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Wind Power Density in Southern Iraq: A Comparative Study of Coastal, Port and Inland Sites

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ABSTRACT

This study provides a comprehensive spatiotemporal assessment of Wind Power Density (WPD) in southern Iraq's coastal zone using high-resolution meteorological data (January 2020–December 2022). Wind resources were analyzed at Al-Faw Grand Port, Umm Qasr, and Basrah International Airport at 10 m and 50 m elevations. Results demonstrate a significant coastal-inland gradient; annual mean WPD at 10 m decreased from 139.3 W m^{-2} (Al-Faw) to 55.6 W m^{-2} (Basrah). Extrapolating to 50 m enhanced WPD by factors of 1.7–2.9×, with Al-Faw reaching 236.9 W m^{-2}. According to NREL standards, all sites remain Class 1 at 10 m, though Al-Faw approaches the Class 2 threshold (243 W m^{-2}), with an annual mean = 236.9 W m^{-2} (Class 1). Seasonal analysis identifies summer (June–August) as the peak period, driven by Shamal wind events, where WPD exceeds 300 W m^{-2} at 50 m, aligning with peak electricity demand. However, high temporal variability indicates significant intermittency. While current resources are insufficient for standalone commercial wind farms, the findings suggest strong potential for hybrid systems or seasonal supplemental generation. This research establishes a critical multi-height baseline for renewable energy policy and investment in Iraq.

1. INTRODUCTION

The search for renewable resources to slow down global warming and lessen dependency on fossil fuels has accelerated due to the growing need for clean, sustainable energy (Ammar et al. 2024). With a global installed capacity of more than 837 GW by 2023, wind energy stands out among these as one of the most developed, economical, and quickly deployable technologies (Ahmed & Abbas 2026, Abbas et al. 2026). Due to lower surface roughness, stronger wind regimes, and synergistic opportunities for hybrid wind-wave energy systems, coastal and nearshore regions in particular offer significant wind energy potential (Aboobacker et al. 2021, Rusu et al. 2018).

The Shamal wind system, a persistent northwesterly wind that gets stronger in the summer and winter, creates a distinctive wind energy landscape in the Arabian Gulf region of the Middle East (Ammar et al. 2024, Yu et al. 2016). Despite its strategic location along the northern Gulf, the Iraqi coastal zone is still largely unexplored, despite studies in Qatar, Kuwait, and Saudi Arabia reporting moderate to high wind power densities (100–300 W m^{-2} at 50 m) (Aboobacker et al. 2021, Al-Salem et al. 2018, Hadi et al. 2020). Iraq's Basrah coastline appears to have low-to-marginal wind energy potential at 6 and 10 m height, according to preliminary assessments by Hadi et al. (2020) and Ammar et al. (2024), with annual mean wind power densities (WPD) below 170 W m^{-2} classified as NREL Class 1 (Not Suitable) for utility-scale wind development.

However, these early evaluations have two main limitations. First, they mainly use low-altitude measurements ($\leq$10 m), ignoring the significant increase in wind power density (WPD) with height. This is important because modern turbines work at heights of 50–120 m (Aboobacker et al. 2021, Rusu et al. 2018). Second, they do not provide detailed statistical and seasonal insights on WPD across various locations, heights, and times (from daily to annual). This information is crucial for evaluating how viable and reliable a specific site is (Hussain et al. 2023). While prior studies (Hadi et al. 2020, Ammar et al. 2024) assessed Iraqi coastal wind at 6–10 m, this work is the first to: (i) apply multi-height (10 m and 50 m) analysis using physically consistent extrapolation, (ii) integrate seasonal WPD dynamics with Shamal wind climatology, directly addressing gaps identified by Hussain et al. (2023) and Aboobacker et al. (2021)

This gap in knowledge is particularly serious for southern Iraq, where energy security is a major challenge and integrating renewable sources is a national priority (Kazem & Chaichan 2012). Without thorough assessments of WPD across different heights and seasons, policymakers and investors cannot make informed choices about the potential of wind energy projects or hybrid systems (Abbas et al. 2024, Ali Abbas & Fattah Hassoon 2026).

