

Meteorological and Hindcast Data-Based Evaluation of Hybrid Wind–Wave Energy Potential Using WECl for Optimal Site Selection in Oman Sea

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Abstract

The intertwined challenges of rising global temperatures and accelerating sea-level rise underscore the urgent need for integrated and sustainable strategies to advance climate adaptation and the global energy transition. This study presents a comprehensive feasibility assessment of hybrid wind–wave energy resources along coastline of the Oman Sea in the Middle Eastern region. The regional wave climate was analyzed using ECMWF ERA5 hindcast data, validated against experimental measurements reported in previous studies. To quantify the temporal distribution and variability of wave energy, a novel Wave Energy Concentration Index (WECl) is introduced, enhancing the accuracy of energy resource evaluation and supporting the development of improved control strategies for hybrid systems. Utilizing three decades of reanalysis data (1995–2024), the study characterizes wave dynamics and identifies four promising candidate sites exhibiting significant hybrid energy potential. These locations, distributed along the southeastern coast of Iran and the eastern coast of Oman, were further analyzed for their seasonal wind and wave variability to assess their suitability for integrated offshore energy development. The findings establish an evidence-based framework for advancing hybrid offshore renewable energy systems in the Middle Eastern maritime domain, contributing to regional energy diversification, sustainability, and climate resilience.

Keywords: Optimal Site Selection - hybrid wave and wind energy- Wave Energy Concentration Index- ECMWF ERA5

1. Introduction

The accelerating pace of climate change characterized by rising global temperatures, sea-level rise, and shifting storm dynamics is fundamentally reshaping coastal environments and the associated energy resource landscape. Given that a substantial proportion of the world’s population resides in coastal areas, the advancement of sustainable and locally sourced renewable energy has become increasingly imperative. Ocean energy, derived from both wave and offshore wind resources, represents a promising alternative to fossil fuels. Nevertheless, its inherent spatiotemporal variability, compounded by uncertainties associated with future climate change, poses considerable challenges that necessitate comprehensive and integrated assessment approaches (Gao et al. 2023; Melikoglu 2018). The 2024 State of the Science Report underscores the potential of wave energy to supply power to remote coastal regions, estimating that wave power could fulfill up to 10% of local energy demands globally. The report identifies regions with consistent wave resources and highlights the minimal environmental impacts observed in monitored deployments. Conducted across 16 countries, the study emphasizes the need to advance wave energy technologies in order to meet climate targets and support the transition to sustainable energy systems (OES-Environmental 2024; Sriram 2024). Recent advancements in climate modeling and downscaling methodologies have substantially improved the capacity to assess and project wave and wind energy potentials with greater accuracy and spatial resolution (Jin et al. 2024; Jin-Lin et al. 2024; Soklin et al. 2024). For instance, Pourali et al. (2023) utilized a high-resolution CMIP6 model under the

high-emission SSP5-8.5 scenario and proposed a novel Weibull-based bias-correction approach to improve near-surface wind inputs for wave modeling applications. Their findings indicated a projected increase in wave power of 21–45% in certain regions under future climate conditions, underscoring the sensitivity of wave energy potential to both climate change impacts and model resolution. In parallel, Alizadeh et al. (2020) performed a multi-model ensemble analysis incorporating both GCM outputs and CORDEX regional simulations to capture the seasonal and interannual variability of wave energy. Ahn and Neary (2024) examined long-term global wave energy trends using 42 years of reanalysis data, demonstrating that contrasting changes across distinct wave systems often obscure significant nonstationary shifts in the global wave climate. In the Oman Sea region, several studies have assessed the feasibility of harnessing wave energy across different coastal sites. For example, Abbaspour and Rahimi (2011) evaluated wave energy resources across multiple coastal locations, whereas Saket and Etemad-Shahidi (2012) identified zones along the northern coast of the Gulf of Oman with comparatively high energy potential. These studies ultimately identified the most suitable sites for wave energy extraction by considering not only energy output and water depth, but also coastal accessibility as well as broader economic, environmental, and political factors. At the device scale, the effective harnessing of wave energy depends critically on the performance and efficiency of wave-energy converters (WECs) (Bryson et al. 2016; Bryson et al. 2019; de Andrés et al. 2015; Kumars et al. 2025; Levi et al. 2023; Xinxin et al. 2020). Khalifehei et al. (2018) investigated the Sea-wave Slot-cone Generator (SSG) system, a novel wave-energy converter tailored for the Persian Gulf and the Sea of Oman, through detailed computational fluid dynamics (CFD) simulations. Their analyses demonstrated that although the hydraulic efficiency of the SSG remains low under mild wave conditions, such as wave heights below 0.5 m, optimal performance exceeding 60% and reaching peaks near 97% occurs at wave heights of 1–2 m with favorable periods of approximately 5–6 seconds. These results highlight the critical importance of integrating realistic device performance metrics into resource assessments to ensure the economic feasibility of wave energy projects. Wave energy harvesting systems encounter multiple economic challenges that must be addressed to ensure their technical and financial feasibility (Abbaspour and Farshforoush 2024). One potential approach involves the use of hybrid energy harvesting platforms, which combine a wind turbine with an array of wave energy converters (Abbaspour and Farshforoush 2025; Farshforoush and Abbaspour 2024). The deployment of such hybrid systems necessitates the identification of sites with substantial wave and wind energy potential. Complementing wave energy assessments, research on offshore wind resources in the Oman Sea region indicates a relatively more stable energy potential (Amirinia et al. 2017a; Gohari and Akpinar 2025; Hosseini Dehshiri 2022; Mahmoodi et al. 2020; Majidi Nezhad et al. 2022). Band et al. (2021) analyzed MENA-CORDEX wind speed outputs, applying a vertical extrapolation to convert near-surface values to turbine hub height in order to evaluate the wind power potential. Their results show that although wind power potential demonstrates considerable spatial variability, projected long-term changes under high-emission scenarios remain minimal, less than 5 percent, thereby reinforcing the reliability of wind as a renewable energy resource. This relative stability of wind resources, when combined with the inherent variability of wave energy, provides a foundation for hybrid renewable energy systems that can enhance overall energy yield and improve system reliability (Neshat et al. 2024; Neshat et al. 2025; Sergiienko et al. 2025). Although considerable progress has been made in independent evaluations of wave and wind resources, most prior studies have addressed these energy forms in isolation. In regions such as the Middle

