced by international commitments, such as the COP28 agreement to triple global renewable energy capacity by 2030 (UNFCCC United Nations Climate Change, 2023). Wind and solar photovoltaics (PV) are expected to dominate this expansion, accounting for more than 95% of global renewable capacity growth due to rapid cost reductions and technological maturity (Renewables Analysis and Forecast to 2030, 2024). However, large-scale onshore deployment is increasingly constrained by land-use conflicts, environmental pressures, and social acceptance challenges. This has prompted growing interest in offshore environments, where higher-quality resources and reduced spatial competition offer new opportunities for renewable energy development (Soukissian et al., 2021).

Offshore wind energy is currently the most mature offshore renewable technology, with rapid global expansion driven by larger turbine capacities, improved foundation concepts, and declining levelized costs of energy (LCOE) (Global Offshore Wind Report, 2023; Briggs et al., 2021). In parallel, floating solar photovoltaics (FPV) have emerged as a promising option for expanding solar generation where land availability is limited. Although commercial FPV deployment remains largely confined to inland and near-shore waters, recent experimental studies and pilot projects demonstrate the technical feasibility of offshore FPV systems under suitable metocean conditions (Essak and Ghosh, 2022; Clemente et al., 2024). The co-location of offshore wind and floating solar systems has therefore attracted increasing attention, as hybrid configurations can maximise energy yield per unit marine area while enabling shared infrastructure, grid connections, and operational synergies (López et al., 2020; Ara et al., 2021).

A key advantage of offshore wind-floating solar hybrid systems lies in their ability to mitigate the inherent intermittency of individual renewable resources. Wind and solar power often exhibit weak or negative correlations across hourly to seasonal timescales, reducing the frequency of simultaneous low-generation periods and enhancing overall system reliability (Nikolakakis and Fthenakis, 2011; Prasad et al., 2017; Jurasz et al., 2020). This complementarity has been widely quantified using correlation-based metrics such as Pearson's r , Spearman's ρ , and Kendall's τ , alongside variability indicators including the coefficient of variation and event-based availability indices (Xu et al., 2017a; Lavidas et al., 2018; Soukissian et al., 2021). Collectively, these studies demonstrate that co-located wind-solar systems can smooth

power output, reduce grid-firming requirements, and improve utilisation of shared offshore infrastructure compared with standalone deployments.

Several recent studies provide important reference points for offshore wind-solar co-location while also illustrating the limitations of existing approaches. López et al. (2020), through a regional case study in Spain, demonstrated that combining floating offshore wind and solar PV can substantially increase energy production per unit marine area and significantly smooth power output via a power-smoothing index. Similarly, Soukissian et al. (2021) conducted a basin-scale assessment of offshore wind and solar resources in the Mediterranean Sea, focusing on variability, complementarity, and synergy using robust statistical and event-based metrics derived from ERA5 reanalysis data. While existing studies demonstrate the energetic and statistical benefits of wind-solar co-exploitation, offshore wind and floating solar developments remain constrained by resource intermittency and the demanding marine environment. Harsh wave climates and extreme metocean conditions limit installation and maintenance access and pose survivability challenges for floating solar platforms, yet these factors are rarely embedded within spatial assessment frameworks and are often treated only through broad exclusions or isolated engineering analyses. These challenges are compounded by high capital and transmission costs, limited offshore grid infrastructure, and regulatory and marine spatial-planning uncertainties, especially for hybrid systems. In response, the present study incorporates wave-related operational constraints together with resource availability, variability, and complementarity within a decision-oriented spatial framework, alongside alternative wind-solar allocation scenarios and sensitivity analysis to evaluate the robustness of suitability outcomes. As a result, locations identified as highly complementary and resource-rich may prove impractical for deployment once wave-induced operational constraints are taken into account (Kamranzad and Hadadpour, 2020; Silalahi and Blakers, 2023; Delbeke et al., 2023).

This limitation highlights a clear research gap in the current literature: the absence of integrated, wave-aware site-selection frameworks that explicitly combine wind-solar complementarity metrics with operational accessibility and survivability criteria in a spatially explicit decision-support context. Addressing this gap requires analytical approaches capable of harmonising heterogeneous offshore datasets and evaluating multiple interacting criteria at scale, ensuring that hybrid offshore renewable concepts are not only resource-optimal but also technically viable.

Australia offers a compelling case for applying such an integrated framework. The country possesses one of the world's largest Exclusive Economic Zones (EEZs), with strong offshore wind resources in southern latitudes and high solar irradiance in northern regions (Briggs et al., 2021; Copper and Bruce, 2018). Although Australia's offshore wind sector is still in its early stages, multiple offshore wind areas have been declared and feasibility licences awarded, creating a timely opportunity to explore innovative hybrid offshore energy concepts (DCCEEW, 2024). At the same time, Australia's commitment to achieving 82 % renewable electricity by 2030 highlights the need for robust spatial planning tools to support integrated offshore renewable deployment (CEC, 2023).

Geographic Information Systems (GIS) have been widely adopted as a core analytical framework for offshore renewable energy site-suitability analysis, owing to their ability to integrate diverse spatial datasets and support spatially explicit decision-making across large marine domains. Previous studies have successfully employed GIS-based approaches to identify suitable offshore wind and hybrid renewable energy sites by combining resource availability with environmental, bathymetric, and operational considerations (Hosseinzadeh et al., 2025; Dimitriou et al., 2025). In the context of offshore wind-floating solar systems, GIS provides a spatial decision-support environment in which wind and solar resources, wave climate, bathymetry, and regulatory or environmental constraints can be jointly analysed at the grid-cell level, allowing spatial patterns of energy potential and operational feasibility

to be examined consistently. Building on this foundation, the present study develops a national-scale, GIS-based framework for identifying suitable locations for co-located offshore wind and floating solar farms within Australia's EEZ. The framework advances beyond conventional resource mapping by integrating wind and solar resource magnitude, temporal variability, wind–solar complementarity, and wave-related operability and survivability considerations within a unified spatial assessment, using 11 years of high-resolution hourly wind, solar irradiance, and wave data. In doing so, the study provides a reproducible and transferable decision-support approach that supports marine spatial planning and the development of technically viable offshore wind–floating solar hybrid systems in Australia and comparable offshore regions.

2. Methodology

2.1. Study area and data sources

Australia's EEZ is among the largest globally, spanning approximately 10 million km², and it is substantially larger than the 7.69 million km² mainland. It extends from 47.19°S in the sub-Antarctic to 8.88°S in the tropical Timor Sea and from 109.23°E in the Indian Ocean to 163.19°E in the Coral Sea, extending 200 nautical miles from the coast (Fig. 1). Australia's extensive coastline provides significant opportunities for offshore renewable energy development. The entire EEZ was considered in this study due to the diverse and abundant renewable resources, with strong winds, particularly in the southern latitudes, and high solar irradiance in the north (Copper and Bruce, 2018; Briggs et al., 2021).

Wind data were obtained from the BARRA, which provided hourly horizontal wind components (v_x , v_y) at 100 m hub height with 12 km spatial resolution, for 2009–2019 (Su et al., 2019). Previous validation studies have demonstrated that BARRA outperformed global reanalyses such as ERA5 and MERRA-2 in capturing mesoscale atmospheric processes relevant to offshore wind (Palmer et al., 2023).

The 11-year period considered here meets the minimum recommended duration of 10 ± 3 years required to achieve a 90% confidence level in long-term wind energy yield estimates (Lee et al., 2018; DNV, 2016). Solar irradiance data were also sourced from BARRA to ensure

consistency and comparability with the wind dataset. Specifically, this study used hourly surface downwelling shortwave radiation (*RSDS*), which includes both direct and diffuse radiation components. The dataset covers the same period (2009–2019) and the same spatial resolution, allowing for joint assessment of wind and solar variability and complementarity across the EEZ. *RSDS* has been widely adopted in global and regional solar resource assessments due to its reliability and ability to capture the diurnal and seasonal variability of solar radiation (Bayo-Besteiro et al., 2023).

Wave data were sourced from the Centre for Australian Weather and Climate Research (CAWCR) wave hindcast developed by CSIRO and the Bureau of Meteorology, which provided a continuous record of significant wave height (*H*) for the period from 1979 to 2025 (Smith et al., 2021). The CAWCR wave hindcast has been validated against satellite altimeter and buoy observations, with high correlation coefficients (0.9) indicating strong model performance (Hemer et al., 2017). To ensure consistency with the wind and solar datasets, this study used the CAWCR wave hindcast subset spanning 2009–2019 (i.e., the same spatial and temporal resolution as those of BARRA data). As with all atmospheric reanalysis and hindcast products, BARRA and CAWCR datasets are subject to residual model bias and spatial smoothing inherent in their numerical and assimilation methods, such that surface winds, irradiance, and wave heights may differ from local observations at individual points; nevertheless, previous validation studies demonstrate that BARRA outperforms global reanalyses for mesoscale surface meteorology (Su et al., 2019) and that the CAWCR hindcast has been validated against satellite altimeter and buoy observations and shows strong agreement with correlation coefficients above 0.9 across Australian waters (Hemer et al., 2017), making these datasets appropriate for a high-level regional-scale screening and resource assessment.