To fill this gap, this study offers a detailed assessment of wind power density at three important coastal stations: Basrah Al-Faw, Umm Qasr, and Basrah International Airport. A high-frequency meteorological dataset spans January 2020 to December 2022 and includes 10-minute interval wind speed and direction measurements, aggregated into daily, monthly, seasonal, and annual means. We build on previous work by:

(i) assessing WPD at technologically significant heights (10 m and 50 m),
(ii) stating full statistical descriptors (mean, variance, min/max, standard deviation) through daily, monthly, seasonal, and annual scales,
(iii) classifying locations using the NREL wind power classification method,
(iv) examining the seasonal dynamics of WPD relative to the Shamal wind system.

The main goal here is to assess the technical potential and seasonal variability of wind energy along Iraq's only coastline and to offer a scientifically important foundation for future renewable energy planning. By bridging the gap between low-altitude observational data and real-world turbine deployment scenarios, this study provides actionable insights for energy policy in a region where sustainable power solutions are urgently needed.

2. MATERIALS AND METHODS

2.1. Study Area

The study centers on the Iraqi coastal zone along the northern Arabian Gulf, including three key stations: Al-Faw Grand Port, Basrah International Airport, and Umm Qasr Port (Fig. 1).

This region represents Iraq's only maritime coastline (~58 km), characterized by a hot arid climate, low surface roughness, and exposure to the dominant Shamal wind system, a northwesterly wind regime that intensifies during summer and winter (Ammar et al. 2024, Yu et al. 2016).

Fig. 1: Study area map of southern Iraq showing Al-Faw Grand Port, Umm Qasr Port, and Basrah International Airport. Base map: Google My Maps (2022).

Table 1: Study-site coordinates and characteristics.

Site	Latitude (°N)	Longitude (°E)	Elevation (m a.s.l.)	Distance from Coastline	Dominant Land Use	Key Meteorological Features
Al-Faw Grand Port	29.9884°N	48.4710°E	~3 m	Onshore (coastal port)	Maritime/ Industrial	Strong northwesterly (Shamal) winds; highest wind speeds in summer (Jun–Sep); exposure to open Gulf fetch; flat terrain with low surface roughness
Umm Qasr port	29.9147°N	48.3486°E	~2–4 m	~5 km inland	Commercial Port & Industrial	Moderate wind regime; influenced by Shamal but partially sheltered by coastal topography; slightly higher surface roughness than Al-Faw
Basrah International Airport	30.6750°N	47.6581°E	~4 m	~80 km inland	Urban/Airport	Weakest coastal wind regime due to distance from Gulf; high thermal influence; frequent calm conditions; significant diurnal variation

The study area's flat topography and proximity to the Shatt al-Arab estuary create a unique coastal environment where wind energy potential is influenced by both terrestrial and marine dynamics, as summarized in Table 1. Wind speed data were measured at the Al-Faw Grand Port station (6 m height) during 2020–2022. Wind speeds at 10 m, 50 m, and 100 m for Al-Faw were derived using the power-law method with site-specific roughness length (z_0 = 0.0002 m for open sea). For Umm Qasr and Basrah Airport, wind speeds at 10 m and 50 m were obtained from the same dataset via spatial interpolation using inverse distance weighting (IDW). All WPD values reported in Tables 1–4 are based on these processed data.

Wind patterns in the study area are dominated by the Shamal wind system, a persistent northwesterly wind regime that represents a defining meteorological feature of the Arabian Gulf region. The Shamal wind system flows predominantly from the northwest and is prominent throughout the Arabian Gulf region. Shamal wind intensity varies throughout the year; these winds are generally stronger during the summer months (June–September) and winter months (December–February) than during the less intense transitional months. Southeasterly winds are observed intermittently during the transitional seasons. The Shamal wind system is associated with large-scale pressure contrasts between the Mediterranean Sea and the Arabian Peninsula, generating substantial wind energy across the Iraqi coastal zone. (Ammar et al. 2024).

