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Spatio-Temporal Characterization of Wind Regimes in the Algerian Basin: Implications for Offshore Wind Energy Development

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Abstract

Wind is a critical meteorological parameter that influences numerous environmental, oceanic, and human activities. This study presents a comprehensive spatio-temporal characterization of wind regimes in the Algerian Basin based on 84 years (1940-2024) of ERA5 reanalysis data. Statistical and geospatial analyses were conducted to explore monthly, seasonal, and annual variability in wind speed and direction. The study also applied anomaly detection, Mann-Kendall trend testing, and Empirical Orthogonal Functions (EOF) to identify dominant wind patterns. The results indicate significant variability, with higher wind speeds recorded in the winter season and stronger gradients observed in the eastern basin. A composite scoring system incorporating wind velocity, bathymetric depth, and distance to shore was used to select optimal sites for offshore wind farm development. Simulation of three candidate sites with 15 MW turbines showed considerable power generation potential. These findings contribute vital data for Algeria's renewable energy planning and marine spatial strategy.

Subject Areas

Environmental Sciences

Keywords

Wind Regimes, Spatio-Temporal Variability, Algerian Basin, Offshore Wind

Energy, ERA5, Renewable Energy Potential

1. Introduction

The global transition toward sustainable energy has accelerated the need to harness renewable sources, such as wind and solar, as alternatives to fossil fuels [1]. Wind energy, in particular, offers the advantage of scalability and technological maturity, with offshore wind farms playing an increasingly important role in meeting renewable energy targets [2]. While considerable attention has been given to onshore wind resources, the potential of offshore wind energy remains underutilized in several regions, including the southern Mediterranean. Algeria, located along the southern coast of the Mediterranean Sea [3], has over 1600 km of coastline and a vast Exclusive Economic Zone (EEZ) [4], yet lacks substantial research on the wind energy potential of its offshore territories. Current national strategies and energy infrastructure continue to focus predominantly on fossil fuels, despite Algeria's commitment to international climate goals and its ambitious target to diversify energy sources. Given the country's growing electricity demand, compounded by population growth and industrial development, identifying sustainable energy alternatives is essential. Offshore wind energy development requires robust site assessments, taking into account wind characteristics, bathymetric conditions, and infrastructure proximity [5]. Previous studies in nearby regions such as Spain, Tunisia, and Italy, have demonstrated the potential of the Mediterranean for wind energy, yet such assessments in Algeria are limited and often based on short-term or low-resolution datasets. This study addresses this gap by providing a comprehensive long-term analysis of offshore wind regimes in the Algerian Basin. By utilizing the ERA5 reanalysis dataset spanning over eight decades [6], this research aims to: 1) Characterize the spatial and temporal variability of offshore wind speed and direction; 2) Identify trends and dominant spatial structures through statistical and multivariate analysis; 3) Develop a spatial model for identifying suitable offshore wind farm locations based on physical and operational constraints; 4) Estimate the potential energy output of selected sites using realistic turbine specifications. By fulfilling these objectives, the study offers valuable insights to guide stakeholders, policymakers, planners, and energy developers in harnessing Algeria's offshore wind resources for long-term energy security and climate resilience.

2. Study Area

The Algerian Basin, a part of the western Mediterranean Basin, is characterized by an Exclusive Economic Zone (EEZ) that spans more than 1600 kilometers of coastline [4]. Also referred to as the Algero-Provencal Basin, it extends between 35˚N and 40˚N latitude, and 2˚W to 8.7˚E longitude (See **Figure 1**). The basin is bounded by the Alboran sub-basin to the east, the island of Sardinia to the west, Algeria to the south and the Balearic Islands to the north [7].

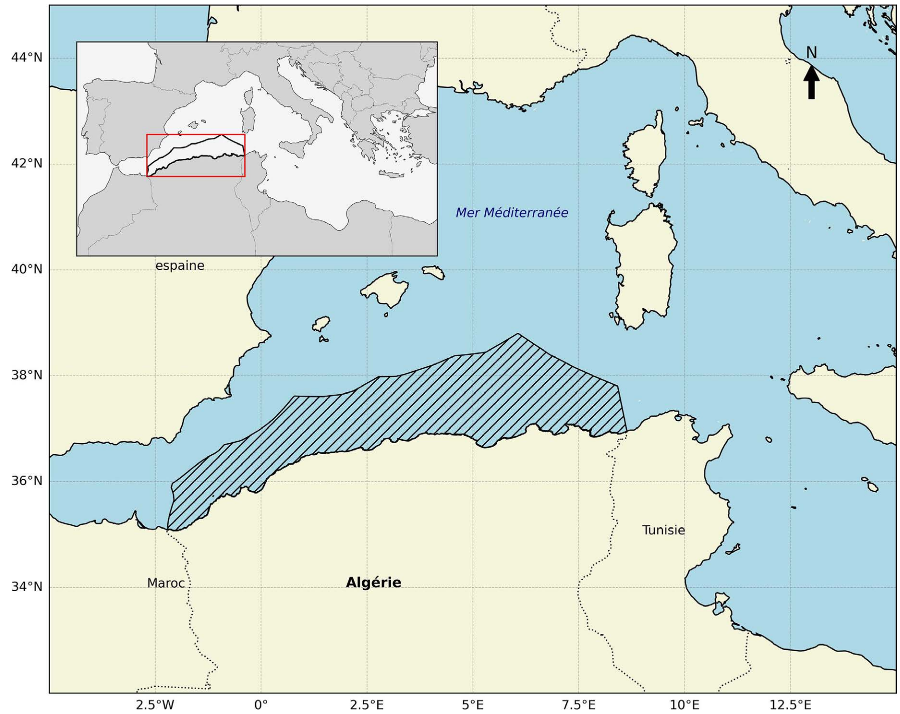

Figure 1. Algerian exclusive economic zone (Algerian Bassin).