Eastern Gulf, where meteorological and oceanographic processes are strongly interconnected, an integrated assessment is essential. To address this gap, the present study introduces the Wave Energy Concentration Index (WECI), a novel metric designed to quantify the spatiotemporal clustering of high-energy wave events. When combined with wind resource assessments that incorporate directional variability, this framework provides a comprehensive basis for identifying optimal sites for hybrid renewable energy systems. The joint evaluation of wind and wave resources within a single framework not only strengthens site-selection strategies but also enhances the reliability and economic feasibility of hybrid energy development in a region where energy security and sustainable growth are critical priorities.

In this study, the hybrid wind–wave energy potential along the Middle Eastern Gulf coasts is evaluated to identify optimal sites for sustainable energy exploitation. Following the IEC 62600-101 TS procedure, the analysis of extreme wave conditions is conducted for the selected locations to assess survivability risks, while seasonal characteristics are examined to determine energy availability and variability. The remainder of this paper is organized as follows. Section 2 details the data sources employed for the study area analysis. Section 3 focuses on the validation of the hindcast meteorological data. Section 4 presents the results, emphasizing the spatiotemporal variability of renewable energy resources and the evaluation of candidate hybrid sites, including the derivation of the WECI and the integration of wind and wave models. Section 5 discusses the implications of the findings for regional energy planning and outlines directions for future research.

2. Study Area and Data Sources

This study employs three decades of wave data (1995–2024) from the European Centre for Medium-Range Weather Forecasts (ECMWF), specifically derived from the ERA5 reanalysis product. ERA5 is widely recognized as a critical resource in climate and oceanographic research due to its high temporal resolution of one hour and spatial resolution of approximately 31 kilometers (Anusree and Kumar 2024; Babagolimatikolaei 2025; Bessonova et al. 2025). The high spatial and temporal resolution of this dataset makes it particularly suitable for feasibility studies in ocean engineering, as it provides reliable representations of surface wind fields, wave characteristics, and other key atmospheric and oceanic variables. The dataset is produced through an advanced data assimilation framework that integrates a wide range of global observations, including satellite altimetry and buoy measurements, with state-of-the-art numerical weather prediction models. This assimilation process, implemented through Optimal Interpolation (OI), yields a comprehensive and internally consistent depiction of oceanic and atmospheric conditions, thereby supporting robust long-term analyses (Amirinia et al. 2017a, b; Hersbach et al. 2020; Kamranzad 2018; Mahmoodi et al. 2019; Muhammed Naseef and Sanil Kumar 2020). The wave modeling framework underlying ERA5 is built upon a third-generation spectral wave model that solves the energy balance equation governing the evolution of the wave spectrum. These formulation accounts for the fundamental processes of energy input, nonlinear redistribution, and dissipation, thereby providing a robust basis for simulating wave dynamics across both deep- and shallow-water environments. ERA5 data, spanning latitudes 22.63°N to 30.13°N and longitudes 47.87°E to 61.37°E, are extracted at a spatial resolution of $0.5^\circ \times 0.5^\circ$ and a temporal resolution of three hours. The boundary conditions applied in ECMWF's wave

modeling system are defined by spectral inputs that represent the directional distribution of wave energy across different frequencies. Unlike parametric spectral models such as JONSWAP or Pierson–Moskowitz, ERA5 wave data are generated dynamically through advanced physics-based modeling, which removes the reliance on predefined spectral assumptions and provides a more accurate representation of real-world wave dynamics. The comprehensive directional wave spectra available in ERA5 are widely used as open boundary conditions in high-fidelity oceanographic models, enabling precise simulations of wave propagation. This capability to generate accurate and detailed wave fields underscores the value of ERA5 as an indispensable resource for both global and regional wave modeling applications. Moreover, the dataset’s capacity to capture the spatial and temporal variability of wave climates makes it an essential tool for assessing offshore energy potential and for informing the design of engineering solutions that support the development of hybrid renewable energy systems. The bathymetric data for the study area were obtained from NOAA’s National Geophysical Data Center (NGDC) and are illustrated in Figure 1. This dataset provides a spatial resolution of 1 arcminute, equivalent to approximately 1.67 kilometers, and delivers detailed information on the topography of the seafloor (National Geophysical Data Center 2024).