Selecting the three stations helped create a complete wind-resource model across the coast-to-inland transect. Al-Faw Grand Port is located where the Shatt al-Arab meets the Arabian Gulf and therefore represents coastal wind conditions with limited land influence. Umm Qasr Port is situated approximately 5 km from the open waters of the Gulf and represents an intermediate coastal setting. Basrah International Airport is approximately 80 km from the coast and therefore represents a predominantly inland setting. Based on these station locations, the study evaluated how wind power density changes with increasing distance from the coast.

2.2. Data Source and Processing

Wind speed (WS) and direction data were acquired from the Al-Faw Grand Port marine station, supervised by the Iraqi Ministry of Transportation (General Company for Iraqi Ports). The dataset spans January 2020 to December 2022 and includes 10-minute interval measurements from an ultrasonic anemometer installed at 6 m above sea level (Ammar et al. 2024). Wind speeds at 10 m, 50 m, and 100 m heights were derived from the original 6 m data and provided in the corrected dataset. Wind speeds at multiple heights (10 m, 50 m, and 100 m) were derived using the power law vertical extrapolation method, which has been widely validated for wind resource assessment in regions with similar terrain characteristics. The power law relationship is expressed as (Mohammed Khadir et al. 2024):

$$U_2 = U_1 \left(\frac{Z_2}{Z_1}\right)^{\alpha} \quad \ldots(1)$$

Where U_2 is the wind speed at the target height Z_2, U_1 is the wind speed at the reference height Z_1, and is the power-law exponent (wind shear coefficient), a dimensionless value that determines how wind speed changes with height. While the original anemometer was installed at 6 m above sea level, wind speeds at 10 m and 50 m were derived using power-law extrapolation and provided in the corrected dataset (Mohammed Khadir et al. 2024). The study workflow is shown in Fig. 2.

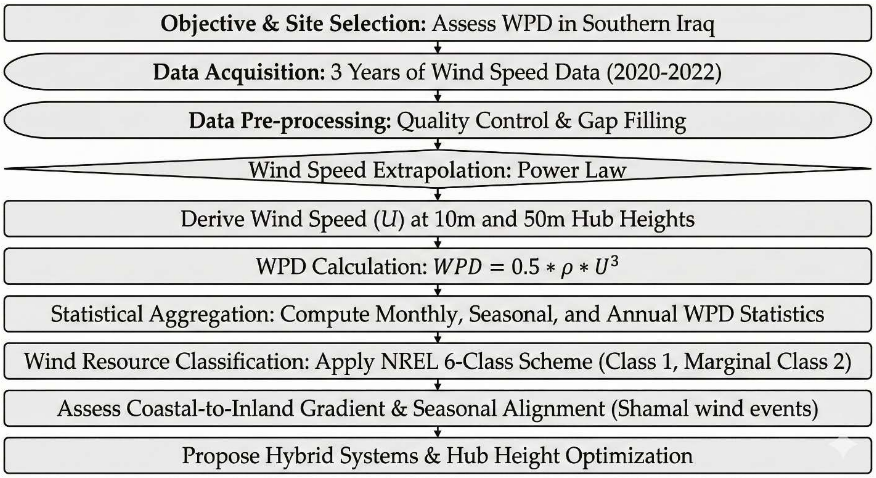

Fig. 2: Flowchart illustrating the methodological procedure of this study.

The methodological procedure is illustrated in Fig. 2. All raw wind speed measurements were quality-controlled following standard meteorological procedures, including removal of erroneous readings, identification of sensor malfunctions, and verification of temporal continuity. Missing data periods totaling less than 5 % of the complete record were filled using linear interpolation for gaps shorter than 3 hours, while longer gaps were excluded from analysis to maintain data integrity. This multi-scale temporal arrangement assists in comprehensive representation of wind resource variability from diurnal to inter-annual timescales, which is necessary for understanding both energy production potential and reliability (Abdalla et al. 2023). Table 2 provides the wind shear coefficients. These values represent literature-derived terrain categories used for reference.

