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Research paper

Evaluation of Australian offshore wind and wave energy resources for joint exploitation

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ABSTRACT

The diminishing supply of fossil fuels and the critical need for environmental protection have increased the emphasis on renewable energy sources to achieve clean energy. Offshore wind and wave energy resources offer significant potential and consistent availability. This study explores the joint exploitability of these energy resources in the Australian offshore region using a two-stage framework. The first stage identifies hotspots based on energy resources potential, variability, cross-correlation, and their complementarity by providing a heatmap using over four decades of re-analysis and hindcast data. The second stage ranks the selected hotspots by assessing extreme weather conditions and site accessibility for operations and maintenance. The study identifies ten optimal sites, on the western and southern coasts of Australia, with high energy potential, low cross-correlation, low variability, high complementarity, and acceptable accessibility. Finally, the performance of four combinations of offshore wind turbines (OWTs) and wave energy converters (WECs) was analyzed at these hotspots. The results showed that the SWT-Wave Star combination generally outperforms others, while SWT-Wave Dragon is optimal in some cases. These combinations offer higher annual energy production, capacity factor, and manageable power variability, making them ideal for maximizing energy production and operational stability.

1. Introduction

The depletion of fossil fuels and the urgent need to protect the environment have prompted a growing focus on renewable energy sources in the pursuit of clean energy. As part of the remarkable array of renewable energy sources and a viable alternative to fossil fuels, ocean renewables such as offshore wind and wave energy offer a compelling solution to address energy and environmental challenges (Robertson et al., 2021).

Wind energy development has traditionally focused on onshore sites, but recently, offshore wind has gained significant attention and experienced remarkable economic growth (Patel et al., 2022). The vast expanse of available space which allows larger wind turbines to be installed and high capacity and more consistent offshore wind energy compared to onshore ones, coupled with limited noise disturbance and minimal visual interface, presents a favorable scenario for planners considering offshore wind energy farms (Wu et al., 2018; Caceoğlu et al., 2022; Zhou et al., 2024). Offshore construction presents increased challenges such as wind turbine accessibility and grid connection, and hence results in greater investment expenses compared to those of onshore projects (Messali and Diesendorf, 2009).

Wave energy possesses the capacity to emerge as a significant contributor to the ocean renewable energy mix owing to its notably higher energy flux compared to other marine renewables (Wen et al., 2022). The higher density, predictability and lower visual and environmental impact of wave energy resources make it a promising source of energy generation (Hadadpour et al., 2014; Kamranzad et al., 2016, 2017; Choupin et al., 2021). In addition, wave energy extraction devices offer the opportunity to serve in flood mitigation and coastal defense; and adapting to rising sea levels, in contrast to conventional coastal protection measures (Penalba et al., 2020). However, the Technology Readiness Level (TRL) of wave energy is relatively low (Ibarra-Berastegui et al., 2023; Selman-Caro et al., 2024) when compared to the more mature offshore wind one. Therefore, its

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exploitation technology has a higher levelized cost of energy (LCOE) (Astariz and Iglesias, 2015).

The inherent randomness and intermittency of offshore renewable energy resources negatively impact the efficiency of wind or wave farms. Hence, these fluctuations result in higher energy costs (Fusco et al., 2010). The combination of different offshore renewable energy resources, such as wind, wave, and solar energy, in offshore multi-source parks has been examined in various studies (e.g., Canales et al., 2020; Jonasson and Temiz, 2023; van der Zant et al., 2024), and their benefits have been discussed. This study focuses on the integration of wave and offshore wind technologies and their benefits. With future competition for limited marine space, conducting comprehensive assessments of these resources is essential (Robertson et al., 2021). Pairing complementary renewable energy options ensures a more reliable energy supply by minimizing power output variations and downtime (Rashidi et al., 2022). Shared infrastructures and facilities such as platforms, mooring systems, and grid connections result in a noteworthy reduction in construction, operation and maintenance costs and an efficiency improvement (Imperadore et al., 2024; Jiang et al., 2023). Optimizing spatial utilization and enhanced annual energy production are other benefits of deploying wind and wave energy farms together (Hu et al., 2020). Additionally, absorbing wave energy by Wave Energy Converters (WECs) can reduce the structural load on Offshore Wind Turbines (OWTs) and make their accessibility easier for operation and maintenance purposes (Erdinc and Uzunoglu, 2012; Veigas and Iglesias, 2013; Astariz et al., 2018). Hence, the integration of various renewable energy sources offers an effective remedy for the challenges faced by individual renewables and enhances energy utilization efficiency.

Studies on development of coupled offshore wind and wave energy focus on different aspects of wind-wave energy farm developments such as resource assessment (e.g., Fusco et al., 2010; Onea et al., 2017; Rusu and Onea, 2019a; Rusu, 2019; Gao et al., 2022; Li et al., 2022; Wen et al., 2022), tropical cyclones impact on the distribution and stability of wind and wave energy (Li et al., 2022), climate change impact on resources pattern in future (Ribeiro et al., 2020; Lira-Loarca et al., 2021), site selection considering various techno-economic, environmental, and social perspectives (e.g., Veigas et al., 2014; Cradden et al., 2016; Vasileiou et al., 2017; Loukogeorgaki et al., 2018; Patel et al., 2022), technological aspects of co-located systems (Pérez-Collazo et al., 2015). Among these aspects, resource evaluation is the preliminary and fundamental step when planning combined wind-wave energy farms. Many studies have focused on this, and the European offshore areas have mostly been considered as the case study (Hosseinzadeh et al., 2023). For example, Fusco et al. (2010) analyzed the raw wind and wave resources across different locations on Ireland's coast and introduced suitable locations for combined exploitability. A Co-location feasibility index was defined and applied by Astariz and Iglesias (2016, 2017) to select the best locations for wind-wave farm development off the Danish coast and the North Sea. Using this index, wind and wave energy resources were assessed concurrently in terms of their availability, correlation, and variability. Rusu and Onea (2019b) analyzed the distribution of wind and wave energy resources in some locations around Southern America and Europe. Ferrari et al. (2020) introduced an Exploitability Index (ES) for the initial assessment of wind and wave energy resources in the Mediterranean Sea. This index integrates the availability of resources and their correlation. Wen et al. (2022). Explored the feasibility of jointly established wind-wave projects based on long-term data along the coasts of South China Sea. A new index was introduced in their study in which in addition to wind and wave power availability and their correlation (as per Ferrari et al., 2020), the synergy index was also considered. The percentage of useful power production time was calculated by utilizing the synergy index. This involved establishing a threshold for wind and wave power, determined by the minimum wind speed and wave parameters required for most energy devices to commence generating electricity (known as 'cut in'). However, the mentioned study fails to account for the upper limit or 'cut out'—the threshold at which energy devices may require shutdown to prevent damage from excessively high wind or wave energies. In addition, there is an absence of examination of the wind and wave energy variability (directed towards energy conversion devices) within the proposed index. The individual variability of wind and wave energy, as somehow indicated by Astariz and Iglesias (2016, 2017), can substantially impact the operational costs of both OWTs and WECs. Hence, it is worthwhile to regard them as influential factors in investigating the suitability of wind-wave farms.

Australia hosts abundant and high-quality offshore wind resources that are comparable with regions such as the North Sea, recognized for its established offshore wind sector (Briggs et al., 2021). There are multiple studies in which different aspects of offshore wind project development have been evaluated in Australia and the most suitable locations have been selected (e.g., Messali and Diesendorf, 2009; Briggs et al., 2021; Golestani et al., 2021; Salvador et al., 2022; Gao et al., 2024). According to those studies, the ideal sites are off the Western Australian coast and predominantly in southern Australia. Australia is also acknowledged as one of the world's most promising regions for harnessing wave energy (Morim et al., 2014). The southern coastline of Australia is exposed to intense storms originating from the Southern Ocean and prevailing westerly winds, encompassing a substantial fraction of the world's wave energy resources (Gunn and Stock-Williams, 2012; Morim et al., 2014). Wimalaratna et al. (2022) conducted a review on the feasibility of developing wave energy as a renewable energy source in Australia, addressing the current limitations and challenges to achieving sufficient wave energy production in the country. According to this study, the primary barriers to expanding wave energy include the lack of high-resolution data, as well as social and environmental challenges.

To the best of the authors' knowledge, only one study has been conducted on combined wind and wave energy exploration in some specific locations of the Australian offshore region (Gao et al., 2022; Hosseinzadeh et al., 2023). Those locations have been previously proposed for wind farm projects or wave energy sea trials. Nonetheless, many sites along the coastline of Australia still lack sufficient investigation that thoroughly explores the combined wind and wave characteristics. In addition, a short time frame (7 years) was considered in the above-mentioned study which is less than the minimum duration of 10 years suggested by the International Electrotechnical Commission (International Electrotechnical Comission. IEC TS 62600-1012015). Hence, long-term periods, crucial for considering the long-term climatic changes for informed decision-making and sustainable development have been overlooked.

Long-term analysis provides a comprehensive understanding of wind and wave patterns, resource availability, and system behavior. For example, natural events such as El Nino and La Nina, which occur every 3–7 years, have a major influence on weather and climate conditions in Australia (ARC Centre of Excellence for Climate Extremes). Considering these shortcomings, a comprehensive analysis based on the long-term offshore wind and wave resources in Australia is a must. This will help bridge the gap in the existing literature, explore potential interactions between these resources, and pinpoint promising regions for future combined energy utilization in the entire Australian offshore area.

This study aims to evaluate the potential exploitability of offshore wind and wave energy resources across the entire Australian coast, using long-term data from 1979 to 2022 available from the Centre for Australian Weather and Climate Research (CAWCR) (Durrant et al., 2019). A new index is proposed, which improves the one proposed by Wen et al. (2022). This index incorporates the variability of energy resources and sets an upper limit (cut-out) for the synergy index to account for useful power production time and consider the operational costs associated with energy resource variability. As a result, a heatmap can be provided for the entire study region, highlighting the hotspots for the development of a combined wind-wave energy farm. Additionally, in the selected hotspots, extreme weather conditions and the accessibility of energy devices for operation and maintenance purposes are evaluated. These factors have been omitted for site selection in the Australian offshore area. Finally, to optimize energy production and operational efficiency of different combined wind-wave energy farms, the performances of four combinations of wind and wave energy devices are investigated.