Additional spatial datasets were incorporated to support the site selection process. Bathymetric information was obtained from Geoscience Australia's Australian Bathymetry and Topography Grid, together with the General Bathymetric Chart of the Oceans (Whiteway, 2009). To ensure environmental and regulatory compliance, marine protected areas (MPAs) were identified and excluded using the Collaborative Australian Protected Areas Database (Department of Climate Change et al., 2025). These datasets provided essential spatial constraints, ensuring that the geospatial framework for assessing offshore

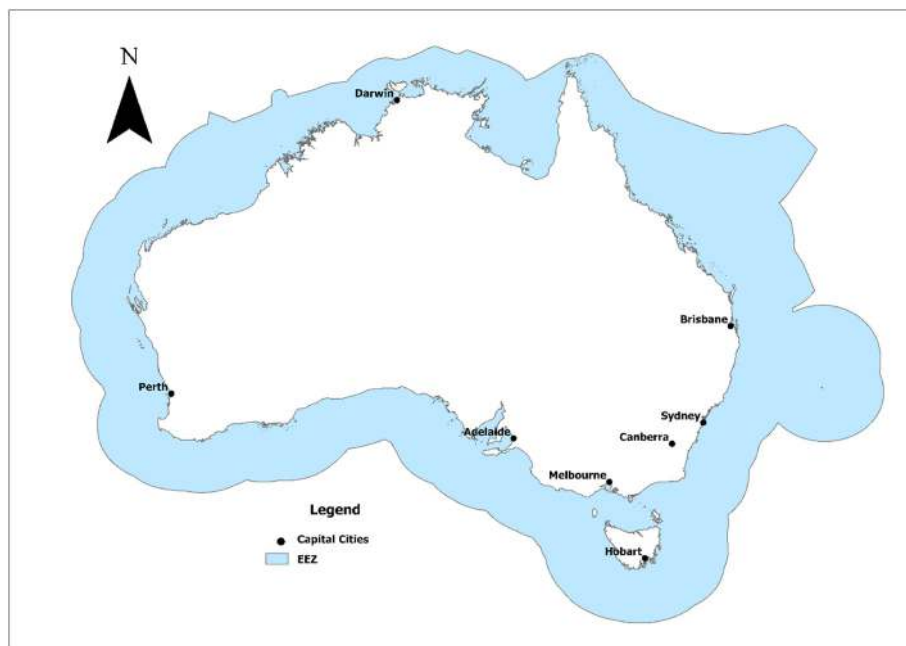


Fig. 1. Study area, Australian EEZ and capital cities.

wind–solar co-location in Australia was both technically robust and environmentally responsible.

2.2. Methodological framework

This section presents the framework for optimal site selection of offshore wind and floating solar farms within Australia's EEZ. A composite Suitability index (*SI*) and its wave-adjusted form (*SI_w*) integrate criteria on resource availability, variability, complementarity, and marine conditions. Spatial exclusions, such as depth limits, resource thresholds, and protected areas, ensured that only technically and environmentally viable sites were retained. The resulting suitability maps, produced under alternative wind–solar scenarios, highlight potential co-location zones (Fig. 2). summarises the sequential flow of this framework.

All analytical steps were implemented within a GIS environment, which served as the primary platform for integrating wind, solar, wave, bathymetric, and exclusion datasets. Raster-based spatial operations were used to harmonise all layers to a common spatial resolution and to perform pixel-wise integration of multi-criteria indicators. This GIS framework enabled spatial masking, scenario-based weighting, and the generation of continuous suitability surfaces across Australia's EEZ.

2.2.1. Analysis of wind–solar resource metrics

The estimation of wind energy potential was determined by calculating the wind power density (*WPD*) at each grid cell using the following equation:

$$WPD = \frac{1}{2} \rho_a v^3 \quad (1)$$

where ρ_a is the air density, 1.23 kg/m^3 , (Ferrari et al., 2020b; Y. Wen et al., 2022) and v is the wind speed at the hub height of an offshore wind turbine (OWT). The Vestas V164-8.0 MW turbine, featuring a hub height of 100 m, was used as the OWT for this study.

The potential for solar energy generation was assessed using *RSDS*, which accounts for both direct and diffuse solar radiation at the sea surface. Hourly *RSDS* values were analysed over the same period as the wind data to maintain temporal consistency, thus providing a coherent basis to evaluate solar resource availability and its complementarity with wind. To capture this complementarity, this study introduces the *WSSI* to quantify the proportion of time that at least one of the two resources is available for power generation, in contrast to simple statistical co-location methods, which only describe resource overlap (Pedruzzi et al., 2023). The Wind–Solar Synergy Index (*WSSI*) is a threshold-based indicator designed to directly link resource availability to practical operating conditions of offshore hybrid systems. Rather than estimating energy yield, *WSSI* quantifies the proportion of time during which at least one resource is operationally useable. Availability windows were defined as wind speeds between 6 and 25 m/s or *RSDS* values equal to or exceeding 170 W/m^2 .

The wind-speed range of 6–25 m/s reflects realistic operating limits for large offshore wind turbines. The upper threshold of 25 m/s corresponds to the standard cut-out wind speed specified in IEC design standards and manufacturer datasheets, beyond which turbines are shut down to ensure structural safety (Fig. 3). The lower threshold of 6 m/s represents a conservative operational and economic limit, capturing wind conditions under which offshore turbines can reliably contribute to power generation. Similar thresholds have been widely adopted in offshore wind resource and hybrid energy assessments (Briggs et al., 2021; Nizamani et al., 2024). For solar energy, an *RSDS* threshold of

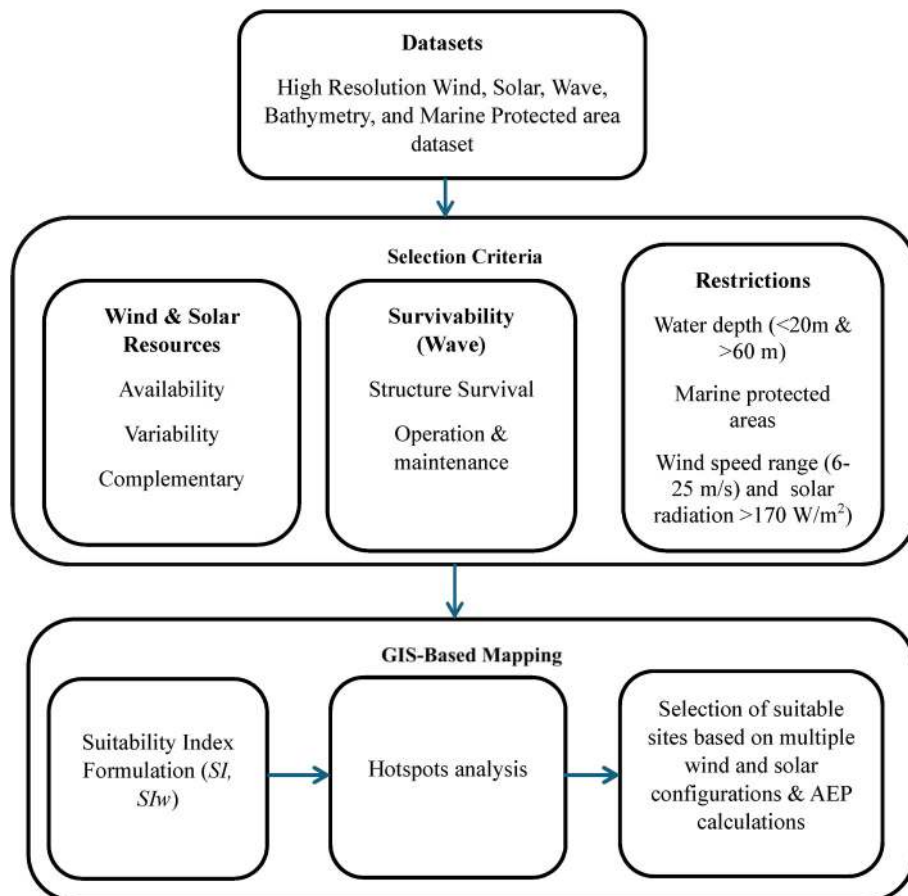


Fig. 2. Flow chart of the methodology for the site selection of suitable co-location sites for offshore wind and floating solar.

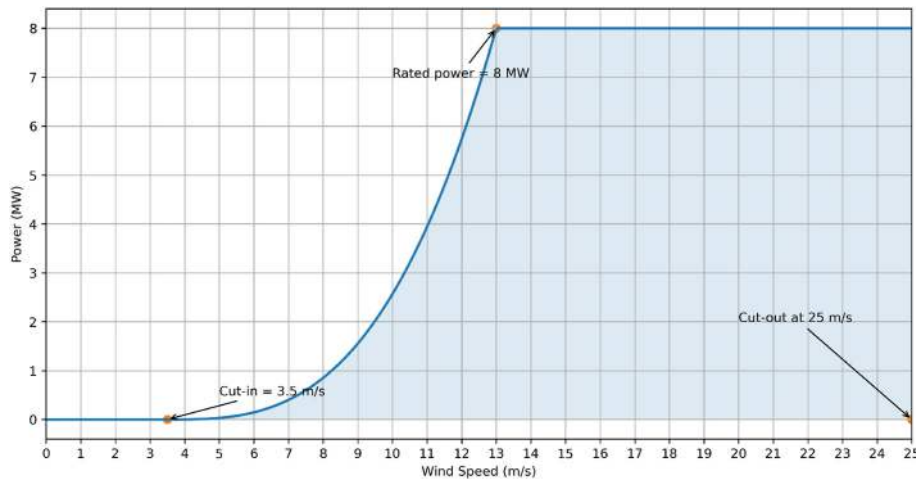


Fig. 3. Power Curve of Vestas V164-8 wind turbine (Vestas V164-8.0 - turbine).