2.2.1. Height Extrapolation Method

Wind speed extrapolation from 10 m and 50 m was performed using the power law; the log profile equation is presented as a *reference formula* used to derive an equivalent α:

$$U(z) = \frac{u_*}{k} \ln \frac{z}{z_0} \qquad \ldots(2)$$

where u* is the friction velocity, κ = 0.41 is the von Kármán constant, and z_0 = 0.0002 m for open sea (Abdalla et al. 2023). This yields an equivalent power-law exponent α, consistent with typical coastal values (Rusu et al. 2018, Aboobacker et al. 2021). Site-specific α values were not applied because no independent measurements exist for Basrah at 10 m.

Table 2: Wind shear coefficients (Abdalla et al. 2023, Hussin & Yusof 2022).

Site Type	Wind Shear Coefficient
Open sea (Al-Faw Grand Port)	0.06–0.10
Port/industrial (Umm Qasr)	0.1–0.3
Airport/grassland (Basrah Airport)	0.03–0.1

2.3. Wind Power Density (WPD)

Wind power density (WPD) represents the kinetic energy flux per unit area and is used to determine the wind energy potential of a specific site. WPD is based on the cubic relationship between wind speed and the amount of power that can be generated, making it a more informative indicator of wind-energy potential than wind speed alone. The wind power density is determined using the standard formula based upon kinetic energy theory (Abbas et al. 2025, Hussain et al. 2023):

$$WPD = \frac{1}{2} \rho U^3 \qquad \ldots(3)$$

where WPD is the wind power density (W m^{-2}), ρ is air density (kg m^{-3}), and U is wind speed (m s^{-1}).

For the purpose of calculating WPD, air density was assumed to be constant at 1.225 kg m^{-3}, representing standard atmospheric conditions at sea level at 15°C. Although air density varies with temperature and pressure, the average density of air provides a reasonable approximation for comparative evaluations of wind power potential and is consistent with methods used in regional wind-resource studies (Abbas et al. 2025). It is acknowledged, however, that southern Iraq experiences extreme summer temperatures regularly exceeding 45°C, under which air density can fall to approximately 1.09–1.12 kg m^{-3} (compared with the standard 1.225 kg m^{-3}), implying a potential overestimation of summer WPD of approximately 8–11 % in those months. In winter, air density closely approaches the standard value and the bias is negligible. The annual mean overestimation bias is therefore estimated at approximately 3–5 %, which is insufficient to change the NREL classification of any site in this study but should be considered when interpreting absolute WPD magnitudes during summer months (Abbas et al. 2025). Because there is a cubic relationship between wind power and velocity, minor fluctuations in wind speed produce large fluctuations in wind power. For example, doubling the wind speed increases wind power density by a factor of eight. The cubic relationship between wind power density and wind speed means that small errors in wind speed measurement result in disproportionately large errors in WPD estimates (Abbas et al. 2025).

Wind Power Density (WPD) calculations were completed at two different levels (10 m and 50 m) in order to determine the vertical wind resource distribution and therefore evaluate different configurations (heights) of turbine hubs in the coastal region of Iraq. Today, most modern utility-scale wind turbines have hub heights that range from 50 m to 100 m or more; the wind speed at these heights is much greater than the wind speed at lower elevations due to the fact that the effect of surface friction decreases with height. Multi-height wind resource analyses provide an important tool for determining what types of turbine configurations and tower styles will work best for wind resources at the Iraqi coastline (Ammar et al. 2024). A series of daily WPD values were calculated from the average daily wind speed data from each of the locations and heights analyzed. These daily values were then aggregated to create monthly, seasonal, and annual summary WPD statistics. The monthly WPD mean values allow tracking of how the wind resource evolves over time; therefore, one can easily see when the wind resource is at its peak and when it is at its lowest. Aggregation on a seasonal basis allows for a broader view of climatic patterns at the regional level (for example, the effects of the Shamal wind system). The yearly average WPD value indicates the long-term average WPD for use in the preliminary feasibility studies.