2. Materials and methods

2.1. Study area and data characteristics

The extensive coastline in Australia presents significant opportunities for offshore renewable energy farm developments. This study is focused on the entire Australian offshore region due to significant offshore wind and wave resources, particularly in the southern latitudes, characterized by their exceptional quality and abundance (Briggs et al., 2021; Hemer et al., 2017).

The used wind and wave datasets originated from CAWCR ocean wave hindcast from 1979 to 2022 (44 years), were generated using wave watch III (Durrant et al., 2019). Version 4.08 of the wave model was used for the hindcast spanning from 1979 to May 2013, with the subsequent switch to version 4.18 from June 2013 onwards. The model was forced with global re-analysis NCEP CFSR and CFSv2 hourly winds respectively for durations of 1979–2013 and 2013 to 2022 as well as daily sea ice. The model was implemented on a global 0.4-degree (24 arcminutes) grid, with nested Australian and western Pacific sub grids of 10 and 4 arcminutes resolution. The current study employs a high-resolution marginal area of 4 arcminutes (equivalent to 7 km in the study area), extending from the shoreline to a distance of 150–370 km, varying depending on the specific location along the Australian coastline. It is worth noting that the used dataset has been validated by Hemer et al. (2017) invoking both in-situ buoy measurements and satellite altimeter observations. The validation results relative to altimeter data showed a strong overall correlation ($R = 0.928$) between the model and altimeter-observed significant wave heights. Their obtained negative bias (−0.04 m) indicated a tendency for the model to slightly underestimate altimetry values, with an average RMSE of 0.44 m around Australia. The used numerical model also aligned well with the available buoy observations, showing an average correlation coefficient of 0.86, an overall bias of 0.08 m, and an RMSE of 0.38 m for the significant wave height. Fig. 1 illustrates the expansion of the study area from the shoreline along with the corresponding bathymetry (Whiteway, 2009).

Collaborative Australian Protected Areas Database (CAPAD) 2022 –Marine data was used to exclude those areas from the study region as it conflicts with the development of offshore renewable energy farms.

2.2. Analysis methodologies

The estimation of wind energy potential relies on the calculation of Wind Power Density (WPD) per unit of swept area, which is determined as (Ferrari et al., 2020; Kalogeri et al., 2017):

$$P_{wind} = \frac{1}{2}\rho_a v^3 \tag{1}$$

where ρ_a is the air density assumed as 1.23 kg/m^3 (Ferrari et al., 2020; Wen et al., 2022) and v is the wind speed at hub height of OWT. Based on the literature and the height of available wind resources for most of OWTs, the hub height of 100 m (Gao et al., 2022; Wen et al., 2022) was considered.

Since the CAWCR wave hindcast model provides wind data only at 10 m, it is required to obtain wind speed at a hub height of 100 m. Using the power law (Hsu et al., 1994; Wen et al., 2021) the wind speed is extrapolated to a height of 100 m (z_{100}):

$$v = U_{10}\cdot\left(\frac{z_{100}}{z_{10}}\right)^{\alpha} \tag{2}$$

where U_{10} is the wind speed at a reference height of 10 m (z_{10}) and α is the friction coefficient, assumed to be 0.1 under open water terrain (Gao et al., 2022; Masters, 2013).

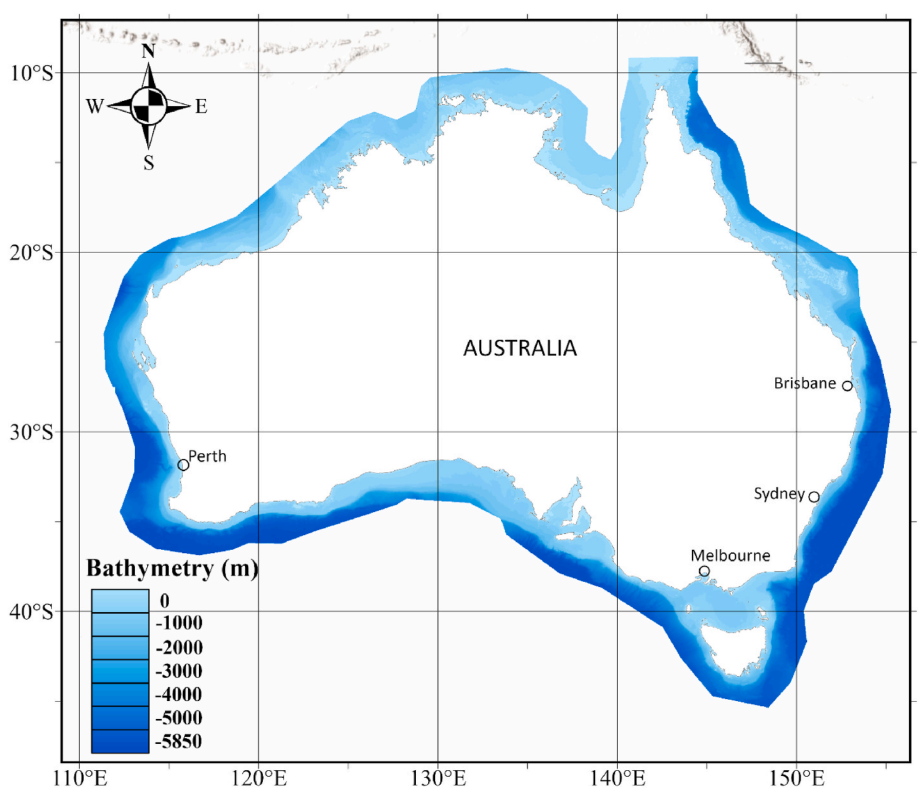

Fig. 1. Study area and corresponding bathymetry.

Using the linear wave theory, Wave Power Flux (WPF) (power per unit of crest width, kW/m) was calculated as (Besio et al., 2016; Hemer et al., 2017):

$$P_{wave} = \frac{\rho_w g^2}{64\pi} H_s^2 T_e \tag{3}$$

where ρ_w shows the water density, g represents the gravitational acceleration, H_s is significant wave height and T_e is wave energy period.

In the literature, an event-based method has been used to evaluate the complementarity between two resources such as offshore wind and solar (Prasad et al., 2017; Soukissian et al., 2021) and offshore wind and wave (Kardakaris et al., 2021; Wen et al., 2022). Based on this method, the rate of occurrence of two energy resources (e.g. wind and wave energy) above their respective Electrical Generation Threshold (EGT) is estimated and used to assess the synergy of resources. The used EGT was considered based on the power curve/matrix of widely used WTs/WECs and their maximum starting wind speed/pairs of H_s and T_e (Wen et al., 2022). In the case of the WPD/WPF being higher than the EGT, the availability and persistence of the resource could meet its development. However, it should be mentioned that energy devices are operating in a range of wind speed/wave climate and are stopped operating (cut-out) in extreme value due to safety concerns. Therefore, the minimum and maximum values of wind speed as well as significant wave height were used in this study to define the synergy index as the lower and upper bound of device operation. After investigation of different devices, the wind speeds between 5 m/s and 25 m/s (Wind turbines database; Weiss et al., 2018; Wen et al., 2022, 2021) and significant wave heights between 0.5 m and 4 m (Kamranzad and Hadadpour, 2020; Lavidas et al., 2018) were selected for their operational ranges. Based on the identified lower and upper limits of wind speed and wave height, the wind and wave synergy index (*WIWAS*) is stated as follows:

$$WIWAS = \frac{\text{Number of hours with } 5\,\text{m/s} < \text{v} < 25\,\text{m/s or } 0.5\,\text{m} < H_s < 4\,\text{m}}{\text{Total number of hours}} \times 100 \tag{4}$$

This index represents the percentage of time when wind or wave energy can be harnessed. Areas with high WIWAS values are more reliable and have longer operating time windows, making them more suitable for combined wind-wave farms.

The variability poses challenges for grid integration and stability, conversion efficiency as well as safety and durability of offshore devices (Astariz and Iglesias, 2017; Lavidas, 2020). In order to evaluate wind and wave power variability, the Coefficient of Variation (*CoV*), the ratio between the standard deviation of wind/wave power and its corresponding mean value was used.

A key factor for the joint exploitation of wind and wave energy resources is their diversification. It is not desirable to have a high correlation with a short time lag since in this case the wind and wave are highly synchronized, and the power peak and valley occur simultaneously. The wind and wave energy resources with low correlation can complement each other and reduce the power output variation and make it smooth (Gao et al., 2022). Therefore, the Pearson cross-correlation (Fusco et al., 2010) was used to calculate the correlation of resources as:

$$C(\tau) = \frac{1}{N} \sum_{k=1}^{N-\tau} \frac{[x(k) - \mu_x] \cdot \left[y(k+\tau) - \mu_y\right]}{\sigma_x \sigma_y} \tag{5}$$

where, N represents the length of sample data, and τ refers to the time lag between wind power density (x) and wave power density (y). μ_x, μ_y and σ_x, σ_y are the mean values and standard deviations of WPD and WPF, respectively. $C\ (\tau)$ refer to correlation at time-lag of τ can vary between -1 and 1 and C (0) shows the instantaneous ($\tau = 0$) cross correlation.