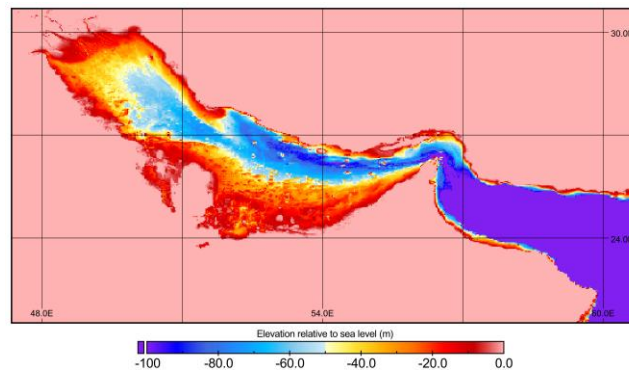


Fig.1: Bathymetric data of the study area obtained from NOAA’s National Geophysical Data Center (NGDC) (National Geophysical Data Center 2024)

3. Validation of Extracted ECMWF Data According to IEC 62600-101 TS

To address uncertainties in meteorological and oceanographic data, the IEC-TS 62600-101 provides a standardized framework for wave energy resource assessment, including data validation and statistical evaluation. In this study, the extracted ECMWF reanalysis data were assessed according to this specification and classified as Class 2 (feasibility level) (International Electrotechnical Commission 2020). The validation is based on the study by Kamranzad et al. (2013), who calibrated and validated ECMWF wind fields using the SWAN model and buoy observations over a five-year period. Their procedure reduced uncertainties in significant wave height and wave energy estimation. Here, the extracted data are compared with the validated results of Kamranzad et al. at three reference points (West, Middle, and East points are shown in Figure 2). After interpolation, the dataset is evaluated using IEC-TS scatter table procedures. The results indicate that both systematic (and random errors (remain within acceptable limits, confirming the reliability of the dataset for further analysis as shown in Table 1. Although slightly higher errors are observed in

the western boundary due to greater distance from validation points, the five-year dataset enhances overall robustness and exceeds the minimum IEC requirement.

Table.1: Locations of the considered stations for validation checkpoints and the associated error indices, including mean systematic and random errors.

Station	Longitude (° E)	Latitude (°N)	Depth(m)	b_{ep} (wave power)	σ_{ep} (wave power)
W	49.5	29.3	30	7.25%	15.41%
M	52.5	26.7	76	6.54%	13.5%
E	56.3	26.7	71	4.74%	9.46%

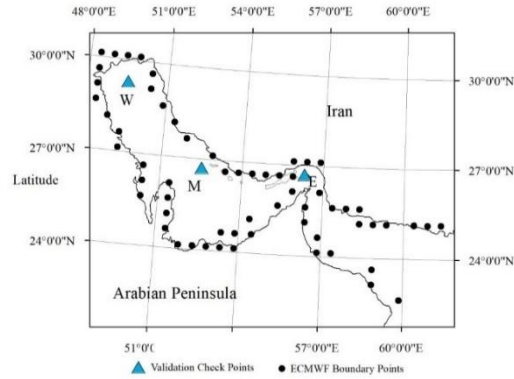


Fig.2: Spatial distribution of boundary analysis points and validation checkpoints, used to validate ECMWF data reliability across the study area in accordance with IEC TS standard

4. Results and Discussion

This section presents the results of assessment of wave and wind energy resources for the deployment of hybrid energy platforms, based on the validated datasets described in the preceding section.

4.1 Site Selection for Hybrid Offshore Energy Platforms

The feasibility stage is used to examine the maximum occurrences of both energy period and significant wave height over the study period, providing a preliminary assessment to identify regions with substantial wave energy potential. Both parameters are fundamental indicators of wave energy potential; however, higher significant wave heights are particularly advantageous given the quadratic relationship between wave energy and wave height. Specifically, the wave power per unit length is proportional to the square of the significant wave height for a given energy period, underscoring the influence of wave height as a dominant factor in energy yield estimation (Neshat et al. 2024). The maximum occurrences over the 30-year period are extracted, and their corresponding significant wave heights and energy periods are plotted in Figure 3.

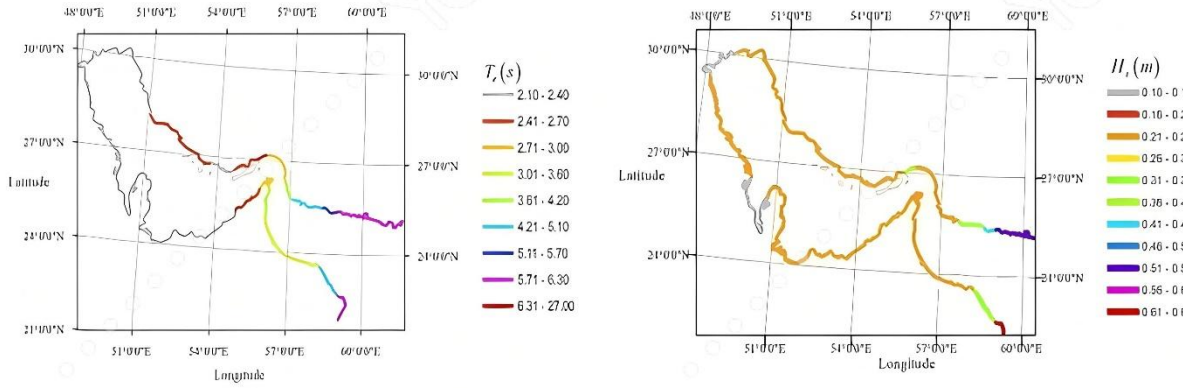


Fig.3: Maximum occurrences of energy period and significant wave height in study region