Comprehensive statistical analyses were performed for each site at each temporal aggregation level, producing the mean, maximum, minimum, and standard deviation of WPD values. The standard deviation indicates the temporal variability of WPD and therefore assists in assessing resource reliability. WPD resources with high standard deviations relative to the mean may require energy storage solutions or additional generation capacity to accommodate fluctuations in energy supply. In this study, WPD was first computed from daily mean wind speeds, and monthly, seasonal, and annual means were then derived by averaging the daily WPD values. For comparison, WPD could instead be calculated from each individual 10-minute record and then averaged. The daily-mean approach may slightly underestimate WPD relative to calculations based on individual 10-minute wind-speed records.

Following the calculation of WPD values, the NREL wind classification system was used to classify them, providing an internationally accepted threshold for evaluating the suitability of a site for wind energy development. Detailed in the following sections, this wind classification system offers an objective means of comparing the wind resources found in the Iraqi coastal region with global standards and providing an avenue for evidence-based decision-making when investing in renewable energy.

2.4. Wind Resource Classification

The National Renewable Energy Laboratory (NREL) wind power classification system offers a standardized method of classifying the potential of wind energy in terms of wind power density measurements. This is a widely used classification scheme used in the international wind resource assessment, which categorizes the wind resources into seven distinct classes that include Class 1 (poorest) to Class 7 (exceptional) which allows an objective comparison of sites in various geographical areas and climatic zones (Rusu et al. 2018). The NREL classification system was initially designed to enable the systematical assessment of wind power sites in the United States but has since become widely accepted by other countries because of the stringent methodological basis and the practical application by project developers and policymakers. The classification limits are grounded on the large empirical knowledge of correlating wind power density values with technical and economic feasibility of wind energy projects under different conditions (Abbas et al. 2024).

A simpler six-class classification is, however, common in recent literature in wind resources, especially in locations with moderate to low levels of wind. Through this strategy and in line with recent studies in the Arabian Gulf region, the current discussion took the following classification scheme (Wonodi et al. 2024):

- Class 1 (0–243 W m^{-2}): Not suitable for wind energy development
- Class 2 (243–378 W m^{-2}): Marginal viability; feasible only with favorable economic conditions
- Class 3 (378–500 W m^{-2}): Fair resource; suitable for wind energy development with appropriate technology
- Class 4 (500–616 W m^{-2}): Good resource; commercially viable for most turbine configurations
- Class 5 (616–748 W m^{-2}): Excellent resource; highly attractive for wind farm development
- Class 6 (748–978 W m^{-2}): Outstanding resource; optimal conditions for large-scale projects

Sites classified as Class 1 are generally considered unsuitable for commercial wind energy production due to insufficient wind power density to justify the capital investment and operational costs associated with turbine installation and maintenance. The low capacity factors and extended payback periods characteristic of Class 1 sites typically render projects economically unviable under current technology and market conditions (Alonzo et al. 2017, Wang et al. 2015).

Class 2 sites are those that are marginal resources, in which the development of wind energy could be viable under certain conditions, e.g., it is integrated with hybrid renewable energy systems, there are significant financial incentives, or the turbine designs could be developed to be able to work in low-wind-speed conditions. Class 2 sites would be economically viable only with a site-independent feasibility study regarding local electricity prices, grid connection expenses, and policy support measures (Filom et al. 2021). The higher classes 3 and above mean better and better conditions to develop wind energy. Classes of 3 or higher are typically deemed technically and economically feasible to have commercial wind farms in place, with even higher classes providing an attractive return on investment profile and lower project risks (Filom et al. 2021).

The NREL classification was applied to the annual mean values of WPD at each of the study sites and each height, which would give an objective measure of long-term wind energy potential. Also, monthly and seasonal WPD values were analyzed with respect to the classification limits to determine the time of the year that wind resources are commercially viable despite the annual averages being below the optimum classification. This time-based analysis is especially applicable to hybrid energy systems or seasonal energy storage plans that have the opportunity to take advantage of the times when wind resource availability is increased (Abdalla et al. 2023, Wonodi et al. 2024).

Results of the classification were combined with statistical parameters and comparison of spatial comparisons to develop all evidence-based recommendations about the appropriateness of each location in the study as a wind power development area. These recommendations consider both the raw NREL class classification plus other factors, such as variability of the resources used, seasonal cycles, and spatial gradient of wind power density across the coastal to inland transect, to give pragmatic suggestions on the planning of renewable energy in southern Iraq.