3. Data and Methods

3.1. Data

The ERA5 reanalysis dataset is produced by the European Centre for Medium-Range Weather Forecasts (ECMWF) and represents the state-of-the-art in climate reanalysis products. ERA5 provides global atmospheric data at a high spatial resolution ($0.25^\circ \times 0.25^\circ$) and hourly temporal resolution [6]. For this study, 84 years (1940-2024) of hourly 10-meter zonal (U_{10}) and meridional (V_{10}) wind components were retrieved. To calculate wind speed (V), the two wind components were combined using the formula:

$$V = \sqrt{U_{10}^2 + V_{10}^2} \quad [8]$$

The data were processed using Python. Monthly, seasonal, and annual averages were computed to assess variability across different temporal scales. Time series smoothing, outlier removal, and consistency checks were performed to ensure data integrity. Grid points corresponding to land or outside Algeria's EEZ were excluded from the analysis. Bathymetric data from the GEBCO 2023 model were used to assess seabed depth. Depths ≤ 60 m were considered suitable for fixed-bottom wind turbines due to engineering and cost constraints, while deeper waters (>60 m) were evaluated for floating offshore wind turbine potential. This approach allows the identification of candidate sites for both fixed-bottom and floating offshore wind technologies. Additionally, distance-to-shore was calculated for each grid point using GIS tools. Points beyond 40 km from shore were excluded to prioritize economic viability, grid connectivity, and maintenance feasibility.

3.2. Data Analysis

The Seasonal-Trend decomposition using LOESS (STL) was applied to the time series to isolate seasonal patterns and detect long-term trends. Mann-Kendall tests, which are non-parametric and robust against non-normality, were employed to detect statistically significant trends at a 95% confidence level. The Sen's slope estimator was used to quantify the magnitude of trends. Empirical Orthogonal Function (EOF) analysis was used to reduce dimensionality and reveal dominant spatial wind patterns across the Algerian Basin. The first three modes of variability were retained, representing the most significant spatial structures. The corresponding Principal Components (PCs) were examined to determine their temporal variability and association with broader climate phenomena.

3.3. Site Selection and Energy Production Modeling

A composite scoring approach was developed to rank potential offshore sites using three criteria: wind speed (V), depth (D), and distance to coast (C). The scoring equation was:

$$\text{score} = V - (0.01 \times \text{Depth}) - (0.01 \times \text{distance from the coast}) \quad [9]$$

This formulation assigns the highest importance to wind speed while penalizing locations with greater water depth and larger distance from the coast, which may increase installation and infrastructure costs. The coefficient 0.01 was introduced to reduce the influence of depth and distance variables, whose numerical values are significantly larger than wind speed values, thereby maintaining a balanced contribution of the three criteria in the composite score.

Sites in the top 10th percentile of this score distribution were identified as candidates. For each site, hourly 10 m wind speeds from ERA5 were used as input to a turbine power curve model. Instantaneous power was calculated at each time step using the standard wind power equation:

$$P = \frac{1}{2} \times C_p \times \rho \times A \times v^3 \quad [10]$$

where:

- C_p: power coefficient = 0.45;
- ρ: air density = 1.225 kg/m^3;
- A: swept area = π × (radius)^2, with 100 m rotor diameter ($A \approx 7850$ m^2);
- V: wind speed.

Wind speeds at 10 m above sea level serve as proxies for turbine hub-height winds (~100 m) because modern offshore wind turbines are typically installed with hub heights in the range of 100 - 120 m [11]. Wind speed increases with height according to the power law wind profile,

$$V_h = V_{10} \left(H_h / 10 \right)^{\alpha} \quad [11]$$

where α is the wind shear exponent. Literature and industry practice suggest offshore values of $\alpha \approx 0.10$ - 0.14 due to smooth surface roughness over water [12].

Using $\alpha = 0.12$ and $H\_h = 100$ m gives:

$$V_{100}/V_{10} \approx (100/10)^{0.12} \approx 1.32$$

indicating hub-height winds could be ~32% stronger than 10 m winds. Because wind power scales with the cube of wind speed, this implies potential energy output could be up to ~2.3 times larger than estimates based on 10 m mean winds alone. This supports framing the reported energy estimates as conservative lower bounds for offshore wind energy potential.

The capacity factor and annual generation were then estimated assuming 20 turbines per site, each rated at 15 MW, using the standard wind power equation. These estimates provide an initial assessment of site-specific energy potential and allow comparison across candidate locations.

4. Results

4.1. Long-Term Wind Characteristics

The ERA5 reanalysis dataset revealed that wind speeds over the Algerian EEZ exhibit moderate to high variability across space and time. The overall mean wind speed across all marine grid points from 1940 to 2024 was calculated to be approximately 5.59 m/s, with spatial variations ranging from 4.5 m/s in sheltered western regions to over 6.5 m/s in exposed eastern offshore zones. The mean wind direction predominantly exhibited a north westerly flow pattern, aligning with climatological expectations for the western Mediterranean region. Interannual variability, measured by the coefficient of variation (CV), ranged from 28% to 55%, with the most stable regimes located in the northeast quadrant of the EEZ.