The suggested index in this study is a modification of a preceding work (Wen et al., 2022), with an emphasis on incorporating the variability of energy resources. The Suitability Index (*SI*) was defined as:

$$SI = \frac{\left(C_{wind}\frac{\overline{P}_{wind}}{max(\overline{P}_{wind})} + C_{wave}\frac{\overline{P}_{wave}}{max(\overline{P}_{wave})}\right) WIWAS}{(CoV_{wind} + CoV_{wave})\ e^{C(0)}} \times 100 \tag{6}$$

Here, C_{wind} and C_{wave} represent the weighted factors of WPD and WPF (their sum is 1). The assignment of values to these parameters depends on the weightage of wind and wave power usage in the combined energy farms. In this study, it is assumed that wind and wave energy developments have the same proportion ($C_{wind} = C_{wave} = 0.5$) as per (Wen et al., 2022). $\overline{P}_{wind}$ and $\overline{P}_{wave}$ denote the average values of wind and wave power calculated over a period of 44 years. As $C(0)$ values span from -1 to 1, an exponential function was implemented to guarantee that the output values are always positive (Wen et al., 2022). CoV_{wind} and CoV_{wave} serve as dimensionless indicators of individual variability in the input wind and wave energy destined for energy conversion devices. Considering the variability of each energy resource is crucial in the site selection process as it significantly affects the operational expenses of energy conversion devices (Astariz and Iglesias, 2016, 2017). The values of CoV_{wind} and CoV_{wave} can vary between 0 and any positive value. Considering all the indicator values employed in Eq. (7), the *SI* ranges from 0 to infinity, with a higher *SI* indicating a more suitable location for the combined exploitation of wind and wave energy.

After providing a heatmap for the entire study region obtained from *SI* and selecting the most optimal locations, the accessibility of Energy devices for Operation and Maintenance (O&M) purposes as well as the extreme event condition as representative of the design wave of energy devices were evaluated in this study to re-rank the selected locations. Evaluating accessibility is essential to identify the optimal time when sea conditions allow for the safe deployment of crews and vessels (Kamranzad et al., 2021; Kamranzad and Hadadpour, 2020; Lavidas et al., 2018). This is determined by the percentage of time when the wave height at a location is at or below a certain threshold. Such thresholds are generally set at 1–3 m, within which the majority of vessels can operate (Lavidas et al., 2018). In this study, $Hs = 1.5$m as the accessibility threshold and the 99th percentile of *Hs* as the extreme event condition were considered (Kamranzad et al., 2021). Therefore, the most suitable locations selected in the first stage of analysis were re-ranked by a suitability index considering wave climate (SI_w) expressed as:

$$SI_{w=}\ SI \times \text{percentage of time with } H_s < 1.5\,m \times \frac{\min\ (Hs_{99th} percentile)}{Hs_{99th} percentile} \times 100 \tag{7}$$

2.3. Energy devices selection for performance analysis

Two common commercial wind turbines including Gamesa G128 5 MW (Ferrari et al., 2020; Gao et al., 2022) and SWT-6.0-154 6 MW (Wen et al., 2022), which can be deployed in both onshore and offshore conditions, are used in this study and their power curve are shown in Fig. A.1.

For the harnessing of wave energy resources, the Wave Star C6 600 kW, which has been commercially tested and recognized as a relatively mature technology (TRL 7) (Gao et al., 2022; Pecher, 2017), as well as the Wave Dragon 6 MW, noted for its productivity and performance (Kamranzad et al., 2021; Veigas et al., 2015; Wen et al., 2022), were selected as WECs. The power matrix and performance characteristics of these WECs are provided in Fig. A. 2 and Fig. A. 3 in the appendix.

The study examined the performance of four different combined wind-wave energy farms using selected OWTs and WECs. A total rated power of 60 MW was considered for each combined wind-wave farm, with the number of each device adjusted to achieve a 50 % wind and 50 % wave energy distribution.

3. Results and discussion

3.1. Wind and wave power potential

As seen in Fig. 2, the offshore wind energy potential is highest in the southern coastal regions of Australia, particularly near Tasmania and southern Victoria. The southern Tasmania areas exhibit mean WPD exceeding 1800 W/m^2, highlighting a significant potential for wind energy extraction. In contrast, the northern and northeastern coastlines show considerably lower mean WPD values, around 10 W/m^2 especially in the northwest region, indicating limited wind energy potential in these regions. The highest mean WPF values are concentrated in the southern coastal regions as well (Fig. 3). For instance, the southern part of Tasmania exhibits maximum values up to 103 kW/m, indicating a significant potential for wave energy extraction. Regions around major cities such as Melbourne and Perth in the south and southwest show moderate to high mean WPF values. Conversely, the northern and northeastern coastlines display much lower mean WPF values, suggesting limited wave energy potential in these regions. These findings are consistent with those obtained by (Gao et al., 2022).

3.2. Complementarity of wind and wave energy

To examine the complementarity between offshore wind and wave energy resources, the synergy index values for the entire study region are illustrated in Fig. 4. As seen, the temporal synergy between wind and wave resources increases from the northern to southern regions, reaching its peak value (almost equal to 1). The synergy observed on the southern, western, and eastern coasts of Australia makes these areas highly attractive for wind and wave projects. However, from a technological standpoint, areas with low values of *WIWAS*, such as the northern region and nearshore areas of the northeast and northwest, are not recommended. This is because neither the wind nor wave sources there support effective and smooth energy production with non-operational periods.

3.3. Variability of energy resources

Figs. 5 and 6 illustrate the variability of wind and wave energy resources across the study region using *CoV*, respectively, highlighting their significance as cost drivers in renewable energy systems (Astariz and Iglesias, 2016; Sjolte et al., 2013). Fig. 5 reveals that the northeast and western parts of Australia exhibit the lowest wind energy variability, with *CoV* values around 0.9. These areas are particularly favorable for wind farm deployment due to the more stable wind conditions, which can lead to more predictable energy outputs and potentially lower costs associated with energy storage and grid integration. However, the northwest region displays considerably higher wind energy variability, with *CoV* values reaching up to 2.4 in some areas. This indicates that wind climate in those areas is nearly three times more variable compared to areas with the lowest variability. Such high variability poses challenges for wind energy exploitation, as it is not stable and may necessitate additional investments to manage the fluctuations and maintain a stable energy supply. The eastern and southern parts of the study region exhibit moderate *CoV* values, suggesting balanced variability. These areas could be suitable for wind energy projects but may need tailored strategies to manage the moderate variability.

As displayed in Fig. 6, the western, southern, and eastern parts of Australia have low wave energy variability, with the lowest *CoV* of about 0.4 in the western region. This suggests that wave energy in these regions is relatively stable and predictable, making them ideal for the deployment of wave energy projects.

In contrast, the northern coasts of Australia, exhibit the highest wave energy variability, with *CoV* values reaching up to about 13. This is a significantly higher variability compared to that of the western region. Such high variability indicates that wave conditions in these northern coastal areas have large fluctuations, which poses substantial challenges for energy exploitation and reliability.

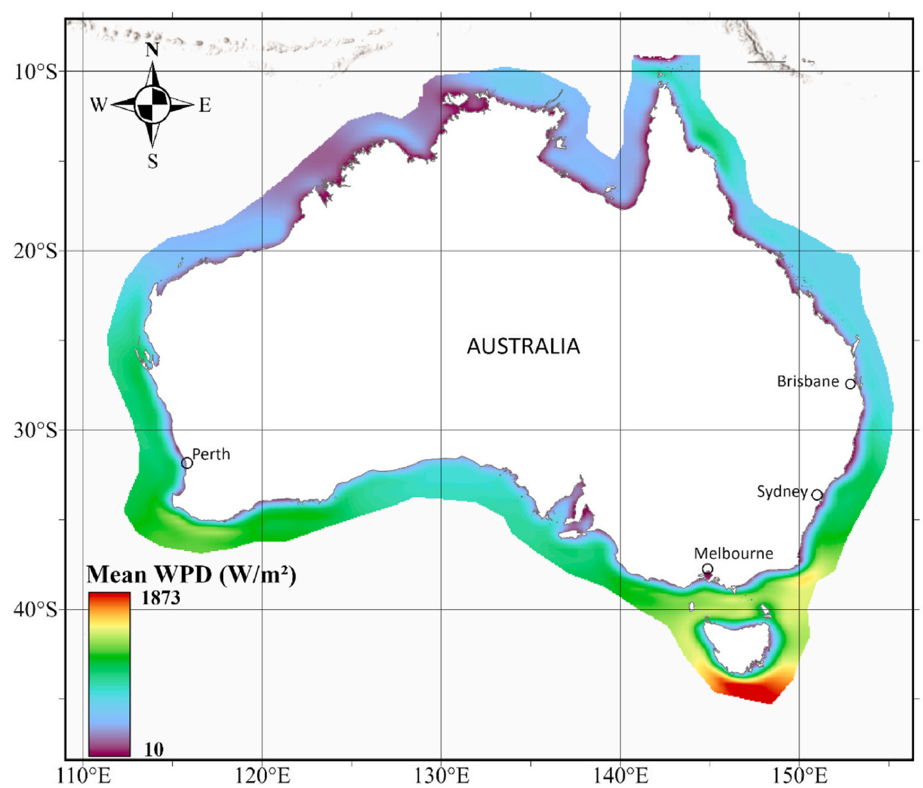

Fig. 2. Mean Wind Power Density, WPD (W/m^2) for the period of 1979–2022.