170 W/m² was selected to represent minimum irradiance conditions under which photovoltaic systems can generate meaningful power output after accounting for conversion losses and offshore operating constraints. Comparable irradiance thresholds have been used in previous solar and hybrid renewable energy studies to distinguish productive from non-productive conditions (Prasad et al., 2017; Wu and West, 2024). The WSSI was formulated as follows:

$$WSSI = \frac{\text{Number of hours with } 6 \leq V \leq 25 \text{ m/s OR } RSDS \geq 170 \text{ W/m}^2}{\text{Total number of hours}} \times 100 \quad (2)$$

The temporal variability of renewable energy resources is a critical factor in assessing their suitability for large-scale deployment, as fluctuations directly affect grid integration, system stability, and operational planning (Das et al., 2022). To capture this aspect, the coefficient of variation CoV was used as a normalised metric of variability, as it allows consistent comparison across different resources and locations. The CoV is defined as follows:

$$CoV = \sigma / \mu \quad (3)$$

Where σ is the standard deviation, and μ is the mean of the time series. A lower CoV indicates more consistent and predictable resource availability, which is advantageous for continuous energy production and reduces reliance on storage or backup systems, while a higher CoV suggests greater variability and increased challenges for system reliability. CoV was calculated separately for wind power, WPD, and RSDS at each grid point using the 11-year hourly dataset. This approach ensured that temporal stability was incorporated as a key criterion in the site suitability assessment alongside resource availability and complementarity.

To quantify the temporal complementarity between wind and solar resources, Kendall's tau (τ) (Chen, 2025) rank correlation coefficient was employed. Kendall's tau is a non-parametric statistic suitable for detecting monotonic relationships, which makes it appropriate for comparing two fluctuating time series, such as wind power density and surface solar irradiance (Xu et al., 2017ab). It is defined as follows:

$$\tau = P[(X_i - X_j)(Y_i - Y_j) > 0] - P[(X_i - X_j)(Y_i - Y_j) < 0] \quad (4)$$

Where (X_i, Y_i) and (X_j, Y_j) are two randomly chosen observations from the joint distribution of variables X and Y and $i \neq j$, P is the probability, and the values of τ range between -1 and $+1$, where negative values indicate inverse relationships and positive values indicate direct relationships.

The level of confidence in calculating Kendall's tau is strongly influenced by the sample size. With small samples, estimates of Kendall's tau are more susceptible to random variation, which leads to wider

confidence intervals and lower reliability of the correlation estimate. As the sample size increases ($>96,000$ hourly pairs from 2009 to 2019), the variance of the estimator decreases, resulting in narrower confidence intervals and greater statistical power to detect true associations between variables. Each metric (WPD, RSDS, WSSI, CoV, and Kendall's τ) was computed at the grid-cell level and stored as an individual raster layer, preserving spatial variability and enabling GIS-based pixel-wise integration during suitability index formulation.

Building on the above indices and following (Hosseinizadeh et al., 2025), an SI was formulated to identify optimal locations for co-locating offshore wind and solar energy systems. The SI integrates indicators of resource availability, temporal variability, and complementarity as follows:

$$SI = \left(\frac{C_{wind} \cdot \overline{WPD}}{WPD_{95}} + \frac{C_{solar} \cdot \bar{G}}{G_{95}} \right) \times WSSI \times \frac{1}{(CoV_{wind} + CoV_{solar}) \times \exp^{\tau^{(o)}}} \times 100 \quad (5)$$

where C_{wind} and C_{solar} are weighting coefficients representing different wind-solar weighting scenarios (0.75W–0.25 S, 0.50W–0.50 S, 0.25W–0.75 S) showing the effect of the change on the suitability of sites when wind- or solar-dominant scenarios are considered, the weighting coefficients (0.75/0.25, 0.50/0.50, and 0.25/0.75) represent scenario-based wind-solar dominance cases within the SI, rather than fixed policy-driven or arbitrary weights. Their purpose is to systematically examine the sensitivity of site suitability outcomes to changes in the relative contribution of wind and solar resources.

The balanced weighting (0.50W–0.50 S) follows established practice in multi-resource offshore energy studies (Kamranzad and Hadadpour, 2020; Hosseinizadeh et al., 2025), while the wind-dominant (0.75W–0.25 S) and solar-dominant (0.25W–0.75 S) cases extend this approach to bracket plausible development scenarios where either resource is prioritised due to technical, geographic, or system-planning considerations. Hence, a sensitivity analysis is inherently embedded in the framework through these weighting scenarios, presenting the effect on the site suitability under different weights. $\overline{WPD}$ is the wind power density (W/m²), $\bar{G}$ is the mean solar irradiance (W/m²) over the analysis period, WPD_{95} and G_{95} are the 95th percentile of wind and solar power density, WSSI is the wind-solar synergy index, CoV denotes the coefficient of variations for wind and solar, and τ is Kendall's tau correlation coefficient. The denominator term $(CoV_{wind} + CoV_{solar}) \exp^{\tau^{(o)}}$ ensures that sites with higher variability or weaker complementarity are penalised (Hosseinizadeh et al., 2025), while negative τ values (indicating stronger complementarity) reduce the exponential factor and thus increase the suitability score. This formulation provides flexibility in assessing sites under different wind-solar weighting scenarios and

integrates resource magnitude, complementarity, and stability into a single comprehensive evaluation. To incorporate marine operational constraints and survivability, the developed *SI* was modified to include wave climate. Operational accessibility was evaluated by calculating the percentage of time during which the significant wave height *H* remained below 3 m, a threshold for safe operation of offshore transfer vessels (Acta Marine, 2019). Survivability was considered by identifying the maximum significant wave height at each grid point, which acts as a proxy for the design and structural requirements of offshore energy devices (Kamranzad et al., 2021; Kamranzad and Hadadpour, 2020). The combined formulation is expressed as follows:

$$SI_w = SI \times \text{percentage of time with } H_s < 3 \text{ m} \times (\min(H_{s \max})/H_{s \max}) \times 100 \quad (6)$$

Where $H_{s \max}$ is the maximum significant wave height observed at each grid point over the analysis period. The minimum of these maxima, $\min(H_{s \max})$, represents the calmest extreme condition across the study area. The ratio of $\min(H_{s \max})/H_{s \max}$ serves as a normalised survivability factor: sites with lower extreme wave heights retain values closer to 1, whereas sites exposed to harsher extreme waves are penalised with smaller values. This normalisation expresses survivability on a relative, dimensionless scale suitable for spatial comparison and does not imply an absolute structural design threshold. Instead, it provides a consistent baseline for penalising sites exposed to harsher extreme wave climates, while avoiding assumptions about technology-specific structural limits that remain highly design dependent, consistent with relative wave-based survivability and operability approaches used in offshore spatial planning studies (Lavidas et al., 2018; Kamranzad et al., 2021).

To evaluate the robustness of the proposed suitability framework and to quantify the influence of individual criteria on site rankings, a sensitivity analysis was conducted using a Leave-One-Out (LOO) approach combined with a Partial Sensitivity Index (PSI). This analysis systematically assesses changes in the suitability index resulting from the exclusion of individual criteria. To maintain clarity and conciseness of the main manuscript, the full sensitivity analysis methodology and detailed results are provided in the Supplementary Material.

The suitability indices (*SI* and SI_w) were implemented using raster algebra within GIS, allowing weighted spatial integration of resource magnitude, variability, complementarity, and wave-operability criteria across the EEZ.

After calculating SI_w , spatial exclusions were applied to ensure technical feasibility and regulatory compliance. Bathymetric filtering was first undertaken to reflect current offshore deployment practice. Only areas with water depths between 20 and 60 m were retained (Yi Wen et al., 2022; Ali et al., 2024; Clean and Council, 2024). Areas shallower than 20 m were excluded, as they typically experience spatial and environmental conflicts, vessel and installation challenges, and limited social acceptance, which make them unfavourable (Wolsink, 2010). Deeper areas (>60 m) were also excluded due to the increased costs and engineering challenges associated with anchoring, mooring, and subsea cable routing (Clean and Council, 2024). The 20–60 m range, therefore, represents a practical compromise between technical viability and economic efficiency for co-locating offshore wind and floating solar systems with current technologies (Jiang et al., 2023). To further refine the candidate areas, a resource-based exclusion mask was applied. All grid points with mean wind speeds below 6 m/s or mean annual solar irradiance values less than 1400 kWh/m²/year were eliminated (Briggs et al., 2021; Salvador et al., 2022; Kumar et al., 2023; Feng et al., 2025). This filtering step ensured that only sites with sufficient resource potential were retained. Finally, locations designated as MPAs were excluded from the analysis (Department of Climate Change et al., 2025). Table 1 summarises the evaluation and exclusion criteria used in this study. This step was taken to ensure compliance with national conservation policies and maritime spatial planning regulations, thereby avoiding conflicts with legally established protection zones. By

Table 1

Summary of evaluation and exclusion criteria.