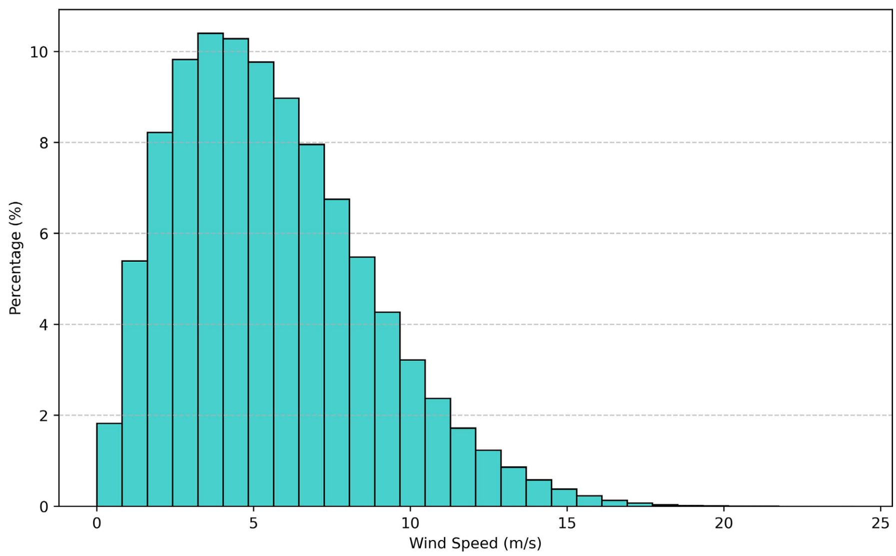

Figure 2. Frequency distribution of wind speeds (%).

The analysis of the wind speed distribution histogram reveals a right-skewed pattern, which is typical of a natural phenomenon subject to high variability. Most observations are concentrated between 3 and 7 m/s, with a peak frequency around 4 to 5 m/s, accounting for over 10% of the total (See Figure 2). This distribution indicates that light to moderate wind regimes dominate throughout the study period. The rapid decline in frequency beyond 10 m/s suggests that high wind speeds are relatively rare.

4.2. Annually, Monthly and Seasonal Wind Variability

Monthly wind speed climatology shows a pronounced seasonal cycle. December to February (winter) months consistently showed the highest mean wind speeds, averaging 6.2 to 6.8 m/s across most of the EEZ. In contrast, July and August recorded the lowest average wind speeds, often below 5 m/s, particularly in the western basin.

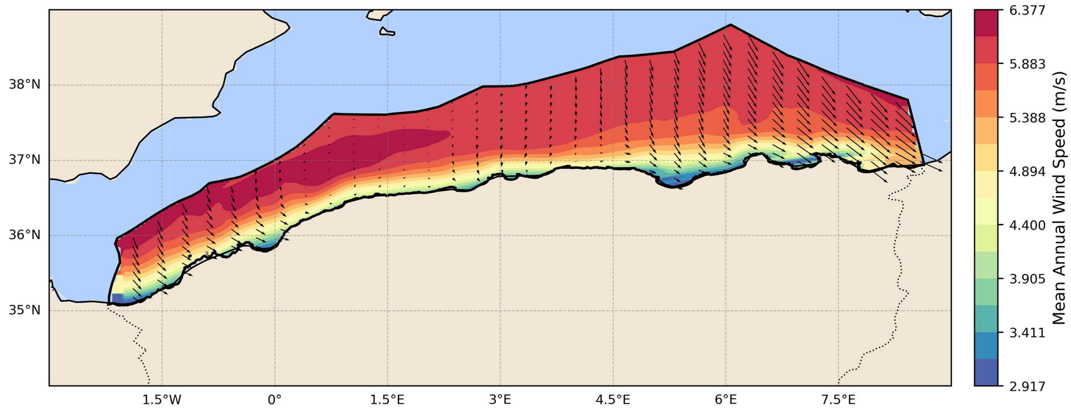

Figure 3. Distribution of the annual mean wind speed (1940-2024).

The assessment of the mean annual wind speed within the EEZ of the Algerian Basin over the period 1940-2024 shows that wind speeds are generally higher along the northern coast, with a maximum in the eastern sector of the EEZ, between approximately 6˚E and 8.5˚E, where the mean annual speed reaches around 6 m/s. In contrast, the central region, roughly between 3˚E and 5˚E, exhibits moderate wind speeds, around 4 - 5 m/s. The western sector, between 1.5˚W and 0˚E, shows slightly lower speeds, averaging between 3 - 4 m/s. A consistency check between spatial averages and mapped wind-speed fields confirms that the basin-wide mean (5.59 m/s) is coherent with the spatial patterns observed in the maps (See Figure 3).

The dominant wind direction throughout the basin is from the northeast to southwest, consistent across most of the EEZ. Overall, wind speeds increase progressively from the western to the eastern sector along the Algerian coast (See Figure 4).

Transitional seasons (spring and autumn) demonstrated moderate wind intensities but with more spatial variability. The STL decomposition confirmed this seasonal cycle as the dominant mode of variability in the time series, with residuals representing minor irregular fluctuations.