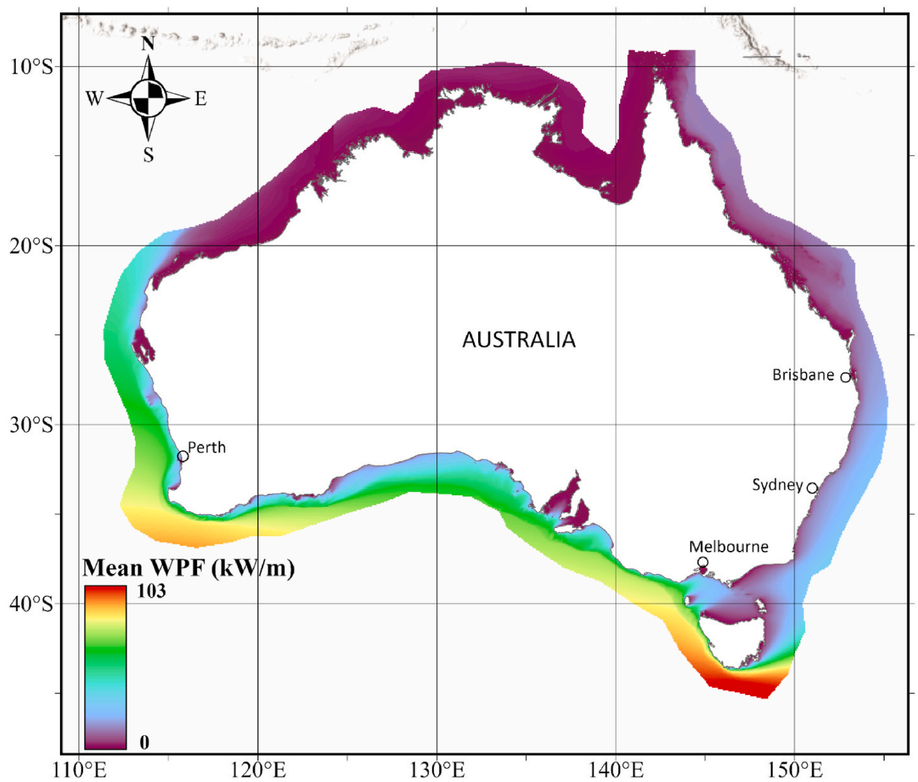

Fig. 3. Mean Wave Power Flux, WPF (kW/m) for the period of 1979–2022.

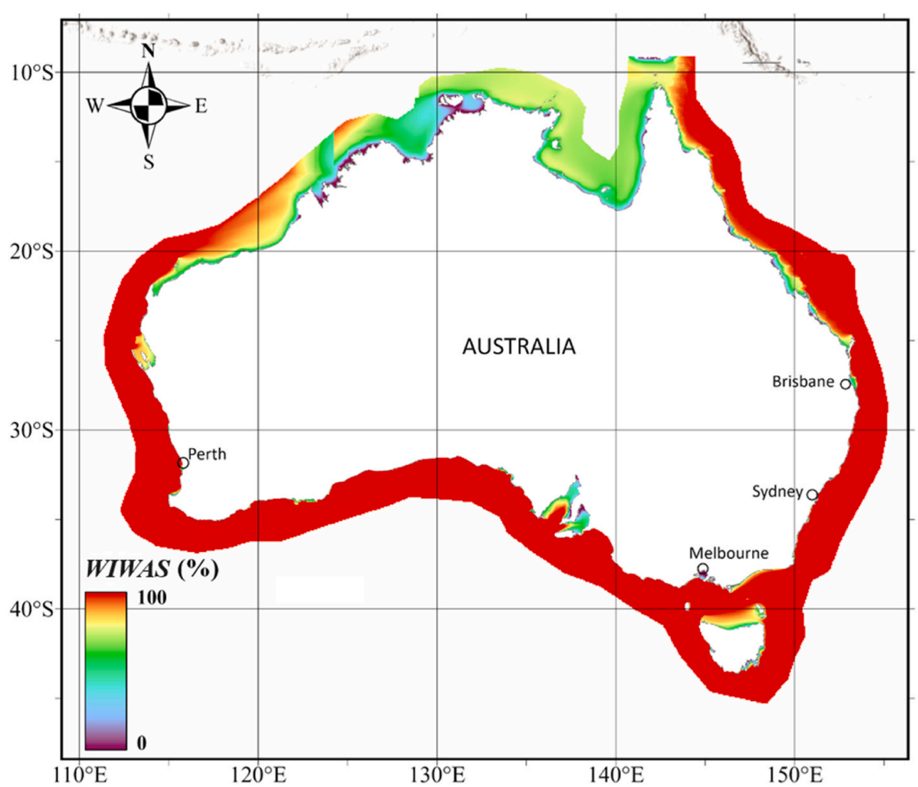

Fig. 4. Wind and wave power synergy index, *WIWAS* (%).

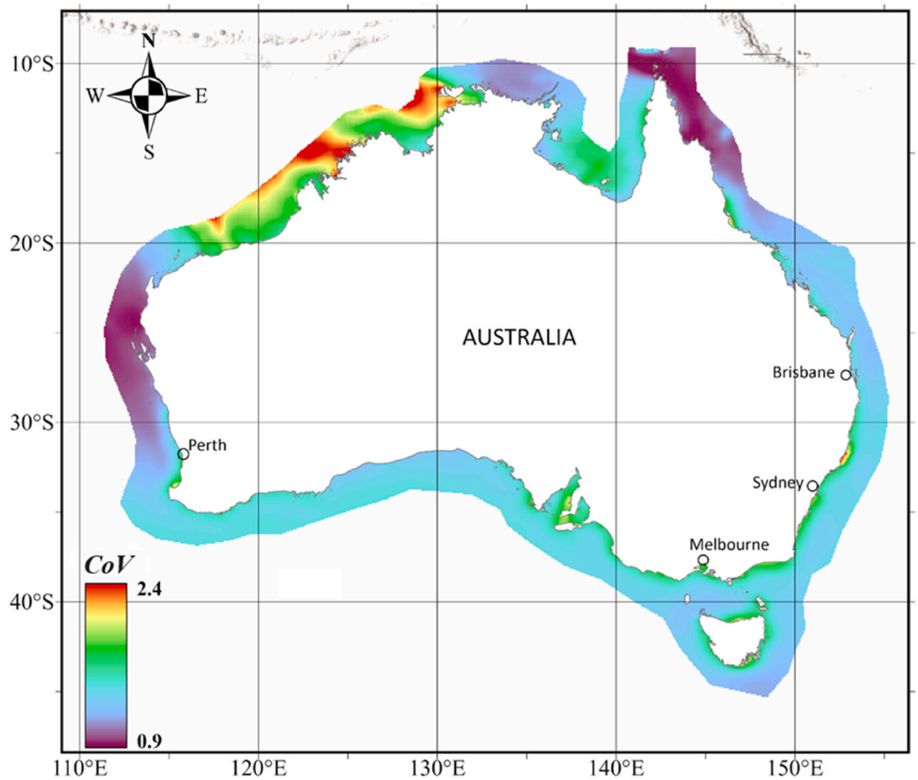

Fig. 5. Coefficient of variation, *CoV* of wind power density.

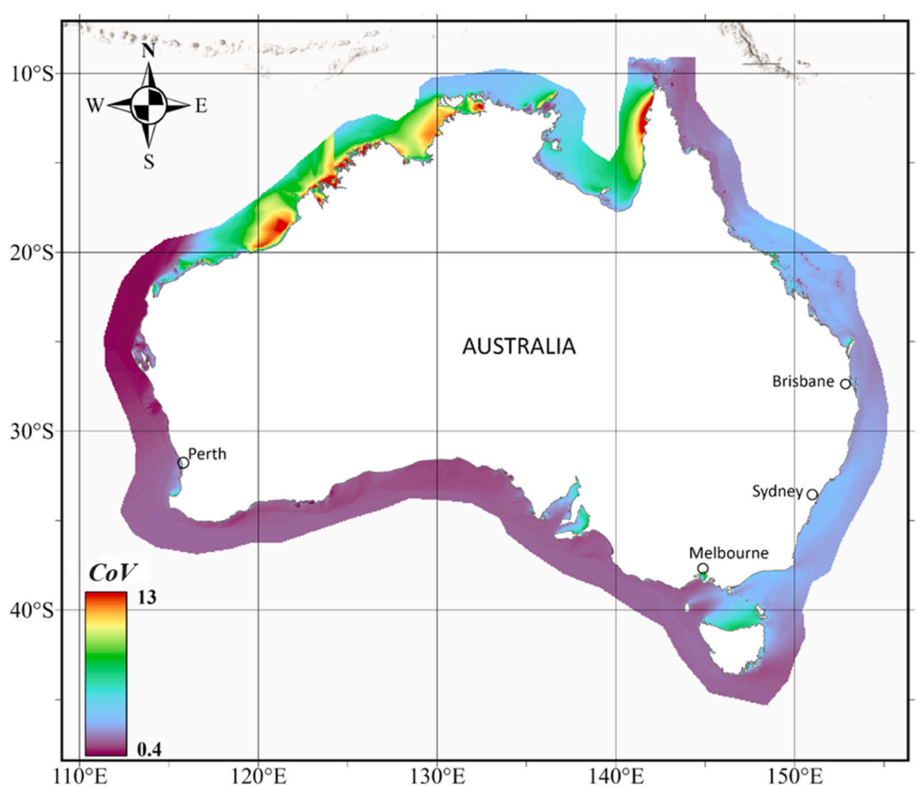

Fig. 6. Coefficient of variation, *CoV* of wave power flux.