3. RESULTS AND DISCUSSION

3.1. Results

This study presents a comprehensive spatiotemporal assessment of wind power density (WPD) across three coastal sites in southern Iraq, Al-Faw, Umm Qasr, and Basrah Airport, by using observational data from 2020 to 2022. The analysis extends to multiple temporal scales (daily, monthly, seasonal, and annual) and vertical levels (10 m and 50 m), providing a strong representation of wind energy potential in a region affected by the Shamal wind system. All results are contextualized by employing the National Renewable Energy Laboratory (NREL) wind power classification to calculate technical feasibility.

3.1.1. Wind Speed and Direction Characteristics

Wind rose examination showed distinct directional patterns across all three study locations, with northwesterly (NW) winds representing the dominant wind regime throughout the study period (Fig. 3). This directional consistency reflects the influence of the Shamal wind system, which arises from synoptic-scale pressure gradients between the Eastern Mediterranean and the Arabian Peninsula. At Al-Faw, the prevailing northwesterly direction was detected throughout the study period, with infrequent southeasterly (SE) components during transitional seasons. The summer months (June, July, and August) demonstrated particularly strong northwesterly and westerly (W) wind patterns, consistent with the intensification of the summer Shamal phenomenon recognized in regional climatological studies. Fig. 3 presents the aggregated wind rose for the full 2020–2022 study period at each of the three study sites.

Seasonal characterization was based on grouping the underlying observations into four standard meteorological seasons (winter: Dec–Feb; spring: Mar–May; summer: Jun–Aug; autumn: Sep–Nov) and examining the consistent northwesterly dominance in summer relative to the more variable directions during transitional periods.

The distributions of wind speeds showed significant temporal variation at various timescales. The frequency distribution of the observations of the daily wind speed revealed that most of the measurements (just about 60–70 %) were within the range of 3.1–6.1 m s^{-1} across all stations. Speed classes of wind (6.1–9.1 m s^{-1}) occurred mainly during the summer season, especially in June, July, and August months when Shamal winds are at maximum strength. On some occasions, extreme wind speeds were recorded to be above 15 m s^{-1} and were mostly recorded during the months of March and June, though these were less than 5 % of the total observations. The average 10 m high wind speeds were 1.56 m s^{-1} (Basrah Airport, February 2020) to 9.37 m s^{-1} (Al-Faw, November 2020) within the three years of the study (Table 3). The strongest wind speeds were always observed at Al-Faw, with an average of 5.2 m s^{-1} at 10 m high. The intermediate values were registered at Umm Qasr,