The analysis shows that higher significant wave heights are generally associated with longer energy periods. The southeastern coast of Iran and the eastern Oman Sea demonstrate strong wave energy potential, primarily due to swell waves propagating from the Arabian Sea. Because these areas exhibit complex wave climates, further assessment is required to evaluate energy concentration patterns. In complex scatter diagrams, system performance depends on whether high wave power occurrences are concentrated within a narrow range of wave conditions or dispersed across a broad spectrum. Concentrated high-energy conditions allow fixed design parameters and significantly improve hybrid platform efficiency. In contrast, dispersed energy distributions require frequent parameter adjustments, reducing overall system performance. To quantify this behavior, the Wave Energy Concentration Index (WECI) is introduced. WECI measures the degree to which high-energy wave conditions cluster within specific wave states. By capturing the consistency of wave energy distribution, WECI provides a practical tool for optimizing the design and deployment of efficient and reliable offshore wave energy systems.

$$WECI = \sum_{i=1}^N \frac{f_i}{\left[\left(\frac{T_{e,i} - T_{e,max}}{T_{e,max}} \right)^2 + \left(\frac{H_{s,i} - H_{s,max}}{H_{s,max}} \right)^2 \right]} \quad \text{Eq. 1}$$

$(T_{e,i})$ and $(H_{s,i})$ represent the energy period and significant wave height, respectively, with an occurrence frequency $o(f_i)$ for each cell (i) in the wave energy scatter diagram. Similarly, $(T_{e,max})$ and $(H_{s,max})$ denote the energy period and significant wave height corresponding to the maximum occurrence in the wave energy scatter diagram. As demonstrated in the formula, the wave energy concentration index increases as the distance between cells with high occurrences of wave energy and the maximum occurrence cell decreases, in terms of both energy period and significant wave height. To account for the desirability of regions with higher maximum energy periods and significant wave heights, this difference is normalized by the parameters associated with the maximum wave energy occurrence $(T_{e,max})$ and $(H_{s,max})$. This normalization ensures that the WECI effectively incorporates the critical characteristics of the maximum occurrences within the scatter diagram, emphasizing areas with greater wave energy potential and better suitability for energy harvesting. In other words, the higher the values of $(T_{e,max})$ and $(H_{s,max})$, the greater the WECI parameter, reflecting a higher concentration of significant wave energy occurrences. Figure 4 illustrates the WECI distribution, indicating that the eastern Oman Sea exhibits a greater concentration of high-occurrence wave energy in

the scatter diagram compared to the southeastern coast of Iran. This suggests that wave energy resources in the eastern Oman Sea are more centralized, potentially offering more favorable conditions for efficient wave energy harvesting.

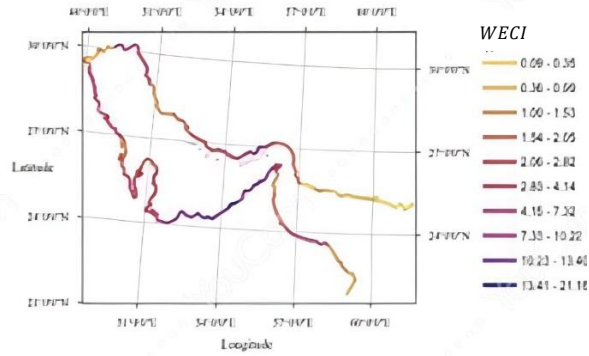


Fig.4: Wave Energy Concentration Index (WECI) distribution in study area

The design of hybrid wind–wave energy systems requires accurate knowledge of wind direction and magnitude, as these factors directly influence turbine efficiency and wave climate characteristics. In this study, ECMWF wind data are used to investigate wind–wave interactions in regions identified as having high wave energy potential. Wind rose diagrams are generated to analyze the spatial and directional distribution of wind at four candidate locations selected based on significant wave height and energy period. These sites represent the most promising areas for hybrid energy exploitation. A high-resolution assessment of these locations is presented in the following section to support evaluation of their hybrid energy harvesting potential. Although future studies should apply a comprehensive multi-criteria decision-making framework incorporating environmental, technical, social, and economic factors, the selected sites effectively represent the high-energy characteristics of the study area. The four locations are listed in Table 2.