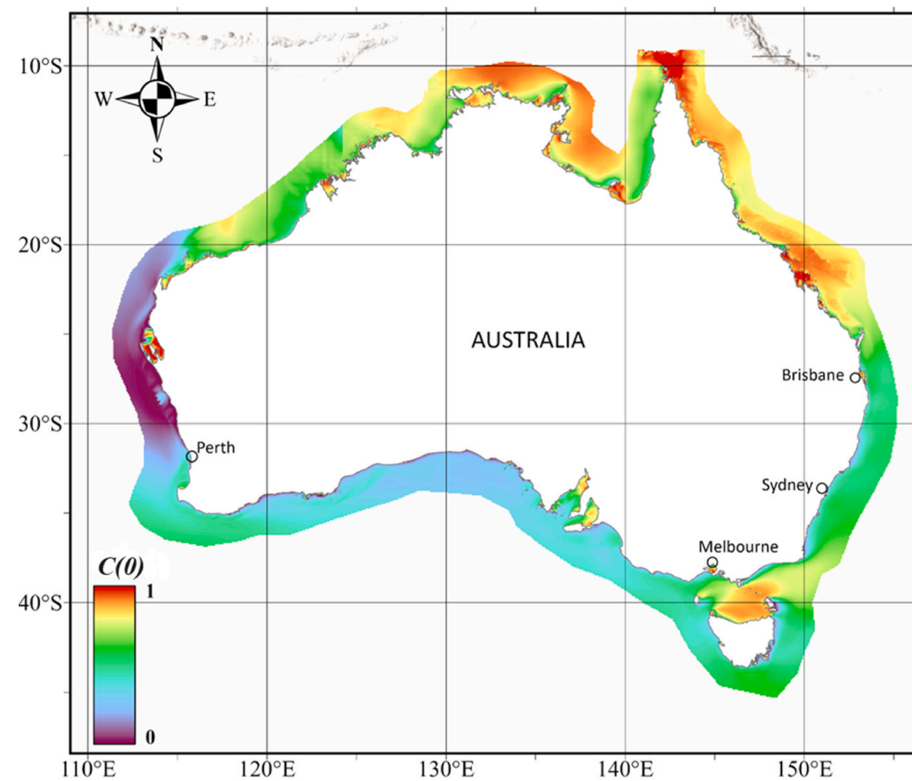

Fig. 7. Instantaneous cross-correlation, $C(0)$, between wind and wave power.

3.4. Correlation between wind and wave energy resources

The combined utilization of various offshore energy resources has the potential to enhance overall energy yield (Lund, 2006; Ferrari et al., 2020) and minimize power output variability, particularly when these resources exhibit low or negative correlation (Stoutenburg et al., 2010; Kalogeri et al., 2017; Prasad et al., 2017). The instantaneous cross-correlation, $C\,(0)$, was calculated and the results are presented in Fig. 7. As seen, the western offshore areas of Australia are identified as the most suitable regions for the joint extraction of wind and wave

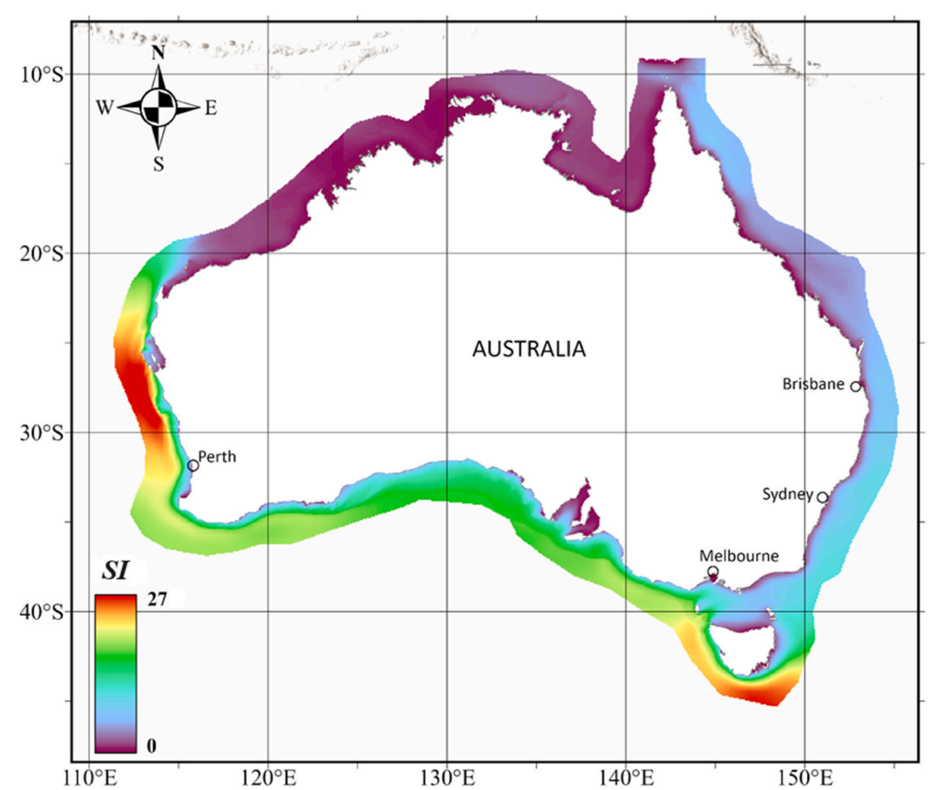

Fig. 8. Suitability index, *SI*.

energy due to their lowest *C* values between wind and wave energy resources. A low correlation indicates that the peaks and troughs of wind and wave energy do not coincide, leading to more stable conditions for energy production. Such stability of power output, as well as a minimal period of zero power production, makes these regions ideal for integrating both wind and wave energy systems.

However, the southern offshore areas exhibit low to moderate correlation values. This suggests that while there is some level of synchronization between wind and wave energy, it is not as pronounced as in other regions. As a result, these areas can still benefit from joint energy extraction, although the degree of stability in energy production may be slightly lower. The northern and eastern offshore areas and some areas between Victoria and Tasmania show relatively high correlation values compared to other areas, with some specific areas reaching correlation coefficients close to 1, as indicated by the red color in Fig. 7. High correlation leads to higher variability in power output as well as a higher non-operational time of energy devices, which is unfavorable.

3.5. Site suitability assessment

A two-stage analysis was conducted in the present study by incorporating the cut-out values of energy devices, variability of energy resources, and impact of extreme events and operation accessibility. This comprehensive approach provides a more accurate assessment of the potential of joint exploitation of wind and wave energy resources in offshore environments.

In the first stage of the analysis, an enhanced *SI* that encompasses wind and wave energy potential, their correlation, variability, and an updated synergy index considering the cut-out value of most energy devices was developed. This index provides a heatmap that highlights energy farm hotspots (see Fig. 8).

The distribution of the *SI* with $C_{wind} = C_{wave} = 0.5$ is shown in Fig. 8. As seen, *SI* values range from 0 to 27, with higher values indicating more suitable locations. The most suitable areas (*SI* close to 27), marked in red, are predominantly found off the western coast and southern coast of Tasmania particularly because of having high potential of energy resources, lower variability and correlation as well as the higher percentage of useful power production (see Figs. 2–8). The regions shown in green to yellow colors have moderate to high suitability index and are scattered along the southern coastlines and some parts of the western coast. Moderate *SI* values suggest a balanced potential where both wind and wave resources can be harnessed effectively, although with some variability and correlation. Areas with low *SI* values are depicted in blue to purple colors ($SI < 0.1$), located along the northern and northeastern coasts. These regions show limited potential for combined wind and wave energy exploitation.

Marine protected areas (MPA) are major restricted zones for offshore renewable energy development. Therefore, these areas are excluded to ensure that the identified locations are feasible for energy infrastructure deployment without significant regulatory and ecological conflicts (Fig. 9).

The water depth range of 20–60 m is critical for the feasibility of offshore energy devices, as it aligns with deployment specifications of the most commercial wind and wave energy systems (Wen et al., 2022). This depth range balances the technical and economic aspects of installation and maintenance. Therefore, the areas with 20 m < water depth <60 m were extracted from Fig. 9 as shown in Fig. 10. As can be seen from Fig. 10, ten optimal locations for the deployment of combined wind-wave energy farms were identified. As seen, the most suitable areas are located along the western and southern coastlines.

The geographic information and specific *SI* of these selected locations are detailed in Table 1. As shown, Western Australia dominates the list with eight sites (A to H). Tasmania and South Australia each have one site (J and I, respectively), showing some geographic diversity but with lower *SI* compared to those of Western Australia in the considered water depth range.

It is also evident from Table 1 that site B has the highest suitability index, making it the most favorable location for combined wind-wave energy farm deployment. However, its longest distance from the mainland of Australia, where the grid connection exists, could be the other

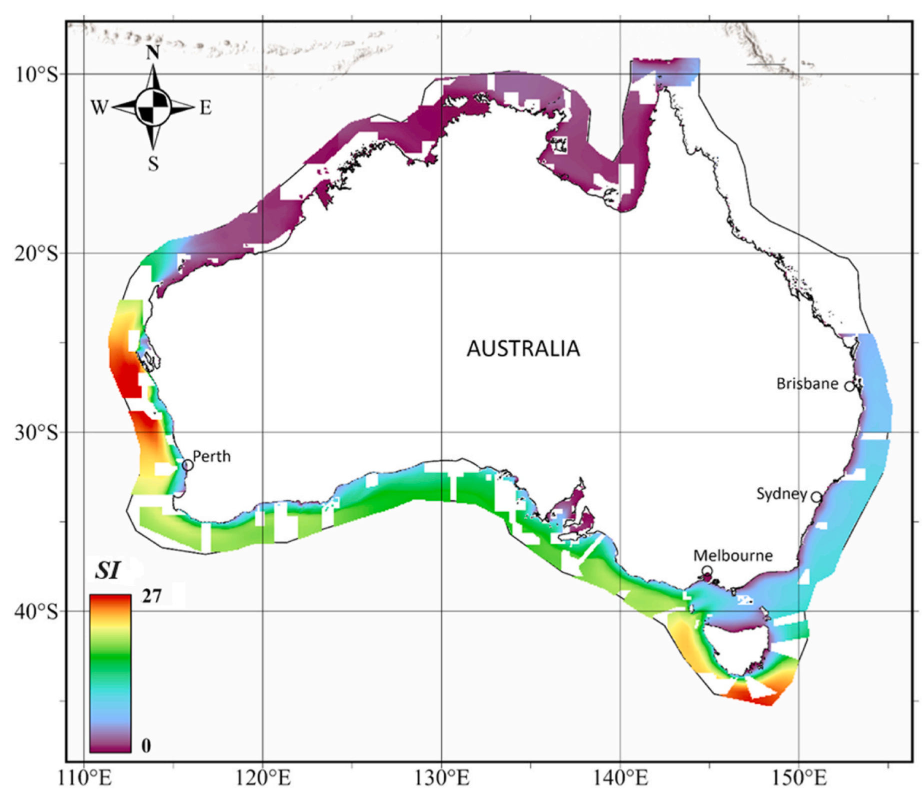

Fig. 9. Suitability index, *SI*, excluding marine protected areas.