Evaluation criteria	1) WPD 2) RSDS 3) WSSI 4) Coefficient of variation 5) Kendal tau 6) Significant wave height
Exclusion criteria	1) Sea Depth (<20 m or >60 m) 2) Windspeed Threshold (<6 m s ⁻¹ or > 25 m s ⁻¹) 3) RSDS Threshold >170 w/m ² 4) Marine Protected Areas 5) Significant Wave height >3 m

incorporating these exclusions, the methodology ensures that the final candidate sites not only demonstrate high renewable energy potential and resource complementarity but also satisfy the critical operational, technical, and regulatory constraints required for sustainable offshore development.

2.2.2. Wind energy production

The power output of a wind turbine as a function of wind speed *v* is given as follows (Carrillo et al., 2013):

$$P_{\text{wind}}(v) = \begin{cases} 0 & v < v_{ci} \text{ or } v > v_{co} \\ q(v) v_{ci} \text{ or } v_r & \\ P_r v_r \leq v \leq v_{co} & \end{cases} \quad (7)$$

where $P_{\text{wind}}(v)$ is the electric power, v_{ci} is the cut-in wind speed in m/s, v_{co} is the cut-out windspeed in m/s, v_r is the rated windspeed in m/s, P_r is the rated power in, and $q(v)$ is the non-linear relationship between power and windspeed. To estimate wind energy production, a time-resolved approach was employed using the Vestas V164-8.0 MW OWT, which is one of the most commonly used turbine models in offshore wind farms around the world (Vestas V164, 2018). The turbine's power curve (Fig. 3) was applied to hourly wind speed data to derive the instantaneous electrical power output of a single turbine. The hourly energy output was then calculated as follows:

$$E_{\text{hourly}} = P_{\text{wind}}(v) \times \Delta t \quad (8)$$

where $\Delta t = 1$ h.

To estimate wind energy production on a per-unit-area basis, the single-turbine output was scaled by the number of turbines that could be accommodated within the available area, assuming industry-recommended spacing of 8–10 rotor diameters in the prevailing wind direction and 5–7 diameters in the crosswind direction to minimise wake effects (Gupta, 2016; ABB, 2011).

The annual energy production was expressed on a per-unit-area basis (1 km²) to avoid assumptions regarding project footprint. For each wind-solar share scenario (75–25, 50–50, and 25–75), the corresponding fraction of the unit area was allocated to wind turbines to determine the number of turbines that could be accommodated per km² based on the adopted spacing criteria. The wind AEP per km² was then calculated by multiplying the 11-year average annual energy production of a single turbine by the number of turbines that could be installed within the allocated wind area.

2.2.3. Solar energy production

Solar energy output was estimated using hourly RSDS values (2009–2019) combined with the technical specifications of the JA Solar JAM66S10-370 W Mono PERC half-cell module, which has been used in major floating solar projects (JA Solar, 2017). This module has a rated efficiency of 20 % and an active surface area of 1.845 m². The instantaneous power output of a single panel at each time step is calculated by the following formula (Dierauf et al., 2013):

$$P_{\text{solar}} = \eta \times A \times \text{RSDS} \times PR \quad (9)$$

where P_{solar} is the solar power, η is the efficiency of the panel, A is the panel area, PR is the performance ratio (taken as 0.70 for a typical solar panel), and $RSDS$ is the hourly solar irradiance at the site.

The annual energy production (AEP) of a single photovoltaic panel was obtained by summing its hourly outputs for each year over the 2009–2019 period and averaging across the analysis duration. To avoid assumptions regarding project footprint, solar energy production was normalised and expressed on a per-unit-area basis (1 km^2). For each wind–solar share scenario (75–25, 50–50, and 25–75), the corresponding fraction of the unit area was allocated to solar deployment to determine the number of deployable panels per km^2 . To reflect realistic deployment density, a coverage ratio of 0.65 was applied to account for inter-array spacing, transmission corridors, and shading losses (World Bank, 2019). The solar AEP per km^2 was calculated by multiplying the 11-year average AEP of a single panel by the number of panels deployable within the allocated solar area of the unit cell, with the correction factor ensuring that the estimates reflect practical, useable output rather than an idealised maximum potential.

3. Results and discussions

3.1. Wind and solar resource potential

The spatial distribution of wind and solar resources across the Australian EEZ highlights distinct but complementary patterns. As illustrated in Fig. 4, offshore wind potential is strongest in the southern coastal regions, particularly near Tasmania and Victoria, where the mean WPD often exceeds 2000 W/m^2 . These areas are highly favourable for wind farm deployment due to their strong and consistent wind regimes. In contrast, significantly lower wind power is recorded in the northwest, averaging approximately 80 W/m^2 , which indicates limited potential for large-scale wind exploitation. The eastern and western coasts show moderate WPD values, suggesting broader but less concentrated opportunities.

The distribution of solar irradiance density, shown in Fig. 5, exhibits an inverse pattern to that of wind. The northwestern EEZ records the highest irradiance values, exceeding 269 W/m^2 , which makes it particularly suitable for FPV deployment. In contrast, the southern regions, while wind-rich, exhibit substantially lower solar irradiance,

averaging approximately 141 W/m^2 . This geospatial contrast underscores the benefits of hybrid offshore systems, where solar-rich northern waters can complement wind-rich southern zones to enhance the overall energy reliability and utilisation of marine space.

3.2. Complementarity and variability of wind and solar resources

The spatial distribution of the wind–solar synergy index across Australia's EEZ (Fig. 6) ranges from ~53% to over 92%, indicating that at least one resource is available most of the time across the majority of offshore regions. The southern and western EEZ, particularly off Tasmania, Victoria, and Western Australia, show the highest values (>90%), which reflects strong complementarity between wind and solar availability. In contrast, lower values (<65%) are observed in parts of the northern EEZ, such as off Darwin and the Gulf of Carpentaria, where simultaneous low wind and solar conditions are more frequent. However, synergy levels remain moderate in these areas, which suggests that co-located systems can still provide more stable generation compared to single-resource developments.

The spatial distribution of the coefficient of variation (CoV) for wind and solar resources across.

Australia's EEZ shows clear regional contrasts, as presented in Fig. 7a and b. Wind CoV ranges from 0.86 to 3.72, with the lowest values in the southern EEZ (Tasmania, Victoria, South Australia) indicating stable wind regimes, and the highest values (>3) in the northwestern EEZ reflecting strong fluctuations. Solar CoV values vary less (1.30–1.58), with the lowest variability in the northwestern EEZ due to consistently high irradiance, and higher values in the south, where seasonal effects dominate. These opposing patterns highlight the spatial synergy of the two resources, with stable winds in the south and more consistent solar availability in the north.

Kendall's τ values across Australia's EEZ range from -0.26 to 0.13 (Fig. 8). Negative correlations dominate much of the northern, northwestern, and western offshore regions, indicating low fluctuations in wind and solar resources. A negative correlation reduces the likelihood of simultaneous low-output periods, thereby enhancing the reliability of hybrid generation in these zones. In contrast, positive to near-zero τ values are more prevalent in the southern EEZ, where strong wind regimes coincide with weaker solar availability, limiting the degree of

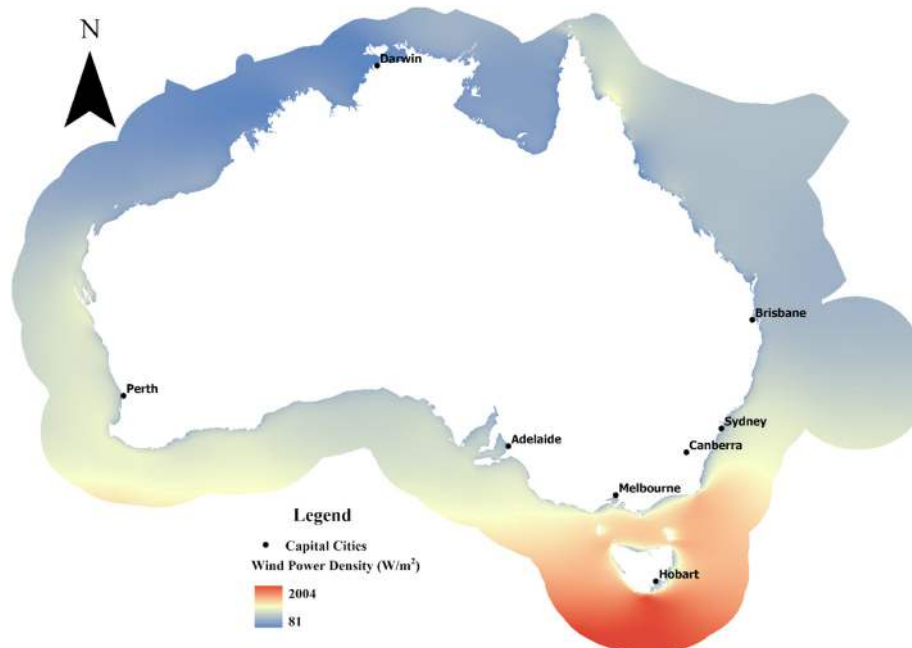


Fig. 4. Spatial distribution of wind power density (W/m^2) from 2009 to 2019 in the Australian EEZ and capital cities.