Table.2: Specifications of wave classification for four locations with high wave energy potential along the coasts of Iran and Oman

Point	Name	Latitude (°N)	Longitude (°E)	Depth (m)	$T_{e,max}$ (s)	$H_{s,max}$ (m)	WECI	Corr (T_e, T_p)
A	Darak	25.13	58.87	120	5.5	0.45	0.69	0.38
B	Bandare Tang	25.13	59.87	145	6	0.55	0.56	0.43
C	Chabahar	25.13	60.37	150	6.5	0.55	0.17	0.33
D	Sur	22.63	59.87	155	6	0.65	1.46	0.41

Points A, B, and C are located along the southeastern coast of Iran, while Point D is situated on the eastern coast of Oman. The wind rose plots for these sites are presented in Figure 5, showing the distribution of wind speeds analyzed at the standard reference elevation of 10 meters above mean sea level. Offshore wind turbine hubs, however, are generally positioned at greater heights than this reference level. To adjust wind speeds to hub height, the logarithmic wind profile equation can be applied, where U_z is the wind speed at the target height, U_{ref} is the recorded wind speed at the reference height, and z is the surface roughness length (Astariz and Iglesias 2016). Nevertheless, because each offshore site requires specific turbine characteristics to accurately assess hub-height wind potential, wind speeds in this study are reported uniformly at 10 m above MSL to maintain comparability across all sites. The wind distribution

along the Iranian coast (Points A–C) is multi-directional, spreading predominantly toward the east, west, and south, with relatively low intensity. By contrast, the wind distribution in Sur (Point D) is more concentrated, primarily oriented in the north–south directions, and characterized by higher intensity. This concentrated wind regime has two significant implications. First, the directional centralization enhances the wave energy concentration, consistent with the highest Wave Energy Concentration Index (WECI) observed at Sur, thereby increasing the applicability of hybrid energy harvesting platforms. Second, the higher intensity and directional consistency of the wind contribute to improved wind turbine performance, as turbines operate more efficiently under predictable wind conditions. Taken together, these characteristics position Sur as the most favorable site among the selected locations for the deployment of hybrid wind–wave energy systems, making it a priority candidate for integrated renewable energy development in the region.

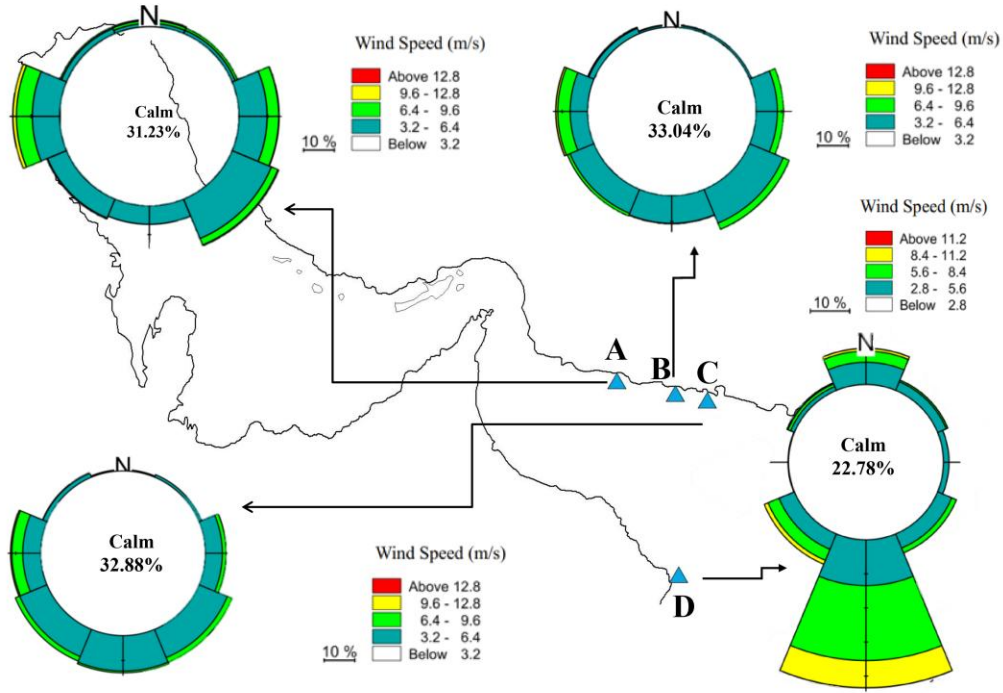


Fig.5: Wind rose plots for Points A, B, C along the southeastern coast of Iran, and Point D on the eastern coast of Oman

4.2 Meteorological Data and Variability at Four Candidate Sites

Building on the identification of four high-potential sites for hybrid wind–wave energy, this section examines the detailed meteorological and seasonal variability of wind and wave resources to support preliminary risk and financial assessments. Figure 6 presents the 30-year mean values of significant wave height, wave energy period, and extractable wave power density at these locations. At Chabahar, year-to-year fluctuations in wave power density reach nearly 30%, indicating that higher mean wave potential is accompanied by greater variability. Although mean significant wave heights are similar at Chabahar and Sur, the longer energy period at Chabahar results in higher overall wave power density, highlighting that wave height alone is insufficient for resource assessment. A slight declining

trend in wave power density over the 30-year record further emphasizes the importance of considering long-term changes. Extreme sea states also differ among sites. At Darak, locally generated wind waves produce maximum heights of ~ 14 m, whereas at Chabahar, longer-period swells lead to lower maxima (~ 8 m) as shown in Figure 7. This contrast demonstrates that local wind waves amplify extremes, while swell-dominated climates are less severe. These findings underline the need to incorporate both variability and extreme-event analyses into site evaluations to ensure reliable energy production and structural resilience of hybrid offshore platforms.