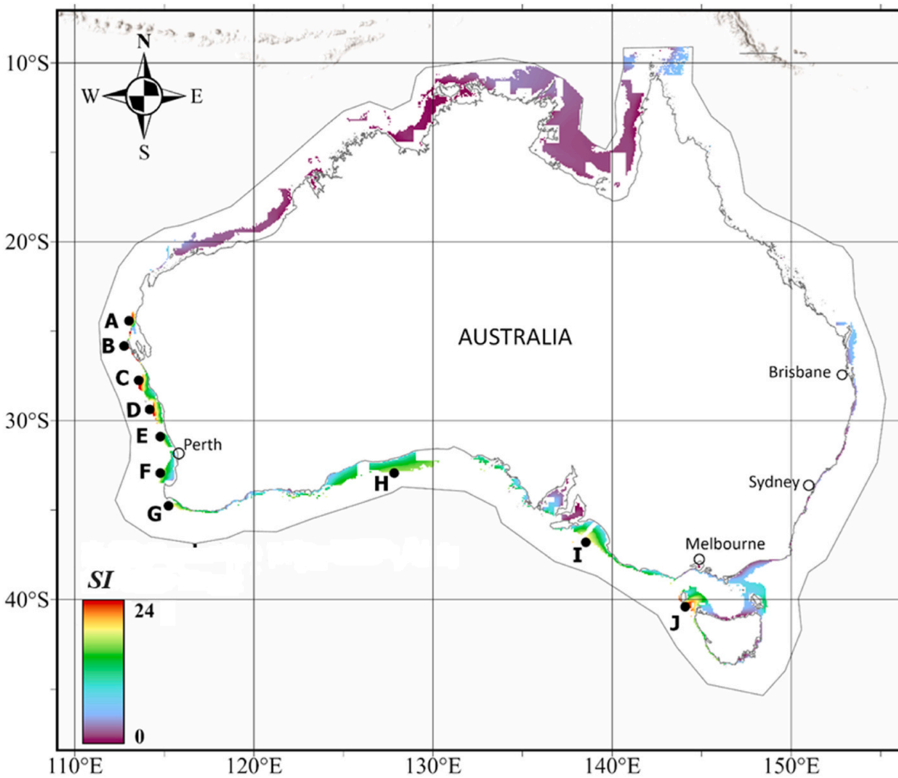

Fig. 10. Suitability Index, *SI*, for entire region excluding Marine Protected Areas with 20 m < water depth <60 m, and selected hotspots (A to J).

Table 1
Geographic information and suitability index, *SI*, of selected sites.

Sites	*SI*	Rank	Lat(° S)	Long(° E)	State	*Depth* (m)	*DC*[a] (km)
B	23.9	1	25.92	113.02	WA	~ 60	~ 105
C	21.7	2	27.92	113.6	WA	~ 56	~ 50
D	21.0	3	29.46	114.27	WA	~ 56	~ 67
J	19.7	4	40.33	144.08	TAS	~ 60	~ 69
A	19.5	5	24.32	113.13	WA	~ 60	~ 27
G	16.3	6	34.72	115.33	WA	~ 50	~ 42
I	15.9	7	36.66	138.48	SA	~ 60	~ 116
E	14.5	8	30.72	114.86	WA	~ 49	~ 26
F	14.1	9	32.99	114.88	WA	~ 60	~ 74
H	13.6	10	32.86	127.67	WA	~ 53	~ 75

[a] Distance to Coast (*DC*).

criterion making it less suitable compared to others (for example c). This needs to be considered in future studies as this study has focused on resource assessment and considering other spatial criteria is out of the scope of the current study. Site C is the second most suitable location, with a water depth slightly less than Site B and a significantly closer distance to the coast. Its proximity to the coast could be beneficial for infrastructure and maintenance. Site E has the shallowest water depth (49 m) and the closest distance to the coast (26 km) among the lower-ranked sites, which may still offer some logistical advantages.

It is important to note that while a high suitability index in Table 1 indicates promising sites, other factors such as extreme weather events and accessibility for operation and maintenance must also be considered when ranking these sites. These factors were included in SI_w as the second stage of analysis, to ensure that the identified sites are sustainable and resilient in the long term (see subsection 2.2). Table 2 shows the statistical characteristics and the ranking of selected locations based on wave climate (SI_w). As shown, site A was identified as the most suitable location with the highest SI_w. This is attributed to its higher accessibility rate (7.9 %) and lower Hs_99th percentile (4.3 m), which facilitate operation and maintenance, reduce construction costs, and minimize the risk of damage or failure during extreme weather conditions. Site C maintains its rank despite its significantly lower SI_w compared to Site A, mainly because of its relatively higher accessibility rate compared with other sites. Site B, while initially ranking as the best site (see Table 1), was subsequently downgraded to rank three (Table 2). This was primarily due to its significantly lower accessibility rate (3.6 %) compared to sites A (7.9 %) and C (5.1 %), which affects the operational

Table 2
Statistical characteristics of selected locations and re-ranking them considering accessibility and extreme event condition.

Sites	SI_w	Rank_w	$\overline{P}_{wind}$ (W/m^2)	$\overline{P}_{wave}$ (kW/m)	*WIWAS* (%)	Accessibility (%)	$H_{s\_99th\ Percentile}$ (m)	*C (0)*	CoV_{wind}	CoV_{wave}
A	2.13	1	856	33	99.9	7.9	4.3	0.18	0.94	0.72
C	1.32	2	992	40	99.6	5.1	5	0.16	1.03	0.78
B	1.06	3	1014	42	99.7	3.6	4.8	0.15	0.99	0.71
D	0.68	4	1021	48	99.4	5.1	6.3	0.48	1.24	0.95
E	0.61	5	558	51	98.7	4.2	6	0.26	1.2	0.87
F	0.59	6	877	51	99	2.7	5.7	0.17	1.1	0.80
H	0.44	7	837	41	99.5	3	5.5	0.37	1.29	0.84
I	0.39	8	962	56	99.3	2.6	6.4	0.43	1.28	0.87
J	0.15	9	1343	69	99.1	0.9	7.1	0.5	1.20	0.91
G	0.14	10	1081	66	98.7	1	7	0.49	1.33	0.91

and maintenance aspects of the energy devices. Site J, located in the northwest of Tasmania, features the highest available wind (1343 W/ m^2) and wave (69 kW/m) energy resources. However, due to its lowest accessibility rate (0.9 %) and highest Hs_99th percentile (7.1 m), it has been significantly downgraded from rank 4 to rank 9. In contrast, Site D has been upgraded, moving from rank 9 to 4, thanks to its relatively higher accessibility rate. Overall, the ranking using SI_w suggests that Western Australia offers more suitable locations for the deployment of combined offshore wind and wave energy resources compared to the southern areas.

It should be mentioned that the intra-annual and seasonal variabilities of mean wind power density and mean wave power flux have been implicitly considered by incorporating the variability of wind (CoV_{wind}) and wave energy (CoV_{wave}) resources over the 44 years. In addition, based on the following studies that have investigated the seasonal variability (Fig. 3 of Morim et al., 2014) and the monthly variability (Fig. 11 of Hemer et al., 2017) of wave energy in Australian offshore areas, the selected locations in the western part of the study area in the current paper have similar variability. This implies that considering their seasonal/monthly variability does not impact their rankings. The locations G and J, which were ranked last in the current study, also align with the findings of the aforementioned studies as they have more seasonal/monthly variability. To investigate the seasonal variability of wind resources and verify if the selected locations maintain their rankings, the seasonal mean wind power density of all selected locations was obtained. The coefficients of variation of these seasonal mean values were calculated and used as input (instead of the variability over the entire 44-year duration) in the proposed index. The suitability index, based on seasonal variability ($CoV_{seasonal\ wind}$), was calculated and denoted as SI_{ws}. Table A. 1 compares the rankings of sites based on SI_{ws} with those based on SI_w.

As shown in Table A. 1, the consistency in rankings for sites A through I indicates that their suitability for wind resource exploitation is stable across different seasons. The only exceptions are sites J and G, which switched their ranks. However, the change in their positions is minor, as indicated by the small difference in their suitability indices.