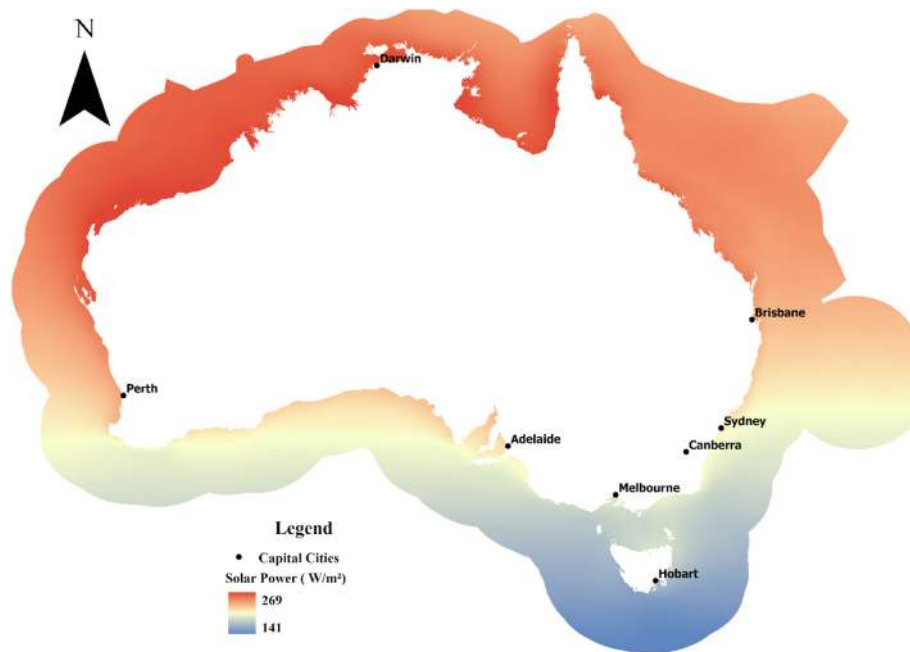


Fig. 5. Distribution of mean solar RSDS (W/m^2) from 2009 to 2019 in the Australian EEZ and capital cities.

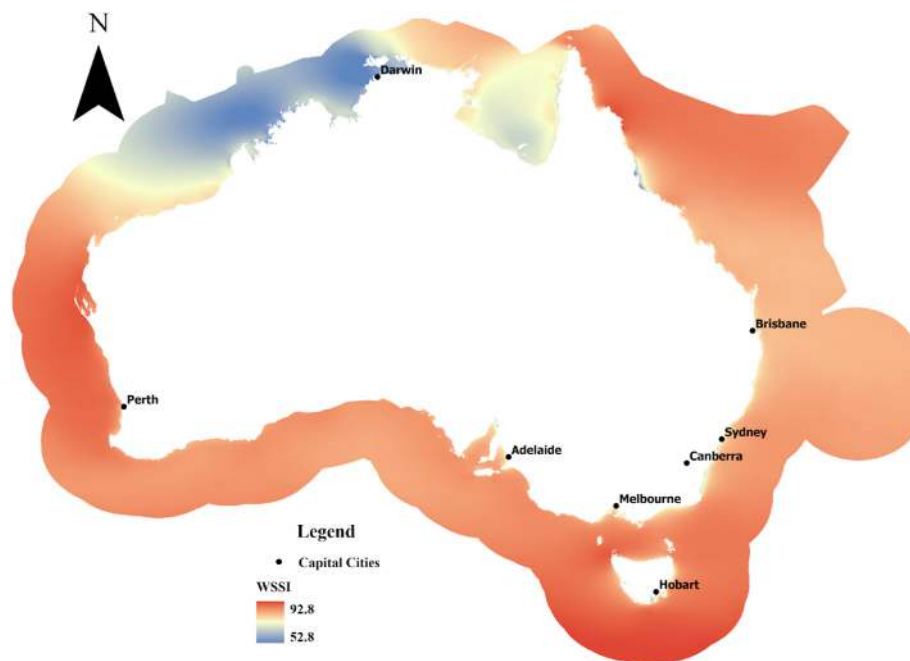


Fig. 6. Wind and solar synergy index distribution in the Australian EEZ and capital cities.

temporal offset between the two resources. Overall, these patterns show clear spatial differences in complementarity, with northern and western regions having stronger wind–solar synergy, while southern regions, although resource-rich, exhibit weaker balancing between the two resources. These complementarity patterns indicate that hybrid offshore wind–floating solar systems can directly mitigate the intermittency that constrains standalone wind or solar generation by reducing the frequency of simultaneous low-output conditions.

The observed wind–solar complementarity behaviour, characterised by reduced simultaneous low-generation periods and lower combined variability, is consistent with findings from hybrid wind–solar studies, where co-located systems demonstrate enhanced reliability relative to

standalone resources (Prasad et al., 2017; Xu et al., 2017a; Jurasz et al., 2020).

3.3. Site suitability analysis under different configurations

The spatial distribution of the 10 most suitable offshore wind–solar co-location sites within Australia's EEZ is illustrated in Fig. 9(a–c), with detailed resource metrics provided in Tables 2–4. The results show notable geographic variations under the three weighting scenarios: wind-dominant (0.75W–0.25), balanced (0.50W–0.50 S), and solar-dominant (0.25W–0.75 S). The site rankings are based on SI_w , the results inherently reflect wave-operability and survivability constraints,

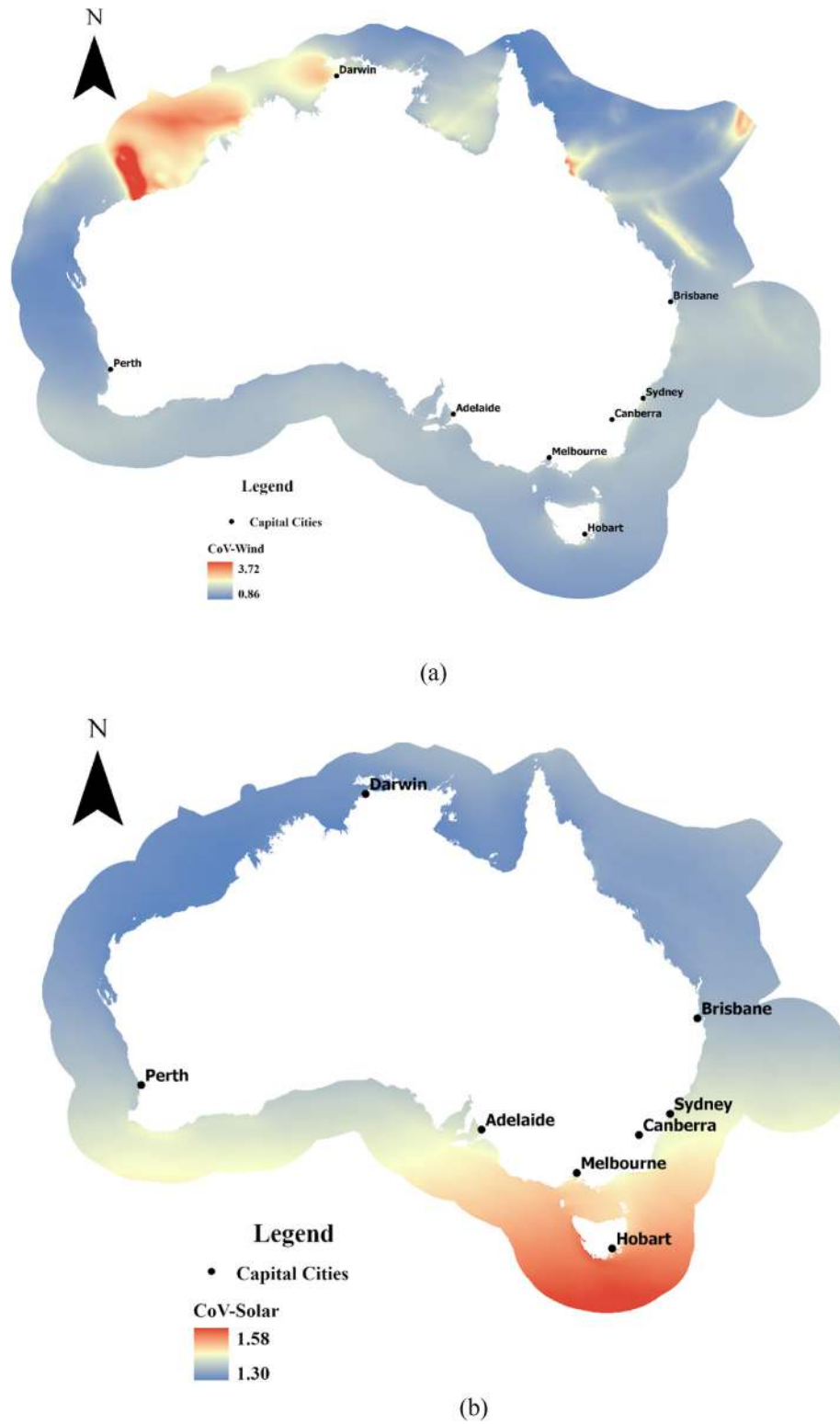


Fig. 7. Maps of (a) the coefficient of variations wind and (b) the coefficient of variations solar across the Australian EEZ and capital cities.

excluding locations where access, maintenance, and long-term floating solar operation would be technically infeasible. High-resolution suitability maps (*Sfw*) for the three wind-solar weighting scenarios are provided in the Supplementary Material (Fig. S1).