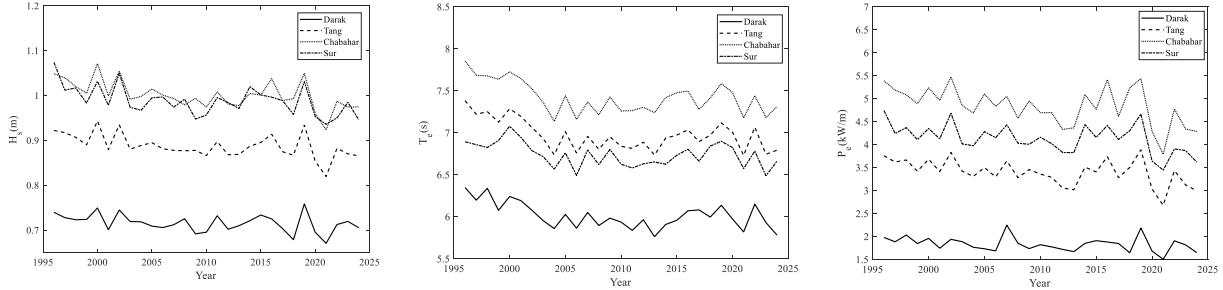


Fig.6: Thirty-year mean values of significant wave height (left), wave energy period (middle), and extractable wave power density (right) at Darak, Bandar-e Tang, Chabahar, and Sur.

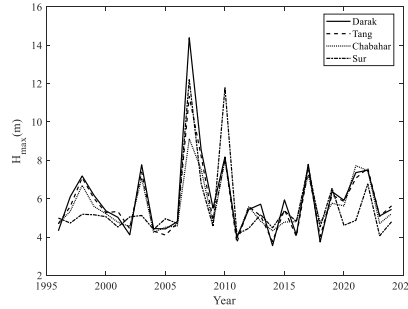


Fig.7: Maximum wave heights over a 30-year period at Darak, Bandar-e Tang, Chabahar, and Sur.

For each site, mean wave and wind power densities, together with the spectral directional width of wave energy, are analyzed over a 30-year period on a seasonal basis. Mean power densities indicate the overall energy potential, while spectral directional width and wave direction variability help distinguish whether the dominant forcing originates from local wind seas or swell systems. This information is also essential for optimizing wave energy converter operations. Unlike WECI, which measures the concentration of maximum wave power occurrences regardless of direction, spectral directional width quantifies directional spreading, affecting array performance. At Darak (point A), seasonal variations are illustrated in Figure 8. Wave power density markedly increases during the summer monsoon, whereas other seasons show relatively similar levels, indicating potential uncertainties in power supply. Local wind power does not fully reflect these patterns; for example, wave power reaches a minimum in autumn, which is not captured by wind data. Figure 9 shows that winter exhibits broader directional spreading due to wind fluctuations, while summer and autumn are more stable with narrower spectral widths, reflecting a swell-dominated wave climate at Darak. These observations guide array design and operational strategies.

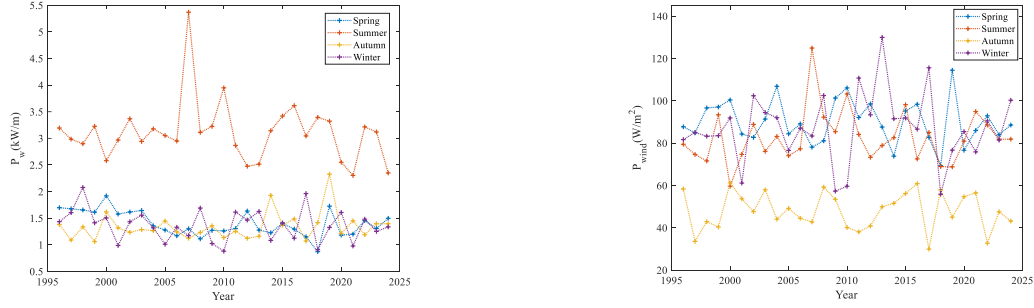


Fig. 8. Seasonal variation of mean wave power density (left) and mean wind power density (right) at Darak over a 30-year period

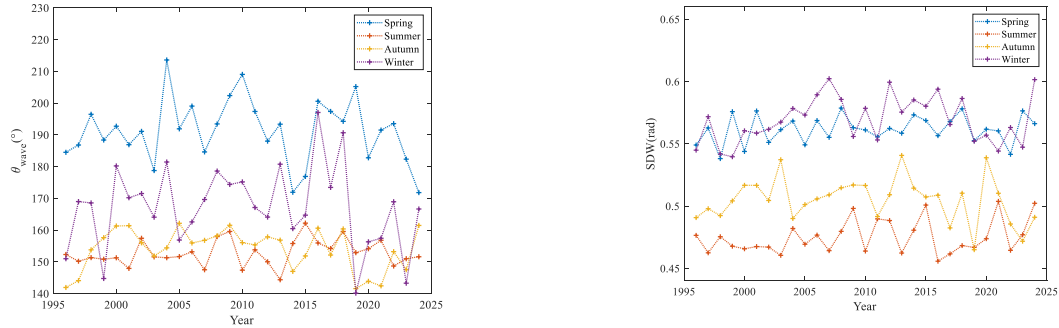


Fig. 9: Seasonal variation of mean wave propagation direction (left) and associated directional spectral width (right) at Darak over a 30-year period