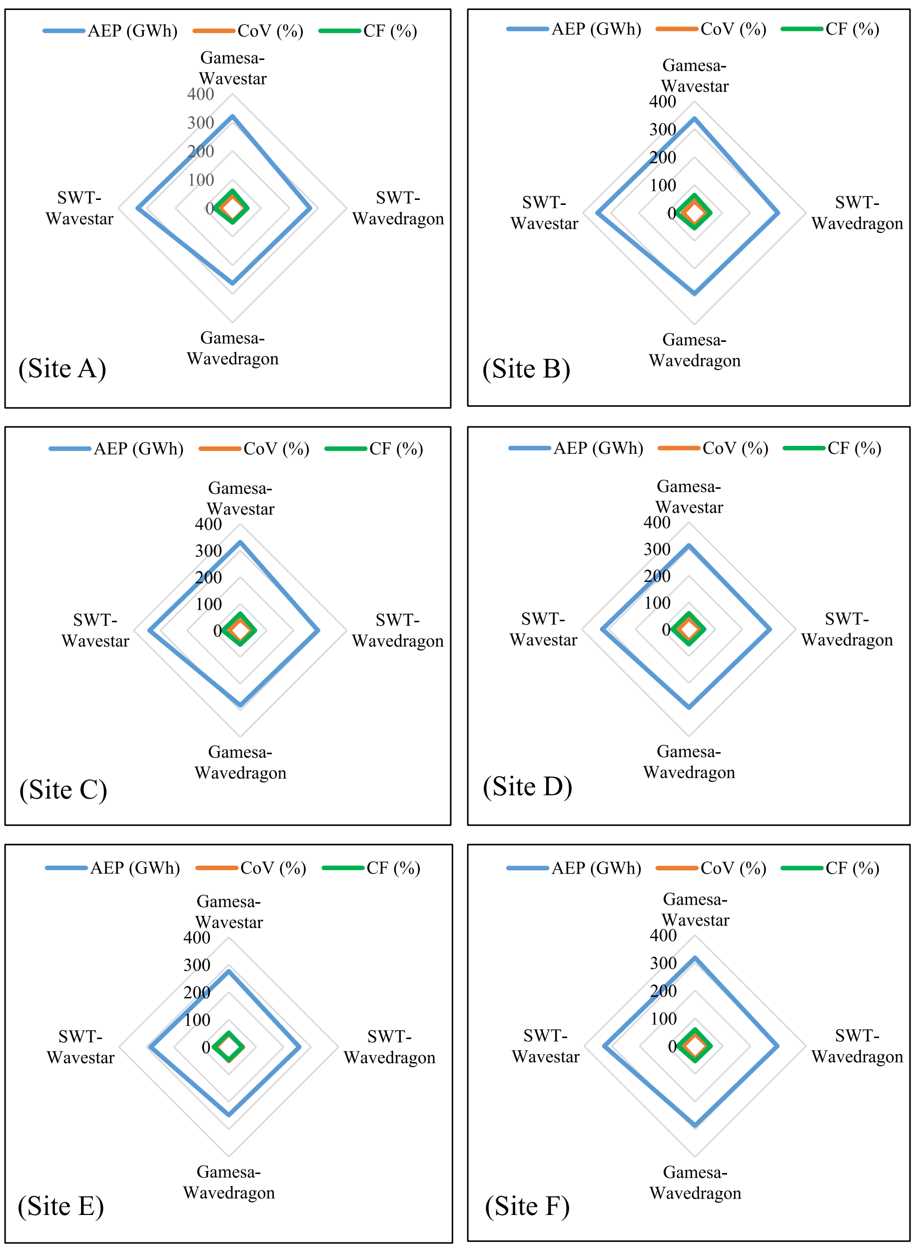

Fig. 11. Performance of different combined wind-wave energy farm at hotspots using comparison metrics: *AEP* (GWh), *CF* (%), and *CoV* (%).

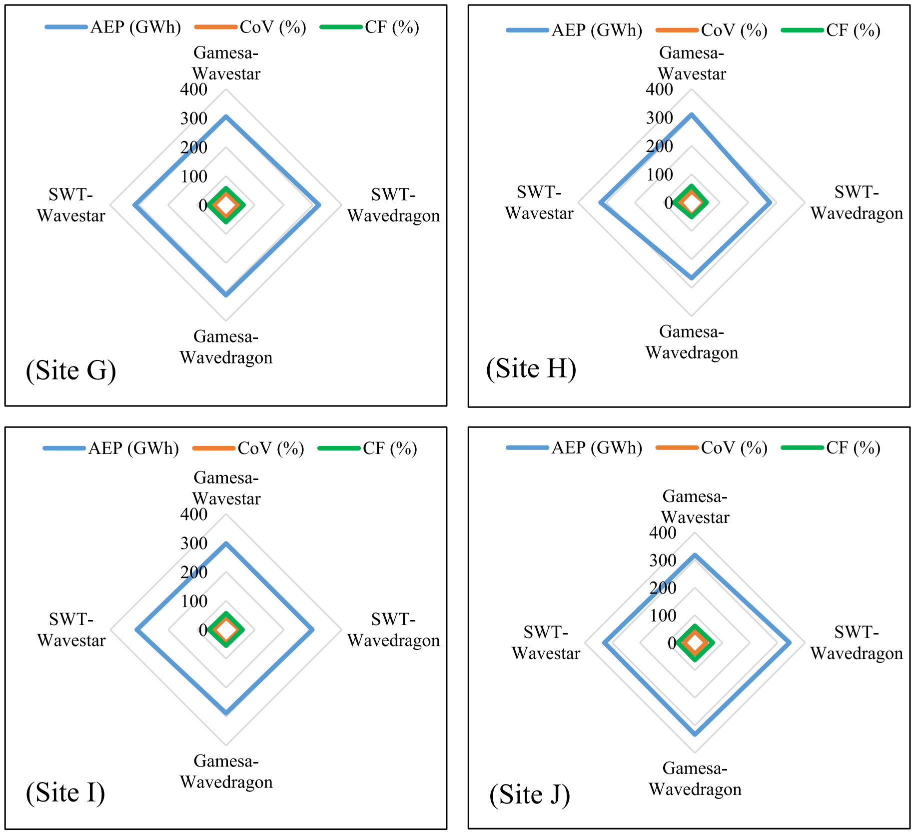

Fig. 11. (*continued*).

This suggests that the seasonal variability of wind energy resources does not significantly impact the overall ranking of most sites. Nonetheless, the shift between sites J and G highlights that, for some low ranked sites, seasonal variability may play a role in their suitability and should be considered in final decision-making processes.

It is worth noting that the current study focuses on using re-analysis data to evaluate the joint wind and wave energy potential, rather than applying the impact of climate change and future projections on decision making procedures. The shorter time spans for such evaluation would certainly impact the results as depicted in Kamranzad et al. (2022). They showed that the selection period for evaluation of wave energy will significantly affect the assessment of available resources, and hence, the recommended 10-year period by the International Electrotechnical Commission (IEC) for wave energy assessment is insufficient for detecting the influence of climate variability. Therefore, in this study, it has been chosen to perform the evaluation based on several decades of available re-analysis data to minimize the impact of climate change.

3.6. Device pairing

In this section, different combined 50 %wind-50 %wave energy devices including Gamesa-Wave Star, SWT-Wave Dragon, Gamesa-Wave Dragon, and SWT-Wave Star were compared for each location to find the best one (refer to section 2.3 for more details). Annual Energy Production (*AEP*), Coefficient of Variation (*CoV*), and Capacity Factor (*CF*) were employed as comparison metrics. The results of analysis were given in Table 3. The analysis of shows that the most suitable combination of energy devices varies depending on the location. SWT-Wave Star demonstrates superior performance in most cases, while SWT-Wave Dragon does so in a few cases due to their high *AEP* and *CF*, as well as lower and manageable variability. These combinations are recommended for maximizing energy production and ensuring stable operation in offshore wind and wave energy farms. The findings for sites G and J (Table 3) indicate that SWT-Wave Dragon outperforms other combined wind-wave farms, and offers superior energy production (321 GWh and 343 GWh) and capacity factor (61 % and 65 %), despite having

Table 3
AEP, *CoV*, and *CF* for four 50 %wind-50 %wave combined energy farms with various OWTs and WECs at hotspots.

Site	Gamesa-Wave Star			SWT-Wave Dragon			Gamesa-Wave Dragon			SWT-Wave Star		
	AEP (GWh)	*CoV* (%)	*CF* (%)	*AEP* (GWh)	*CoV* (%)	*CF* (%)	*AEP* (GWh)	*CoV* (%)	*CF* (%)	*AEP* (GWh)	*CoV* (%)	*CF* (%)
A	321	44	61	271	48	52	263	47	50	331	44	63
B	338	42	64	299	45	57	289	45	55	347	41	66
C	331	42	63	291	46	55	281	46	53	340	42	65
D	313	40	60	302	44	57	292	44	56	323	40	61
E	276	47	52	257	52	49	248	51	47	284	47	54
F	318	44	60	296	46	56	286	46	54	327	44	62
G	305	42	58	321	43	61	311	43	59	314	42	60
H	310	40	59	276	46	53	266	46	51	320	40	61
I	298	43	57	298	47	57	288	46	55	308	44	59
J	318	41	61	343	41	65	333	41	63	328	40	62

moderate variable outputs (43 % and 41 %). For other sites, the results indicate that SWT-Wave Star surpasses other combined wind-wave farms in performance; by offering higher *AEP* and *CF*, and lower *CoV*.

The visual representation of the performance metrics of different combined wind-wave energy farms at all selected sites using radar charts (Fig. 11) clarifies these findings. Each axis of Fig. 11 corresponds to one of the four combinations of energy devices, with labels at the endpoints. Each metric is represented by a polygon: blue for *AEP*, green for *CF*, and orange for *CoV*. The closer a combination's polygon is to the center, the lower its value for that metric. It is evident from Fig. 11 that, in all sites except G and J, the SWT-Wave Star combination is the best option. Its representative *AEP* and *CF* polygons are farther from the center, while the *CoV* polygon is closer, indicating that SWT-Wave Star offers substantial energy production and a stable output profile. For sites G and J, SWT-Wave Dragon provides higher *AEP* and *CF* with the blue *AEP* polygon being farther from the center, demonstrating its suitability.

This analysis provides valuable insights into the performance of different energy device combinations at various locations, helping to inform decisions regarding the deployment of combined offshore wind and wave energy farms off the Australian coast.

4. Summary and conclusions

In this study, 44 years of offshore wind and wave datasets were utilized to assess their combined exploitation potential along the Australian coastlines. The availability, variability, correlation, complementarity, and synergy of wind and wave energy, as well as extreme weather conditions and the accessibility of energy devices, were investigated to identify the hotspots for the development of combined wind-wave energy farm. Finally, an analysis of device pairing was conducted to assess the performance of four different combined wind-wave energy farms at hotspots using metrics such as Annual Energy Production (*AEP*), Capacity Factor (*CF*) of the energy farm, as well as Coefficient of Variation (*CoV*) of the output power.

The analysis indicated that southern coastal regions of Australia, particularly near Tasmania exhibit the highest potential of offshore wind and wave energy. In contrast, the northern and northeastern coastlines show limited potential. Synergy index map showed the strong complementarity between wind and wave resources are primarily located in the southern, western, and eastern coasts of Australia. The variability analysis revealed that the northern parts of Australia, experience higher variability in both wind and wave energy compared to the southern and western regions, offering less stable and unpredictable energy outputs, which are unsuitable. It was also found that offshore areas of Western Australia exhibit the lowest correlation between wind and wave energy resources, suggesting stable conditions for energy production through the deployment of combined wind-wave farms. Conversely, higher correlations in the northern and eastern offshore areas indicate more synchronized fluctuations, which pose challenges for joint energy exploitation.