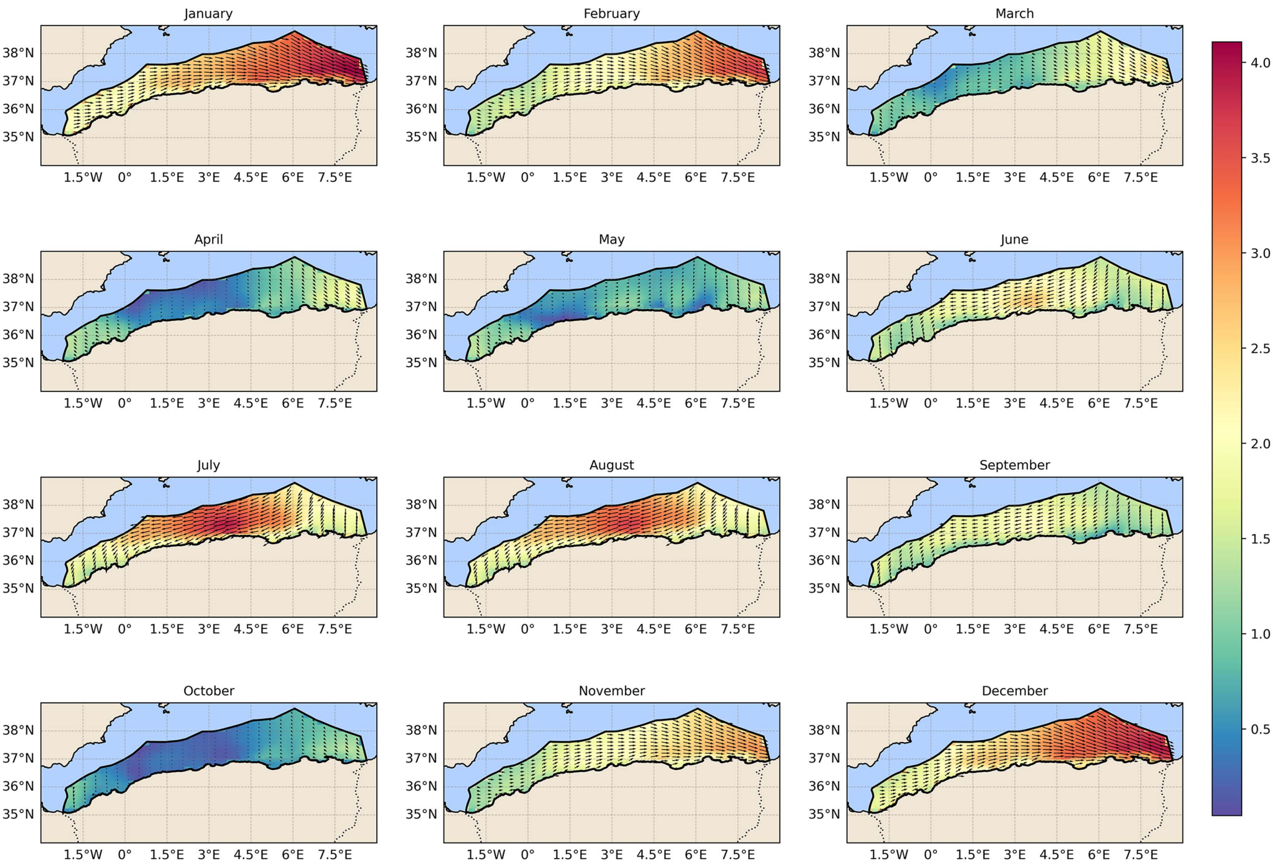

Figure 4. Monthly distribution of average wind speed.

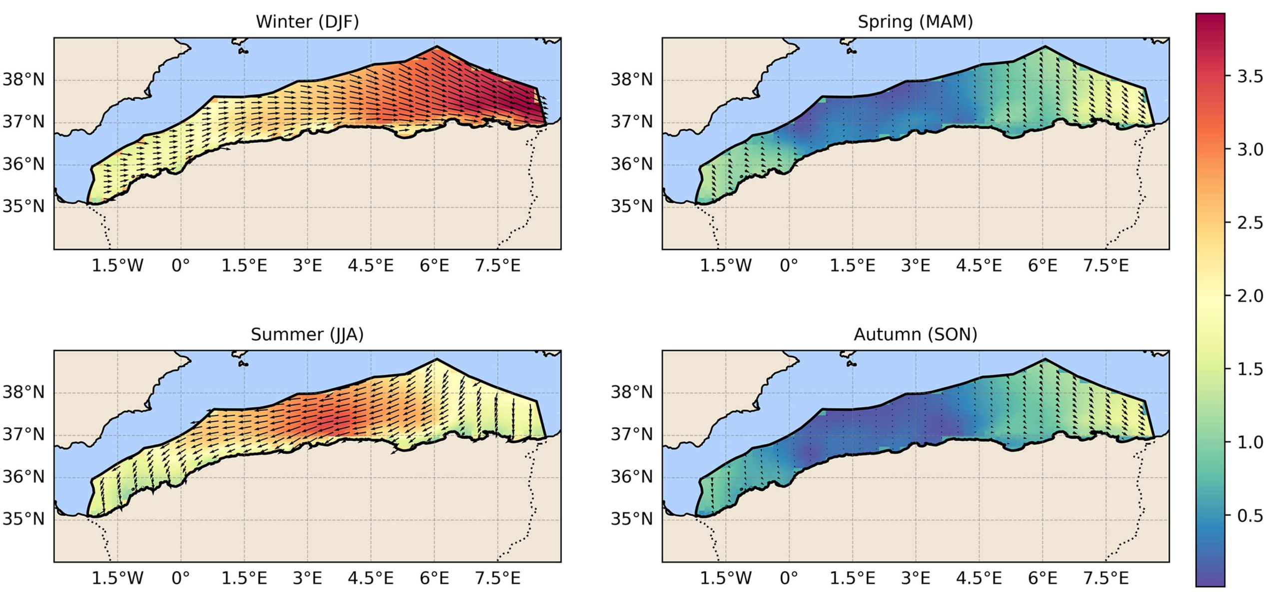

Figure 5. Seasonal variation of average wind speed (1940-2024).

The map illustrates the seasonal average wind speed over the Algerian Basin for the period 1940-2024 (See **Figure 5**). A clear spatio-temporal variability in the wind regime is observable. During winter (DJF), wind speeds are highest, exceeding 3.5 m/s in the eastern part of the basin (between 5˚E and 9˚E), with a dominant northwesterly to southeasterly direction. In summer (JJA), higher wind speeds are concentrated in the central part of the basin, ranging from 3 to 3.5 m/s in the area approximately between 1.5˚E and 5˚E, with predominant winds blowing from the northeast and east. Spring (MAM) and autumn (SON) are characterized by generally weaker winds, with near-zero speeds in the central basin and slightly stronger winds toward the edges, ranging between 1.5 and 2 m/s (See Figure 6).