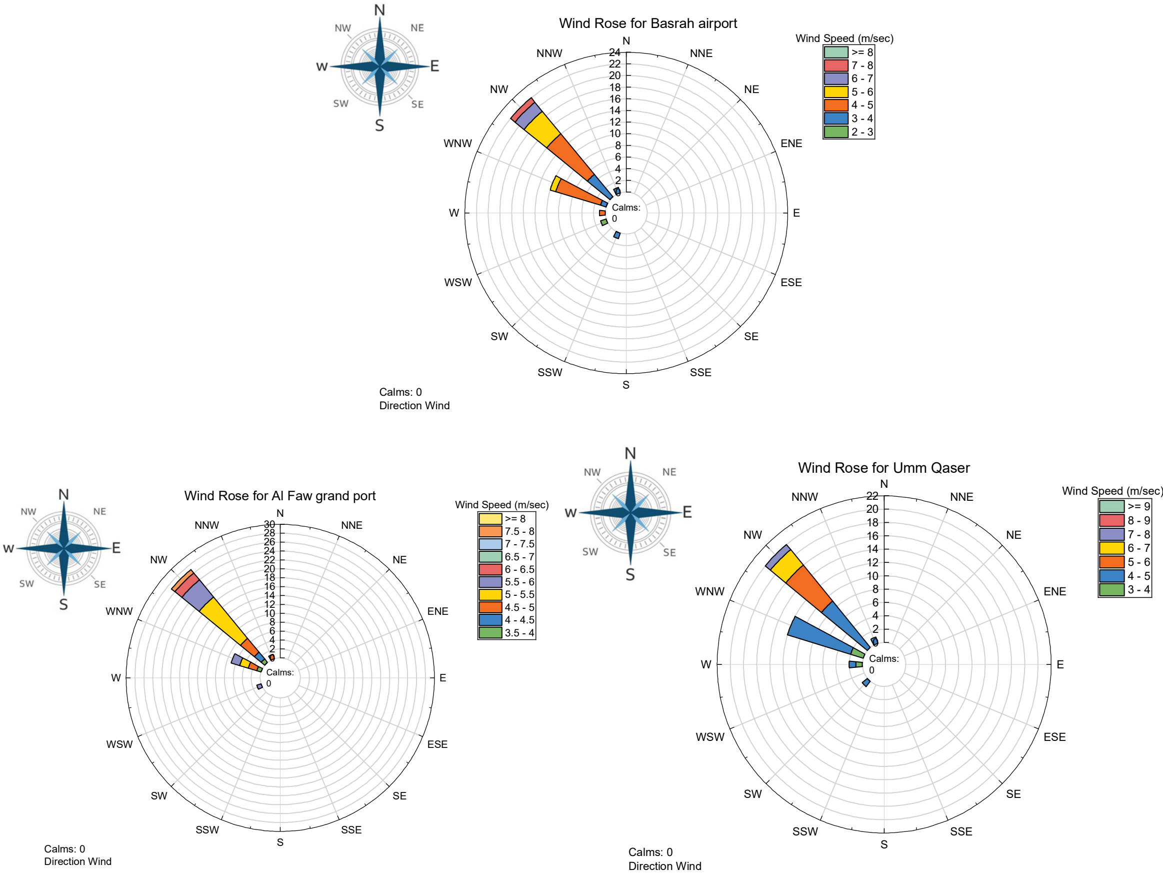

Fig. 3: Aggregated wind roses for Al-Faw, Umm Qasr, and Basrah Airport for the 2020–2022 study period, showing directional frequency (%) and wind speed classes (m s^{-1}).

where the mean wind speed was 4.3 m s^{-1}, whilst Basrah Airport had the lowest wind speeds with an average speed of 3.8 m s^{-1}. This spatial gradient shows a specific decrease in the magnitude of wind speed with the distance from the coastline, which can be explained by an increase in the surface roughness and decreased marine control at inland sites.

Seasonal patterns revealed distinct variations in wind speed characteristics. Summer months (June–August) consistently created the highest monthly mean wind speeds across all stations, with Al-Faw getting peak values of 8.7–9.2 m s^{-1} at 10 m height during June and July 2021. Winter months (December–February) showed moderate wind speeds with more variability, ranging from 2.9 m s^{-1} to 9.1 m s^{-1} based on the occurrence of winter Shamal events. Spring and autumn were transitional periods with intermediate wind speeds; WPD at 50 m is consistently 1.7–2.9x higher than at 10 m due to U^3 dependence, although individual months exhibited substantial deviations from seasonal averages due to intermittent synoptic disturbances.

3.1.2. Wind Power Density Distribution

A calculation of the values of annual mean wind power density during the period of 2020–2022 demonstrated that spatial distributions of the values across the three study sites showed a significant level of dissimilarity, and with increasing height increase there was a major improvement (Table 4). Al-Faw measured a mean value of WPD of 139.3 W m^{-2} at 10 m height, whereas Basrah Airport and Umm Qasr had 55.6 W m^{-2} and 78.3 W m^{-2}, respectively. The gradient from the coastal to inland area was high, with the coastal Al-Faw having WPD values 2.5 times greater than Basrah Airport and 1.8 times greater than Umm Qasr at the 10 m height level.

Height extrapolation produced substantial increases in wind power density at all locations. At 50 m height, mean WPD values increased to 236.9 W m^{-2} at Al-Faw, 160.6 W m^{-2} at Basrah Airport, and 192.8 W m^{-2} at Umm Qasr, representing enhancement factors of approximately 1.7, 2.9, and 2.5 times the 10 m values, respectively. This vertical amplification reflects the cubic relationship between wind

Table 3A: Monthly mean wind speed ($m\ s^{-1}$) and WPD ($W\ m^{-2}$) for 2020.