A similar seasonal analysis is performed for Bandar-e Tang (point B), with results shown in Figure 10. The site exhibits higher mean wave power density than Darak, while seasonal variability is lower during both monsoon and non-monsoon periods. Despite these differences, temporal fluctuation patterns are generally consistent with those observed at Darak. The elevated wave power at Bandar-e Tang is attributed to the longer effective fetch, producing larger significant wave heights and longer energy periods. Figure 10 illustrates that local wind power density is less variable than at Darak, resulting in narrower spectral directional widths and more uniform wind–wave interactions. Because the dominant waves are swell-driven rather than locally generated, the mean wave propagation direction remains stable throughout the year, as shown in Figure 11. This directional consistency indicates that the wave climate is largely governed by remote forcing, providing favorable conditions for hybrid wave–wind energy systems with predictable operational performance.

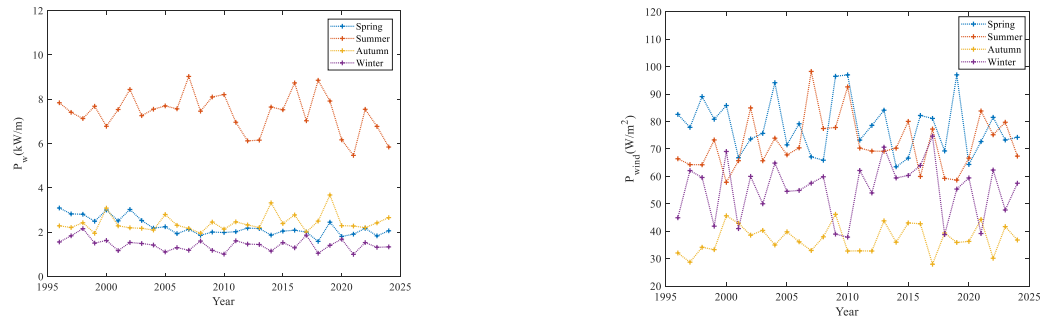


Fig. 10. Seasonal variation of mean wave power density (left) and mean wind power density (right) at Bandar-e Tang

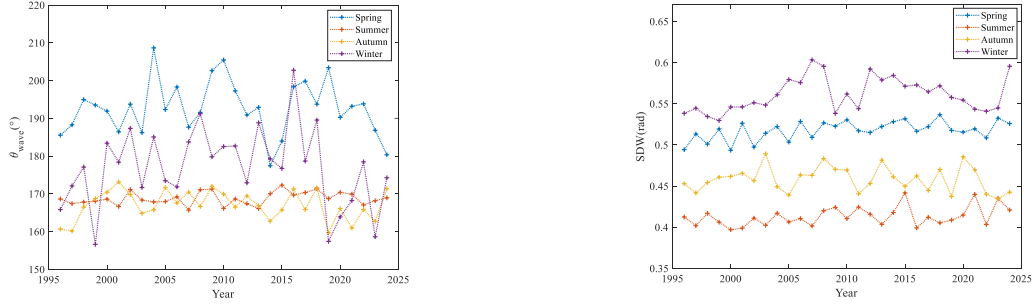


Fig. 11: Seasonal variation of mean wave propagation direction (left) and associated directional spectral width (right) at Bandar-e Tang

At Chabahar (point C) and Sur (point D), mean annual significant wave heights are higher than at the other selected sites. This is due to longer effective fetch lengths, which enhance wave development and increase mean wave energy density, illustrated in Figures 12 and 14. Chabahar has slightly higher wave power density than Sur because of longer energy periods. Frequent swell waves at Chabahar provide a stable directional wave climate, especially during the summer monsoon, as depicted in Figure 13. In contrast, Sur exhibits a broader spectral directional width (Figure 15) due to locally generated wind waves, accompanied by higher wind power density, making it particularly favorable for wind energy harvesting in summer. Overall, Chabahar's swell-dominated and stable wave regime supports consistent wave energy extraction, whereas Sur's stronger and more variable wind conditions enhance its suitability for hybrid wind-wave energy systems.

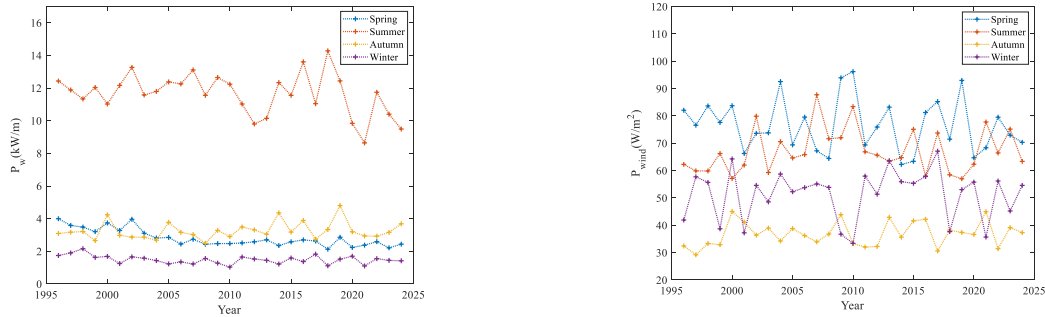


Fig. 12. Seasonal variation of mean wave power density (left) and mean wind power density (right) at Chabahar