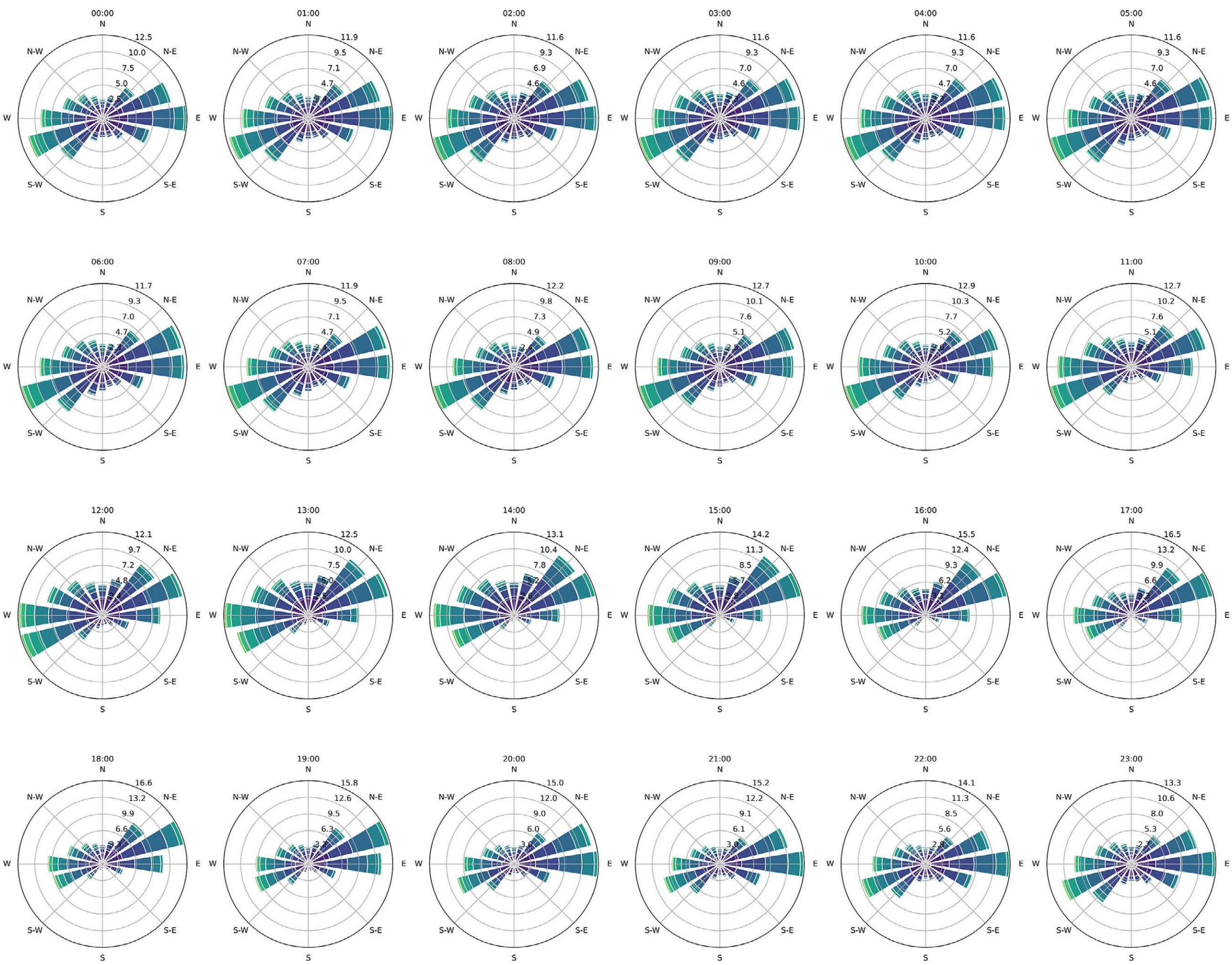

Figure 6. Hourly variation of wind direction and speed.

4.3. Spatial Patterns in Wind Speed Distribution

Spatial mapping of annual mean wind speed across the study area revealed three distinct zones. The eastern region (6.5˚E - 9˚E), especially near the Gulf of Annaba, exhibited consistently high mean wind speeds (>6.3 m/s), making it favorable for energy exploitation. The central basin displayed moderate winds (~5.7 m/s) while the western region showed weaker wind regimes (<5.2 m/s), likely influenced by coastal orographic sheltering. These spatial gradients were consistent across all decades analyzed, suggesting the presence of robust geophysical drivers.

4.4. Temporal Trends and Anomaly Detection

Temporal trends were evaluated using the non-parametric Mann-Kendall test applied to the annual mean wind speed averaged over the Algerian Exclusive Economic Zone (EEZ) for the period 1940-2024 (See **Figure 7**).