A two-stage analysis framework was proposed for selecting and ranking the optimal locations for combined offshore wind-wave energy farm development. The first stage of the framework considers factors such as availability, variability, correlation, and complementarity of energy resources, and provides a heatmap to highlight the hotspots in the entire Australian offshore area. The second stage involved the re-ranking process of previously selected hotspots based on assessing extreme weather conditions and accessibility. The results emphasized that the western and southern coasts of Australia are the most suitable regions, with several sites in Western Australia (WA) identified as particularly favorable. These sites are characterized by stable and effective energy production, lower variability, and synchronization between wind and wave energy resources. They also offer higher accessibility for operation and maintenance purposes, as well as lower extreme weather conditions, resulting in greater survivability.

The analysis of the performance of four different combined wind-wave energy devices at selected hotspots suggests that the combination of SWT-Wave Star outperforms other combinations in most cases, while the combination of SWT-Wave Dragon shows the same in some cases, including hotspots in Tasmania and southwest Australia, in terms *AEP*, *CF*, as well as *CoV*. These combinations offer higher *AEP* and *CF* with manageable variability, making them suitable for energy harvesting.

The proposed index in this study is not site-specific. Hence, it can be used in other parts of the world subject to the availability of relevant data. This flexibility allows the method to aid in the site selection of combined wind and wave energy projects across various geographic locations, promoting the global development of offshore renewable energy initiatives. In addition, the framework proposed in this study serves as an operational preliminary resources-based tool for decision-makers and investors involved in combined wind-wave projects. It is recommended to consider additional factors, such as other techno-economic, environmental, social and legal aspects in the future planning of ocean renewable energy projects.

CRediT authorship contribution statement

Shabnam Hosseinzadeh: Writing – review & editing, Visualization, Software, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization. **Rodney A. Stewart:** Writing – review & editing, Supervision, Methodology, Conceptualization. **Bahareh Kamranzad:** Writing – review & editing, Methodology, Conceptualization. **Amir Etemad-Shahidi:** Writing – review & editing, Supervision, Methodology, Investigation, Conceptualization.

Data availability

All relevant data are available from online repositories (https://data.csiro.au/collection/csiro:39819, https://ecat.ga.gov.au/geonetwork/srv/api/records/a05f7892-fae9-7506-e044-00144fdd4fa6, https://fed.dcceew.gov.au/datasets/782c02c691014efe8ffbd27445fe41d7_0/explore).

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.

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Appendix A

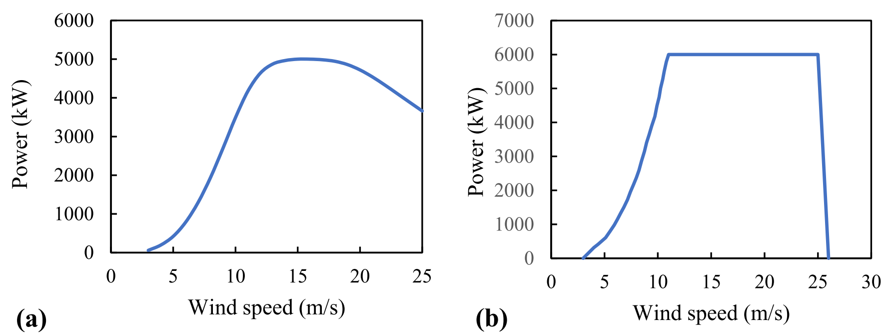

Fig. A. 1. Power curve of (a): Gamesa G128 5 MW and (b): SWT-6.0-154 6 MW wind turbines.

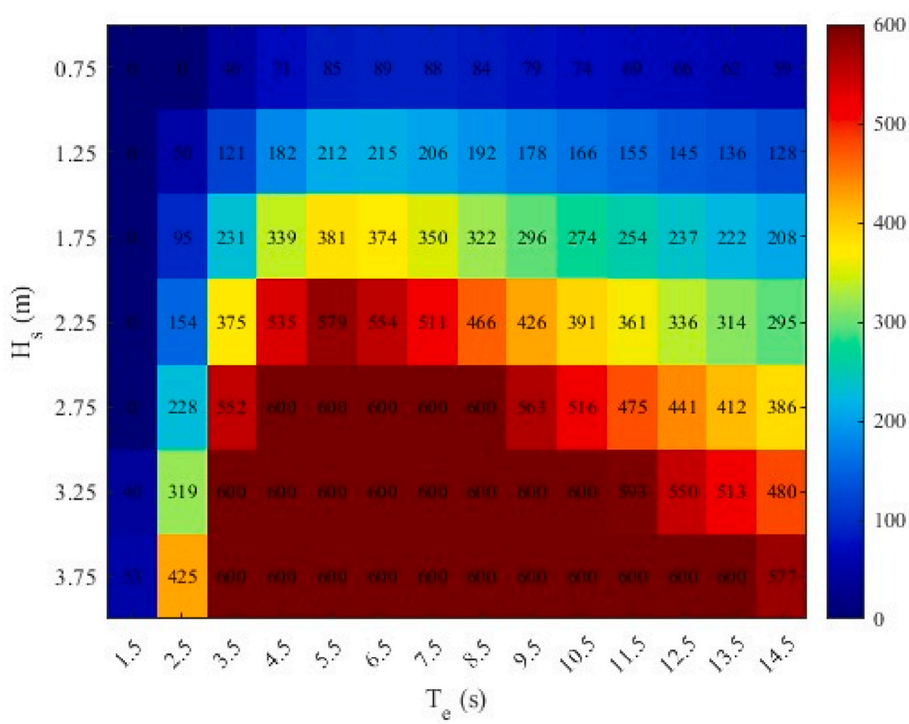

Fig. A. 2. Power matrix of Wave Star C6 600 kW.

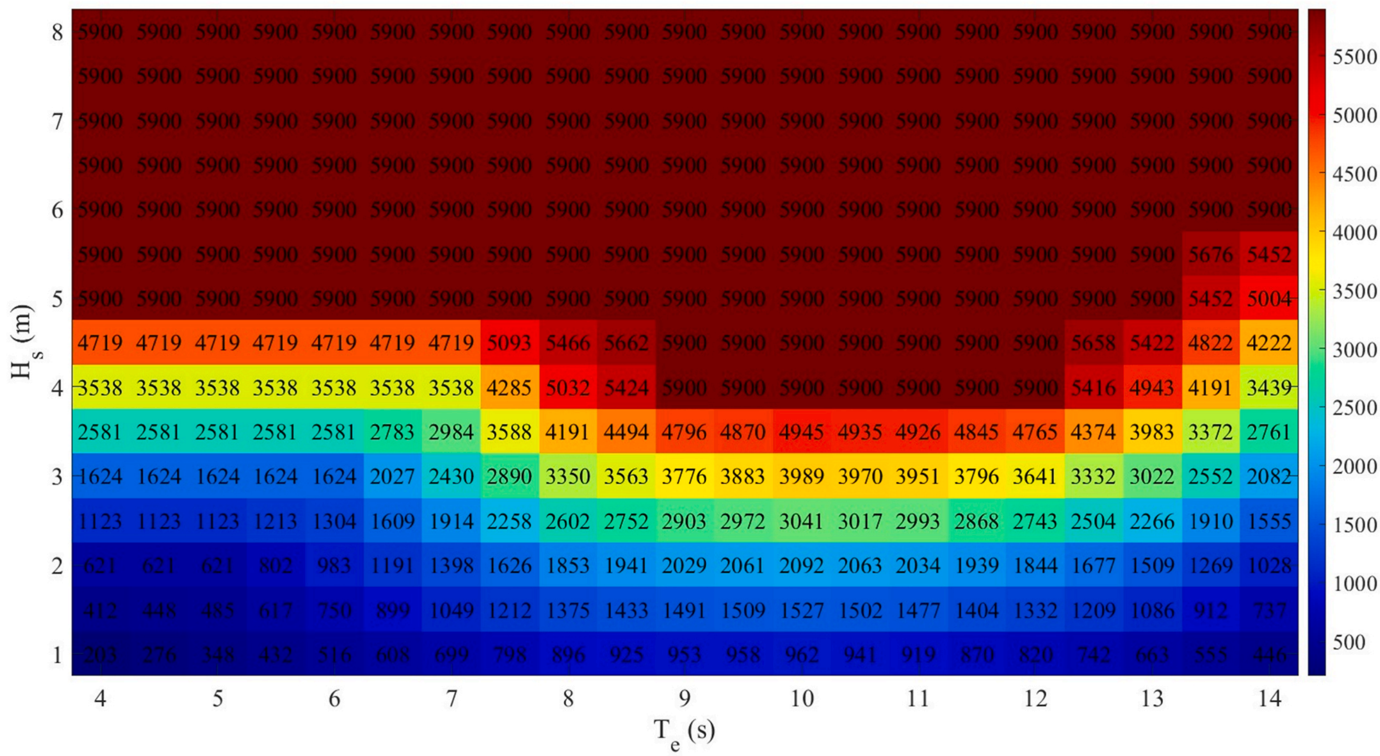

Fig. A. 3. Power matrix of Wave Dragon 6 MW.

Table A. 1
The ranking of selected sites considering the seasonal variability of wind power density

SIws	Sites ranking based on SIws	Sites ranking based on SIw	SIw	Rank
3.64	**A**	**A**	2.13	1
2.12	**C**	**C**	1.32	2
1.78	**B**	**B**	1.06	3
1.29	**D**	**D**	0.68	4
1.21	**E**	**E**	0.61	5
1.07	**F**	**F**	0.59	6
0.83	**H**	**H**	0.44	7
0.77	**I**	**I**	0.39	8
0.29	**G**	**J**	0.15	9
0.26	**J**	**G**	0.14	10

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