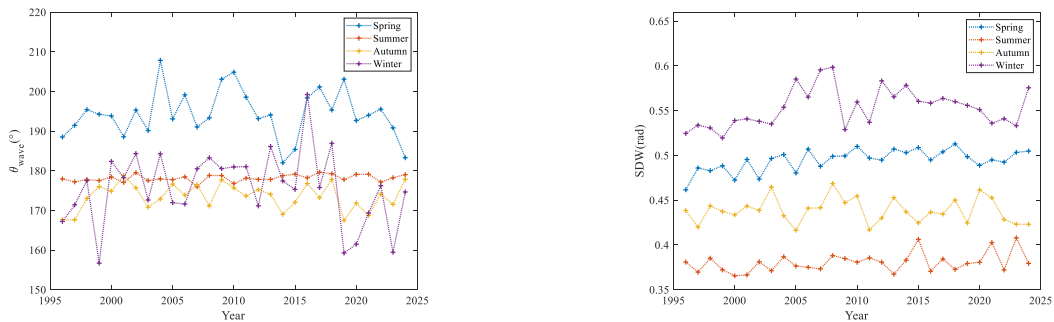


Fig. 13: Seasonal variation of mean wave propagation direction (left) and associated directional spectral width (right) at Chabahar

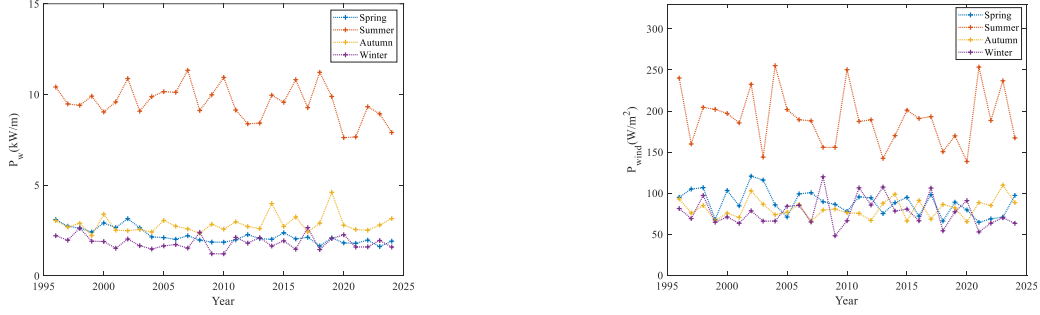


Fig. 14. Seasonal variation of mean wave power density (left) and mean wind power density (right) at Sur

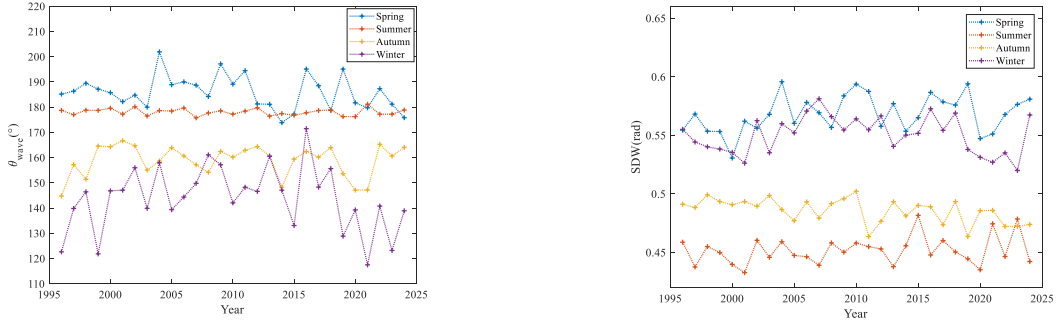


Fig. 15: Seasonal variation of mean wave propagation direction (left) and associated directional spectral width (right) at Sur

5. Conclusion

This study highlights the substantial potential of hybrid wind–wave energy systems along the Middle Eastern Gulf coasts for contributing to the region’s renewable energy portfolio. By using meteorological and hindcast datasets validated under the IEC 62600-101 TS framework, the research ensures reliable energy potential assessments despite limited in situ measurements. The introduction of the Wave Energy Concentration Index enables precise temporal characterization of wave dynamics, distinguishing between low-energy, scattered wave regimes and complex, high-energy fields. This approach led to the identification of four candidate offshore zones suitable for hybrid system deployment. The combined analysis of wave and wind characteristics, including energy density, spectral directional width, and dominant propagation direction, provides a robust basis for assessing the spatiotemporal complementarity of both resources. Integration of WECEI with wind rose analyses and installation feasibility metrics further refines site selection by incorporating technical and operational considerations. This multi-criteria framework supports improved system stability, higher capacity factors, and reduced intermittency in offshore energy production. The results emphasize the importance of high-resolution, region-specific analyses that capture temporal and spatial variability, particularly in the Gulf, where extreme climatic conditions and unique coastal morphodynamics prevail. Future studies should expand this framework to include techno-economic evaluations, life-cycle cost assessments, environmental impacts, and long-term climate projections. Incorporating numerical modeling and machine learning could further enhance the accuracy of hybrid resource forecasting, supporting adaptive planning for resilient offshore energy infrastructure. Ultimately, this research provides a data-driven foundation for sustainable and reliable hybrid wind–wave energy development in a strategically significant maritime region.

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