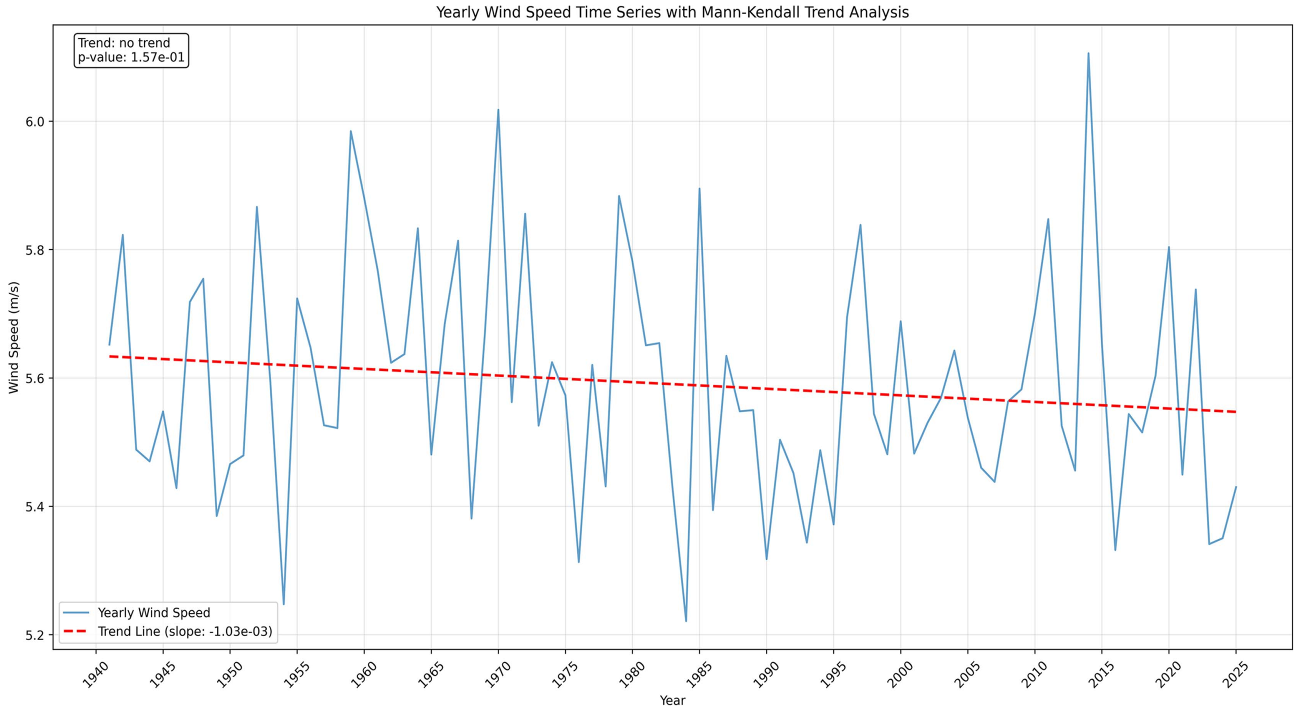

Figure 7. Annual evolution of wind speed (1940-2024) with Mann-Kendall trend test.

The results indicate that no statistically significant long-term trend is present in the basin-averaged wind speed ($p = 0.157$). Kendall's Tau coefficient is −0.10, suggesting a weak but non-significant decreasing tendency. The estimated slope of the trend line is -1.03×10^{-3} m/s per year.

These results indicate that, despite noticeable interannual variability, the overall wind regime over the Algerian Basin has remained relatively stable during the study period.

4.5. EOF Modes of Wind Variability

The EOF analysis identified three dominant spatial modes that accounted for 89% of total variance. Mode 1 explained 61% of variance and captured a zonal gradient in wind strength, corresponding to large-scale west-to-east atmospheric flow. Mode 2 (19% of variance) exhibited a north-south dipole structure, indicating meridional variability possibly linked to the strength of the subtropical ridge (See **Figure 8**).

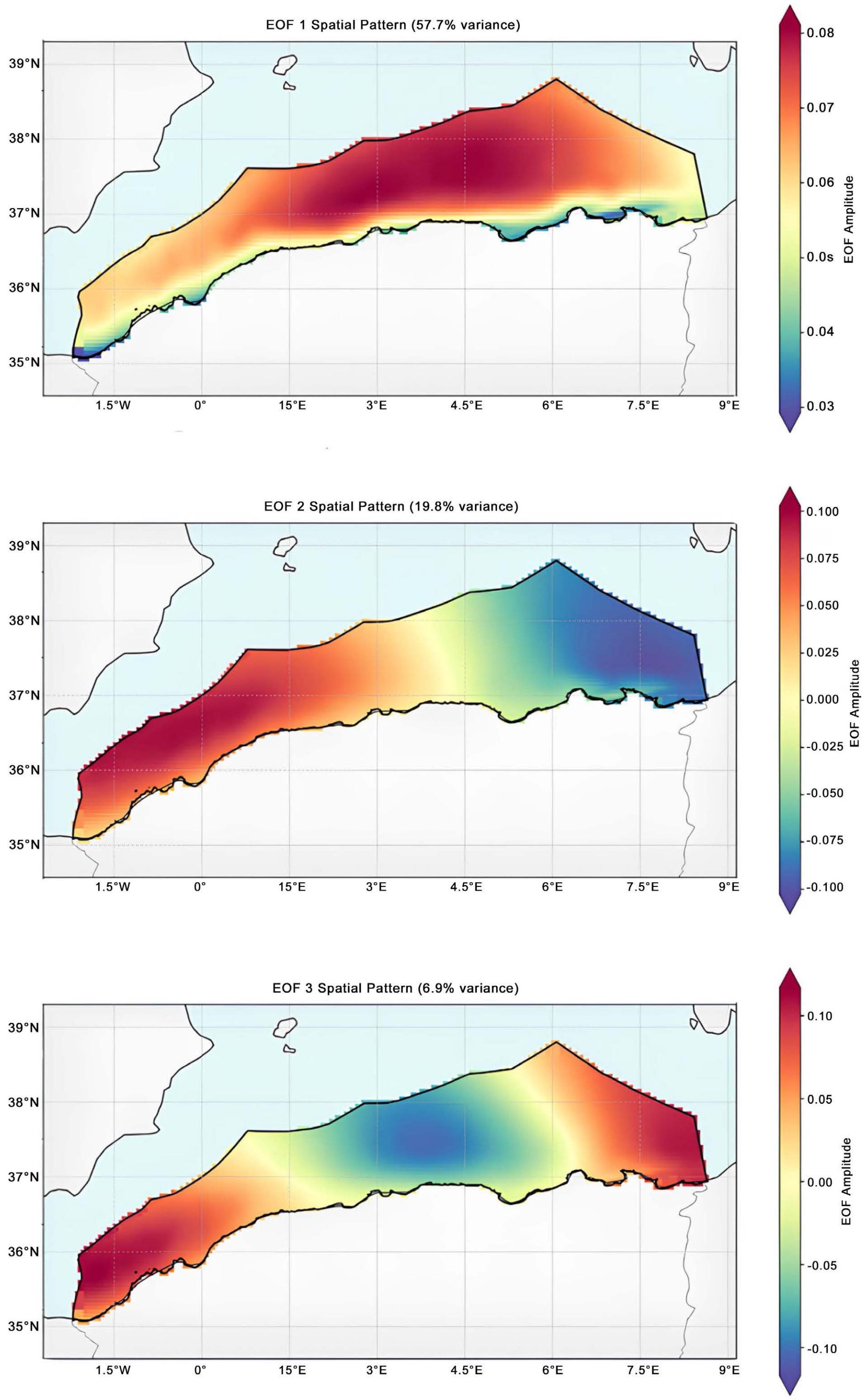

Figure 8. Empirical Orthogonal Function (EOF) analysis applied to EEZ.