The concentration of highly suitable sites toward southern Australia under the wind-dominant configuration is consistent with offshore wind assessments, which identify stronger and more persistent wind regimes

in mid-latitude southern waters driven by prevailing westerlies (Hosseinizadeh et al., 2025; Briggs et al., 2021). Conversely, the northward shift in optimal locations under solar-dominant weighting is consistent with Australian solar irradiation mapping and GIS-based suitability assessments, which consistently show higher long-term solar resource across northern Australia relative to southern latitudes (Copper and Bruce, 2018; Silalahi and Blakers, 2023; Chakravarty et al.,

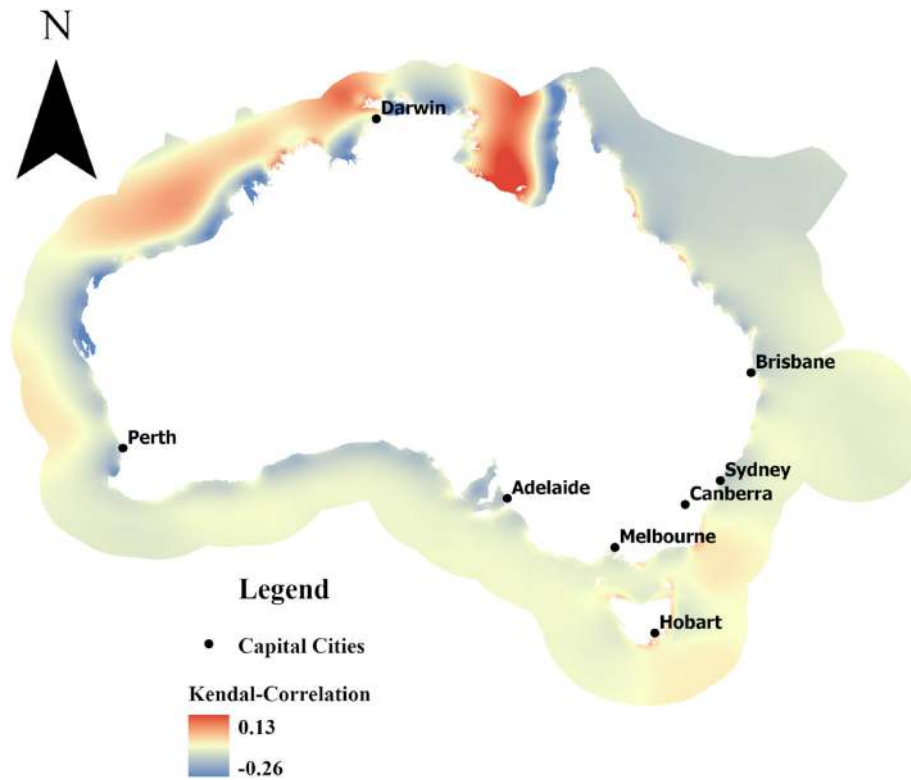


Fig. 8. Spatial distribution of Kendal correlation between wind and solar in the Australian EEZ and capital cities.

2024).

To enable a quantitative comparison between scenarios, the spatial extent of highly suitable areas was quantified for each configuration. Grid cells with SI_w values $\geq 50\%$ of the scenario-specific maximum were classified as highly suitable. Under this criterion, the solar-dominant (25 W–75 S) scenario covers 8.3% of Australia's EEZ, followed by the wind-dominant (75 W–25 S) configuration at 8.1%, while the balanced (50 W–50 S) scenario yields a more restricted footprint of 4.9%. These results indicate that scenario weighting substantially influences not only site rankings but also the overall spatial availability of feasible co-location zones.

In the 75 W–25 S wind-dominant configuration (Fig. 9a and Table 2), the leading site (A) is located off the northwestern coast of Western Australia, which achieves the highest SI_w and $WSSI$ values. The suitability is supported by low wind variability and a strongly negative Kendall's τ , indicating both stability and complementarity. Several additional high-ranking sites (B, C, and F) are located across northern Queensland and the Gulf of Carpentaria, where synergy values remain consistently high and complementarity is maintained. Importantly, the wind-prevailing weighting also elevates a cluster of southern and mid-latitude sites (D, E, G, H, I, and J) that benefit from strong and persistent wind regimes associated with the westerly wind belt. Despite lower solar irradiance, these wind-dominated regions achieve high suitability, demonstrating how wind-focused prioritization extends attention beyond tropical waters to uncover high-potential southern offshore zones.

The 50 W–50 S balanced configuration (Fig. 9b and Table 3) produces a more even spatial spread across the EEZ. Site A again ranks highest, underscoring its robustness across weighting schemes. Alongside the northwestern hotspot, northern sites in Queensland and the Northern Territory (B–D, F, and G) continue to perform strongly, supported by high $WSSI$ values and negative Kendall's τ . Balanced weighting also highlights southern sites such as I, indicating that both tropical solar-driven locations and wind-dominated mid-latitude coasts contribute meaningfully when resources are weighted equally.

In the 25 W–75 S solar-dominant configuration (Fig. 9c and Table 4), the distribution shifts northward and eastward, reflecting the influence of solar irradiance. While Site A retains a strong position due to its combined wind and solar synergy, tropical and subtropical sites (B, C, F, G, H, and J) gain prominence, driven by consistently high irradiance and $WSSI$ values above 80%. These locations illustrate how a stronger emphasis on solar resources reshapes rankings, allowing areas with moderate wind but abundant solar potential to emerge as highly suitable.

Overall, the results show a dual-cluster pattern of optimal locations. The north and northeast (Queensland and Northern Territory waters) consistently perform well due to high solar irradiance paired with moderate winds, while the southern and mid-latitude coasts (Western Australia and Bass Strait) emerge strongly under wind-dominant conditions because of persistent westerly wind regimes. This duality highlights the sensitivity of site rankings to different weighting assumptions and underscores the importance of evaluating multiple configurations to capture Australia's hybrid offshore renewable potential fully. The robustness of the suitability rankings was further examined using a sensitivity analysis, which confirmed that the overall spatial patterns are stable under variation of individual criteria (see Supplementary Material).

3.4. Annual energy production (AEP) across configuration scenarios

Table 5 presents the normalised annual energy production (AEP per km^2) for the top 10 sites under three wind–solar allocation scenarios (75 W–25 S, 50 W–50 S, and 25 W–75 S). Across all sites and configurations, solar energy consistently contributes the dominant share of total generation, while wind energy provides a smaller but complementary contribution. This pattern reflects the higher deployable density of floating photovoltaic panels per unit area compared to offshore wind turbines, which allows solar generation to dominate total energy output even under wind-dominant spatial allocations. The combined generation profiles demonstrate how hybrid deployment alleviates reliability

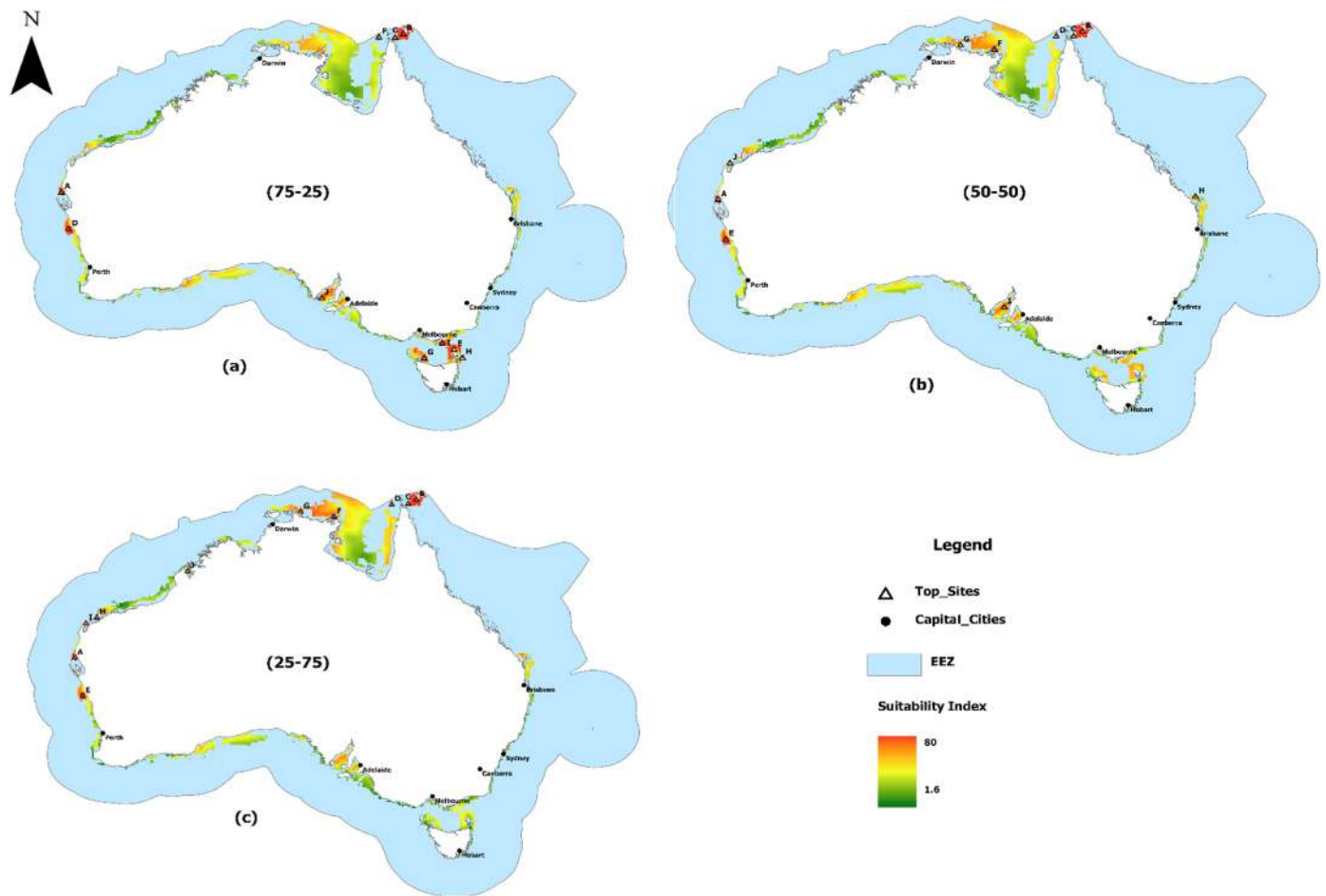


Fig. 9. Distribution of top sites in the Australian EEZ under different configurations (a) 75 W–25 S wind–solar (b) 50 W–50 S wind–solar (c) 25 W–75 S wind–solar.