Mode 3 (9%) suggested more localized wind systems such as sea breezes and topographically induced circulation. Principal Component (PC) time series indicated periodic intensification of Mode 1 during major NAO+ phases and climate anomalies.

4.6. Site Selection Scores and Spatial Ranking

Applying the composite site suitability scoring method, high-scoring zones were concentrated in the northeastern EEZ, particularly between 36.6˚N - 36.9˚N and 7.0˚E - 8.5˚E. Depth and distance to shore constraints were integrated to screen technically feasible locations. Three sites—designated Site A, B, and C—were ranked highest based on their overall composite scores: Site A: Wind speed = 6.6 m/s; Depth = 141.25 m; Distance = 22 km; Site B: Wind speed = 6.4 m/s; Depth = 149 m; Distance = 17 km; Site C: Wind speed = 4.25 m/s; Depth = 30 m; Distance = 12 km. Sites A and B fall within deep-water zones (>60 m) and are therefore suitable for floating offshore wind turbine technologies, whereas Site C lies within the fixed-bottom feasibility range (<60 m depth).

4.7. Offshore Energy Output Simulation

Using the hourly wind speed time series for each selected site, turbine power output was calculated at each time step and summed to estimate annual energy production for a hypothetical offshore wind farm comprising 20 turbines rated at 15 MW each. Assuming a power coefficient of 0.45 and standard air density, the estimated annual energy production was as follows: Site A: Estimated output = 472 GWh/year; Site B: Estimated output = 438 GWh/year; Site C: Estimated output = 419 GWh/year. These energy yields position the selected sites among the most productive in the western Mediterranean region. Sensitivity analyses showed that minor increases in wind speed (e.g., +0.2 m/s) could enhance production by more than 10%, underscoring the importance of selecting high-wind zones (See Figure 9).

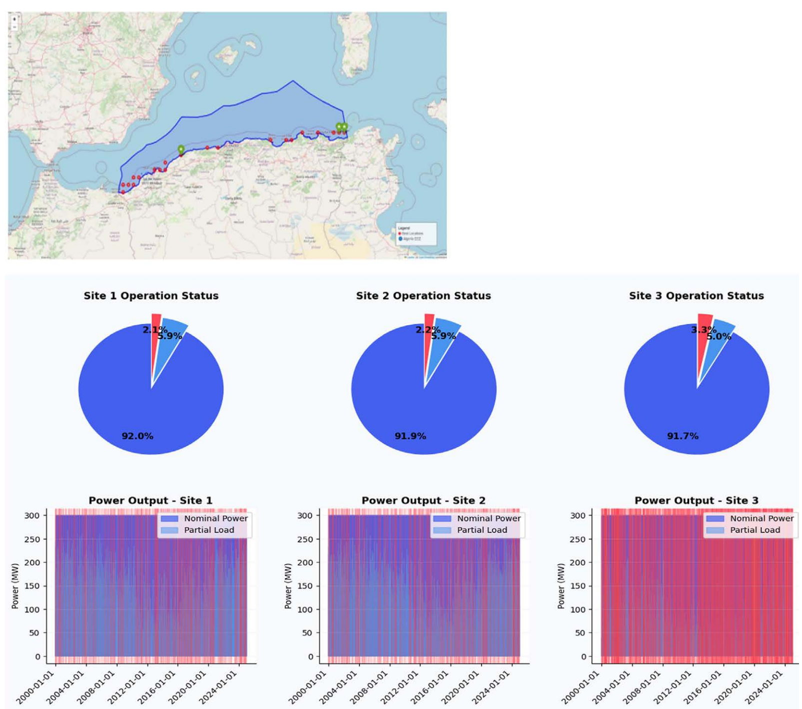

Figure 9. Assessment of offshore wind farm performance.

5. Discussion

The results of this study underscore the untapped potential of the Algerian Basin for offshore wind energy development [13] [14]. The observed east-west gradient in wind speed aligns with atmospheric circulation patterns driven by the prevailing westerlies and modified by Mediterranean climate dynamics [15] [16]. EOF results revealed dominant zonal structures, with winter seasons characterized by strong and stable wind regimes, particularly in the eastern EEZ. These findings are consistent with previous work in the western Mediterranean, including studies in Spanish and Italian waters [3]. The Mann-Kendall analysis indicates no statistically significant long-term trend in basin-averaged wind speed over the period [17] [18]. Such trends may enhance the long-term reliability of wind power generation in the region. However, this also necessitates further investigation into extreme wind events and their implications for turbine design and operational safety. From a methodological perspective, the integration of environmental parameters (wind speed, depth, and distance to shore) into a composite score provides a practical framework for initial site screening. This approach, while effective in identifying priority zones, should be complemented by detailed environmental impact assessments (EIAs), socio-economic analyses, and stakeholder consultations. Additionally, policy alignment and regulatory frameworks must evolve to accommodate offshore wind energy in Algeria. At present, there are limited legal or institutional provisions governing offshore renewables. International cooperation with Mediterranean neighbors and alignment with EU strategies on the blue economy [19], could catalyze investment and knowledge transfer. Limitations of the study include the reliance on reanalysis data [6], which, despite high resolution, may not capture fine-scale turbulence or microclimatic effects. Future work should incorporate in-situ measurements, high-resolution atmospheric modeling, and wave-current interactions to refine site assessments. Seasonal forecasting and climate model projections could also help assess interannual variability and long-term viability.