Table 2

Suitable sites characteristics, 75 W–25 S wind–solar configuration.

Site	Lat	Lon	SI_w	WSSI	CoV_Wind	CoV_Solar	Kendal τ
A	–24.86	113.34	70.6	90.2	1.01	1.32	–0.14
B	–10.12	143.48	61.6	85.0	0.97	1.36	–0.08
C	–10.45	142.82	55.4	86.7	0.92	1.35	–0.07
D	–28.38	114	46	88.9	1.06	1.35	–0.06
E	–39.6	147.99	45	86.8	1.33	1.46	–0.03
F	–10.45	141.39	44.9	84.2	1.08	1.35	–0.13
G	–40.37	145.35	43.2	89.0	1.24	1.48	–0.03
H	–40.37	148.76	40.6	87.8	1.31	1.46	–0.05
I	–38.94	147	39.5	84.6	1.37	1.46	–0.04
J	–34.76	136.33	38.2	84.1	1.36	1.41	–0.08

Table 3

Suitable sites characteristics, 50 W–50 S wind–solar configuration.

Site	Lat	Lon	SI_w	WSSI	CoV_Wind	CoV_Solar	Kendal τ
A	–24.86	113.34	75.4	90.2	1.00	1.32	–0.14
B	–10.12	143.59	65.3	85.0	0.97	1.36	–0.08
C	–10.56	142.82	58.3	86.9	0.92	1.35	–0.06
D	–10.56	141.39	50.6	82.9	1.12	1.35	–0.14
E	–28.27	114	47.9	88.5	1.07	1.34	–0.06
F	–11.66	136.22	41.2	81.3	1.23	1.33	–0.03
G	–11.33	133.47	39	79.3	1.17	1.33	–0.10
H	–24.53	152.94	38	83.0	1.18	1.34	–0.09
I	–34.21	137.1	37.8	83.7	1.31	1.40	–0.11
J	–21.67	114.33	37.7	82.7	1.18	1.31	–0.13

Table 4

Suitable sites characteristics, 25 W–75 S wind–solar configuration.

Site	Lat	Lon	SI_w	WSSI	CoV_Wind	CoV_Solar	Kendal τ
A	−24.97	113.34	80	90.2	1.01	1.32	−0.15
B	−10.12	143.48	69.2	84.9	0.97	1.36	−0.08
C	−10.56	142.82	61.8	86.7	0.92	1.35	−0.07
D	−10.56	141.28	56.3	83.2	1.12	1.35	−0.14
E	−28.49	114	50	88.4	1.08	1.35	−0.07
F	−11.77	136.22	49.1	81.3	1.23	1.33	−0.03
G	−11.33	133.36	47.3	79.2	1.17	1.33	−0.10
H	−21.12	115.21	45.4	80.4	1.29	1.31	−0.10
I	−21.67	114.33	45	82.7	1.18	1.31	−0.13
J	−11.44	134.46	42.5	80.4	1.26	1.33	−0.13

Table 5

Annual energy production of top sites under different wind–solar configurations.

Annual Energy Production (GWh/yr/km ²)									
Site	75 W–25 S configuration			50 W–50 S configuration			25 W–75 S configuration		
	Wind	Solar	Total	Wind	Solar	Total	Wind	Solar	Total
A	20.76	50.56	71.32	13.82	104.10	117.9	6.9	156.1	163
B	19	45.7	64.7	12.6	95.3	107.9	6.3	142.9	149.2
C	20.3	40.8	61.1	13.7	95.3	109	6.8	142.9	149.7
D	19.9	51	70.9	10.4	98.8	109.2	5.1	148.2	153.3
E	21.4	41.1	62.5	13.3	98.8	112.1	6.7	145.6	152.3
F	16.5	41.3	57.8	9.3	100.6	109.9	4.4	153.5	157.9
G	22.8	45.8	68.6	9	102.4	111.4	4.4	153.5	157.9
H	21.5	50.1	71.6	10.3	95.3	105.6	4.7	161.4	166.1
I	19.7	41	60.7	11.4	88.2	99.6	5.3	161.4	166.7
J	17	47.2	64.2	10.6	107.6	118.2	4.7	153.5	158.2

and grid-firming bottlenecks by sustaining total energy output when either wind or solar availability is reduced.

In the 75 W–25 S wind-dominant scenario, the highest energy densities are observed at Sites H, A, and D, with total AEP values of approximately 71–72 GWh yr^{−1} km^{−2}. These sites are located primarily in northern and northwestern waters, where consistently high solar irradiance coincides with strong and persistent wind regimes, resulting in favourable wind–solar synergy conditions. Although a larger fraction of the unit area is allocated to wind, solar energy remains the dominant contributor due to the substantially higher number of deployable panels per km². Additional high-performing sites include B and G (approximately 65–69 GWh yr^{−1} km^{−2}), while sites in the Northern Territory and Queensland (C, E, and I) exhibit competitive energy densities in the range of 61–63 GWh yr^{−1} km^{−2}, reflecting strong complementarity between reliable solar resources and moderate but consistent wind conditions.

Under the 50 W–50 S balanced scenario, total energy densities increase substantially across all sites, with peak values recorded at Sites A, J, and E (approximately 118–112 GWh yr^{−1} km^{−2}). Site A remains the top-performing location, supported by high solar irradiance combined with steady wind conditions that together maximise energy output when space is allocated equally between technologies. Sites E, C, and G also demonstrate strong performance (approximately 109–112 GWh yr^{−1} km^{−2}), highlighting the effectiveness of balanced hybrid deployment in regions where both wind and solar resources are robust. The broader spatial pattern across Western Australia, the Northern Territory, and Queensland reflects the synergistic interaction of high irradiance and favourable wind climates, ensuring consistently high energy densities under equal allocation strategies.

In the 25 W–75 S solar-dominant scenario, the highest energy densities are achieved, with Sites I, H, and A exceeding 165 GWh yr^{−1} km^{−2}. These sites are concentrated in tropical northern waters, where exceptionally high solar radiation levels drive very large photovoltaic outputs when three-quarters of the unit area is allocated to solar deployment. Other locations, including J, F, and G, also exhibit elevated energy densities above 155 GWh yr^{−1} km^{−2}, underscoring the decisive role of

solar energy under solar-centric spatial allocations. In this configuration, wind generation primarily serves as a stabilising complementary resource, contributing to temporal smoothing rather than dominating total output.

A quantitative comparison across the three wind–solar allocation scenarios reveals systematic differences in energy output. Shifting from the wind-dominant (75 W–25 S) to the balanced (50 W–50 S) configuration increases total AEP by approximately 50–70% across most sites, reflecting the higher deployable energy density of floating photovoltaic systems per unit area while retaining wind generation. A further transition to the solar-dominant (25 W–75 S) configuration yields an additional 35–45% increase in total AEP, with peak energy densities rising from approximately 70 GWh yr^{−1} km^{−2} under wind-dominant conditions to 165–167 GWh yr^{−1} km^{−2} at high-performing northern sites. Overall, the shift from wind-dominant to solar-dominant allocation results in a greater than twofold increase in total AEP at several locations. This comparison indicates that total energy output is primarily governed by the relative wind–solar area allocation, with solar contributing higher cumulative generation per unit area, while wind generation consistently provides a complementary contribution that supports temporal balance across all scenarios.

3.5. State-level distribution of top sites

The national-scale mapping shows a significant concentration of highly suitable zones in northern Australia, particularly across the Northern Territory, northern Queensland, and northwestern Western Australia. These regions have been identified as the primary national hotspots for offshore wind–solar co-location and will play a crucial role in any large-scale development strategy. However, an exclusive focus on these areas may obscure other strategically important opportunities. Each Australian state has a different readiness level and appetite for offshore energy exploitation and may promote hybrid wind–solar offshore energy farms. Thus, it is important to also identify and rank sites for each state of Australia.

The state-level distribution of top sites for the 50 W–50 S share, as

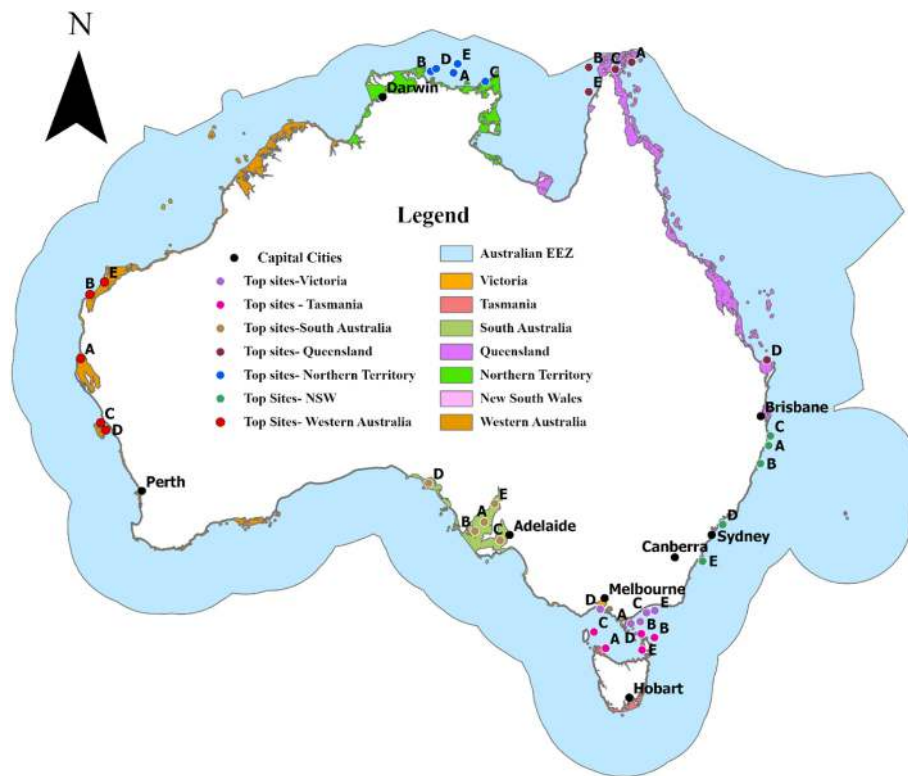


Fig. 10. Top five offshore sites for each State of Australia.

shown in Fig. 10, provides a complementary perspective and ensures visibility across all states. Identifying top candidate sites in each state will allow regions such as Victoria, Tasmania, South Australia, and New South Wales to develop their own highly suitable sites. From a planning standpoint, the state-level analysis is essential, as offshore renewable development in Australia is significantly influenced by jurisdictional governance, environmental permitting processes, and investment priorities that vary across states. Determining priority sites in each jurisdiction facilitates region-specific decision-making and aids in creating a more cohesive and balanced national strategy. Importantly, this dual perspective ensures that the economic, social, and energy security benefits of offshore wind-solar co-location, such as job creation, supply-chain diversification, and enhanced resilience, are more equitably distributed across the country. In this way, the state-by-state mapping complements the national-scale hotspots while reinforcing a coordinated blue economy approach throughout the Australian offshore waters.

4. Summary and conclusion

This study presents the first national-scale geospatial assessment of hybrid offshore wind-floating solar opportunities within Australia's Exclusive Economic Zone (EEZ). An integrated GIS-based framework was developed that combines long-term resource assessment, multi-criteria analysis, and energy yield estimation using 11 years (2009–2019) of high-resolution hourly wind, solar irradiance, and wave data. Central to the framework are the suitability index (SI) and its wave-inclusive formulation (SI_w), which jointly integrate indicators of resource magnitude, temporal variability, wind-solar complementarity, and wave-related operability and survivability, together with spatial constraints such as bathymetry, marine protected areas, and minimum resource thresholds. By explicitly linking resource availability with operational constraints, the framework moves beyond conventional resource mapping to identify sites that are both resource-rich and technically viable for hybrid offshore deployment.

The results reveal clear national-scale spatial patterns with direct relevance for offshore renewable planning. Highly suitable zones are concentrated in northern Australia, particularly across the Northern Territory, northern Queensland, and northwestern Western Australia, where strong solar irradiance, favourable wind-solar complementarity, and relatively moderate wave climates coincide. At the same time, southern and mid-latitude regions, including offshore areas of Victoria, Tasmania, South Australia, and southwestern Western Australia, emerge as highly suitable under wind-dominant scenarios due to persistent westerly wind regimes. These findings demonstrate that hybrid offshore opportunities in Australia are not uniformly distributed geographically and that optimal site selection is sensitive to the relative prioritization of wind and solar resources.

From a policy and industry perspective, the identified suitability hotspots provide actionable insights for Australia's emerging offshore renewable energy sector. The spatial patterns highlighted in this study can directly inform offshore wind leasing and feasibility licence processes by supporting the early identification of priority development zones where strong resource potential aligns with operational feasibility. In particular, the framework can assist policymakers and regulators in screening large offshore areas, guiding staged leasing strategies, and aligning future offshore wind and hybrid energy zones with infrastructure planning, environmental constraints, and state-level development priorities. For industry stakeholders, the results offer a spatial decision-support tool to de-risk early-stage site selection by highlighting locations where hybrid wind-solar systems are more likely to achieve stable generation and favourable operational conditions.

Across the three wind-solar weighting scenarios examined, site rankings were found to be sensitive to changes in resource emphasis, underscoring the importance of scenario-based planning. Northwestern Australia consistently ranked as a high-priority development zone under all configurations. At the same time, tropical waters in the Northern Territory and Queensland gained prominence as the weighting shifted towards solar dominance. Annual energy production (AEP) estimates further showed that solar power contributes the largest share of total

generation across all scenarios, largely due to the high deployable panel density achievable within offshore sites. Even under wind-dominant configurations, wind primarily acts as a complementary and stabilising resource rather than the dominant contributor to total output. These results highlight the value of hybrid system design in improving reliability and maximising energy yield per unit marine area.

While the framework provides a robust basis for national-scale screening, several limitations should be acknowledged. The analysis relies on reanalysis datasets for wind, solar irradiance, and wave conditions, which, although widely validated and suitable for large-scale assessments, may not fully capture localised effects that would be resolved through site-specific measurements. Economic considerations such as transmission distance, grid connection costs, and port infrastructure were not explicitly included, and turbine spacing and array layouts were approximated using industry-recommended standards rather than optimised designs. In addition, the bathymetric range was restricted to 20–60 m to reflect current offshore deployment practice and techno-economic feasibility.

These limitations point to clear directions for future research. The present focus on the 20–60 m depth range reflects the relatively lower cost, technological maturity, and near-term deployability of fixed-bottom offshore wind systems, which currently define the most commercially viable offshore development envelope. As floating wind and floating solar technologies continue to mature and as associated costs, mooring systems, and wave-survivability performance improve, the framework can be extended to deeper offshore waters by incorporating updated mooring, cabling, cost, and survivability models. Future studies could also integrate detailed techno-economic assessments, infrastructure proximity, and regulatory factors to further enhance project-level feasibility analysis. Importantly, the modular and data-driven structure of the proposed GIS-based framework makes it readily transferable beyond Australia. With appropriate local datasets and regulatory constraints, the approach can be applied to other offshore regions worldwide to support spatial planning, policy development, and industry decision-making for hybrid offshore renewable energy systems.

CRediT authorship contribution statement

Fida Ali: Writing – original draft, Visualization, Validation, Software, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Rodney A. Stewart:** Writing – review & editing, Supervision, Funding acquisition, Conceptualization. **Mohammad J. Sanjari:** Writing – review & editing, Supervision, Funding acquisition, Conceptualization. **Jennifer A. Hayward:** Writing – review & editing, Supervision, Conceptualization. **Robert C. Nicholson:** Writing – review & editing, Supervision, Conceptualization. **Amir Etemad-Shahidi:** Writing – review & editing, Project administration, Methodology, Funding acquisition, Conceptualization.

Funding

The authors acknowledge the financial support of the Blue Economy Cooperative Research Centre, established and supported under the Australian Government's Cooperative Research Centres Program, grant number CRCXX000001 (previously 20,180,101). The authors would also like to thank Griffith University for supporting this research by awarding GUIPRS scholarship.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgements

The author gratefully acknowledges the expert input of Benoît Danglede, Service Line Lead at INNOSEA and OWC France, for his valuable insights into floating solar technology development and its current and future prospects, which helped inform the context and interpretation of this research.

Appendix A. Supplementary data

Supplementary data to this article can be found online at <https://doi.org/10.1016/j.ocecoaman.2026.108199>.

Data availability

All the relevant data are available from online repositories:

BARRA Wind and Solar data set (<https://thredds.nci.org.au/thredds/catalog/ob53/output/reanalysis/AUS-11/BOM/ERA5/historical/hres/BARRA-R2/v1/1hr/catalog.html>).

CAWCR Wave Hindcast (https://data-cbr.csiro.au/thredds/catalog/catch_all/CMAR_CAWCR-Wave_archive/CAWCR_Wave_Hindcast_aggregate/catalog.html).

Bathymetry map of Australia (<https://ecat.ga.gov.au/geonetwork/srv/api/records/00648206-505c-4858-8b9d-c2324cc2c7ba>).

Collaborative Australian Protected Areas Database (CAPAD, 2022 – Marine) (<https://fed.dcceew.gov.au/datasets/af6299dce19846e5a8f1e0a577c163f2/about>).

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