Finally, the Algerian Basin possesses significant and consistent wind energy resources, particularly in the eastern zone. This research lays a foundation for integrating offshore wind into national energy planning and contributes to Algeria's broader climate resilience and sustainability goals.

The results of this study confirm the substantial yet underexploited potential of the Algerian Basin for offshore wind energy development. The mean wind speed, estimated at 5.59 m/s, falls within the range reported for other Mediterranean regions [13] [14], with maxima reaching 24.16 m/s and variability spanning from calm conditions to intense episodes, comparable to observations along the Libyan coast [20]. Seasonal variability is pronounced:

- **Winter (DJF):** Strong winds (>3.5 m/s) in the central and eastern basin, dominated by west to southwest regimes, consistent with [16].
- **Summer (JJA):** Reduced speeds (3 - 3.5 m/s) with a predominance of east to northeast winds [3].

- **Transitional seasons (MAM, SON):** Weaker winds (1.5 - 2 m/s) and calm regimes in the central basin, also observed along the Libyan coast [21].

EOF analysis revealed dominant zonal structures, with the first mode explaining 57.7% of the variance, characterized by maximum intensity in the central coastline and winds from north to southeast. Modes 2 (19.8%) and 3 (6.9%) respectively reflect an east-west contrast and localized variations. These patterns align with Mediterranean atmospheric circulation regimes and the influence of prevailing westerlies. The Mann-Kendall trend analysis indicates statistical stability in mean wind speeds over the past 84 years (slope = -1.03×10^{-3} m/s/year), in agreement with [17] and [18], who attribute this lack of a marked trend to natural climate variability and phenomena such as the NAO. However, other studies in the western Mediterranean [10], have reported intensification signals potentially linked to climate change, warranting continued monitoring. The combined assessment of environmental parameters (wind speed, bathymetry, distance to shore) identified 22 favorable sites, including three priority locations:

1) **Sites 1 and 2 (northeast):** High wind speeds, depths > 60 m, moderate distance from shore suitable for floating wind technology [19].

2) **Site 3 (Ténès):** Lower mean speed (4.25 m/s), shallow depth (~31 m), and close proximity to shore (~12 km)—favorable for fixed-bottom foundations [22] and strategically relevant for a technically and economically viable pilot project [23].

Environmental considerations remain critical: while deeper areas may reduce ecosystem disturbance [24], the specific impacts of floating systems remain poorly documented [25] and call for comprehensive Environmental Impact Assessments (EIAs), including socio-economic analyses and stakeholder engagement. From an institutional standpoint, integrating offshore wind into Algeria's energy mix will require regulatory framework adaptation and enhanced policy coordination. Cooperation with Mediterranean neighbors and alignment with European Union blue economy strategies could foster investment and technology transfer. Study limitations include reliance on high-resolution reanalysis data, which may still fail to capture small-scale phenomena. In-situ measurements, high-resolution atmospheric modeling, and wave–current interaction studies are recommended to refine site assessments. Incorporating climate projections would also help evaluate long-term viability. Finally, the Algerian Basin particularly its eastern sector offers favorable and consistent conditions for offshore wind development. These findings provide a robust scientific foundation for integrating this resource into national energy planning, thereby contributing to Algeria's broader sustainability and climate resilience objectives.

6. Conclusion

This study provides valuable insights into the wind dynamics of the Algerian Basin, focusing on a long-term period from 1940 to 2024 one of the most extensive timeframes analyzed in national wind climatology. Using ERA5 reanalysis data and advanced analytical tools such as STL decomposition and Empirical Orthogonal Functions (EOF), we captured the spatial and temporal complexity of wind regimes within the Algerian Exclusive Economic Zone (EEZ). Our findings reveal distinct seasonal and geographic variations in wind patterns. Winter (DJF) shows the strongest wind activity, particularly in the eastern basin (6.5˚E to 9˚E), with average speeds exceeding 3.5 m/s and a dominant north westerly direction. In summer (JJA), wind speeds shift to the central basin (1.5˚E to 5˚E), ranging from 3 to 3.5 m/s, with prevailing winds from the northeast and east. Spring and autumn are characterized by weaker, calmer wind conditions, particularly in the central region. These patterns have important implications for offshore energy development, maritime safety, and coastal planning. Scientifically, this work confirms significant seasonal variability in both wind speed and direction. The EOF analysis helped identify dominant modes of variability and regional structures, supporting a more detailed understanding of atmospheric behavior over the basin. This approach strengthens the foundation for climate-informed infrastructure planning and long-term energy policy. A major contribution of this study lies in identifying three priority zones for offshore wind farm deployment. By integrating climatological analysis with site-selection criteria such as depth, coastal proximity, and accessibility, we determined that two areas require floating turbine technologies, while one site appears viable for fixed-foundation systems. This insight highlights Algeria's potential for offshore wind development and its strategic opportunity to diversify the national energy mix. Beyond its technical contributions, this work fills a major gap in regional wind studies and demonstrates the potential of applying climate data for sustainable development. It underscores Algeria's ability to align with global energy transition efforts and enhance resilience in the face of climate change. Looking forward, this study can serve as a foundation for future research and encourage further exploration in wind climatology and offshore energy. By bridging scientific insight with practical planning, it offers a valuable tool for policy-makers, researchers, and developers aiming to support Algeria's renewable energy transition in a sustainable and socially responsible way.

7. Limitation

The spatial resolution of the data limits accuracy, especially in coastal areas. The reliability of the results is also affected by the availability and quality of observational data used for validation. Computational constraints, particularly processing capacities, reduce the overall effectiveness and precision of the analysis. Coastal zones present specific challenges, where wind variability depends on additional parameters. Future studies should integrate more variables such as atmospheric dynamics, pressure, and air density.

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Conflicts of Interest

The authors declare no conflicts of interest.

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