Month	Wind Speed ($m\ s^{-1}$)						Wind Power Density ($W\ m^{-2}$)					
	10 m Height			50 m Height			10 m Height			50 m Height		
	Al-Faw WS 10 m($m\ s^{-1}$)	Basrah WS 10 m($m\ s^{-1}$)	Umm Qasr WS 10 m($m\ s^{-1}$)	Al-Faw WS 50 m($m\ s^{-1}$)	Basrah WS 50 m($m\ s^{-1}$)	Umm Qasr WS 50 m($m\ s^{-1}$)	Al-Faw WPD 10 m($W\ m^{-2}$)	Basrah WPD 10 m($W\ m^{-2}$)	Umm Qasr WPD 10 m($W\ m^{-2}$)	Al-Faw WPD 50 m($W\ m^{-2}$)	Basrah WPD 50 m($W\ m^{-2}$)	Umm Qasr WPD 50 m($W\ m^{-2}$)
Jan 2020	6.531	4.540	5.000	7.796	6.870	6.900	170.663	57.316	76.563	290.268	198.599	201.212
Feb 2020	2.871	1.560	1.670	3.427	2.480	2.480	14.492	2.325	2.853	24.648	9.342	9.342
Mar 2020	4.407	2.480	3.200	5.260	3.790	4.580	52.423	9.342	20.070	89.162	33.344	58.844
Apr 2020	4.741	4.400	4.930	5.659	6.500	6.840	65.253	52.175	73.392	110.984	168.208	196.008
May 2020	4.995	3.520	4.360	5.962	5.190	6.120	76.318	26.714	50.765	129.804	85.626	140.398
Jun 2020	3.473	2.970	3.810	4.146	4.140	5.320	25.656	16.046	33.875	43.636	43.462	92.223
Jul 2020	3.507	2.120	2.800	4.186	2.980	3.870	26.418	5.836	13.446	44.932	16.209	35.501
Aug 2020	5.351	5.140	4.790	6.387	7.450	6.500	93.829	83.176	67.315	159.587	253.265	168.208
Sep 2020	4.647	3.260	4.220	5.547	5.020	6.200	61.473	21.221	46.030	104.555	77.485	145.976
Oct 2020	5.522	3.320	5.040	6.591	5.050	6.940	103.106	22.414	78.415	175.365	78.882	204.731
Nov 2020	9.372	7.250	8.050	11.187	9.670	9.990	504.124	233.410	319.517	857.427	553.842	610.664
Dec 2020	9.140	6.160	6.860	10.911	8.630	9.030	467.718	143.169	197.733	795.508	393.676	450.993
Annual Mean 2020	5.380	3.893	4.561	6.422	5.648	6.231	138.456	56.095	81.665	235.490	159.328	192.842

Note: WPD calculated as $\frac{1}{2}\rho U^3$ using $\rho = 1.225\ kg\ m^{-3}$. Wind speeds at 50 m derived using power-law extrapolation ($\alpha = 0.07$ for Al-Faw & Basrah Airport; $\alpha = 0.20$ for Umm Qasr). Summer WPD may be overestimated by ~8–11 % due to reduced air density at high temperatures.

Table 3B: Monthly mean wind speed ($m\ s^{-1}$) and WPD ($W\ m^{-2}$) for 2021.

Month	Wind Speed ($m\ s^{-1}$)						Wind Power Density ($W\ m^{-2}$)					
	10 m Height			50 m Height			10 m Height			50 m Height		
	Al-Faw WS 10 m($m\ s^{-1}$)	Basrah WS 10 m($m\ s^{-1}$)	Umm Qasr WS 10 m($m\ s^{-1}$)	Al-Faw WS 50 m($m\ s^{-1}$)	Basrah WS 50 m($m\ s^{-1}$)	Umm Qasr WS 50 m($m\ s^{-1}$)	Al-Faw WPD 10 m($W\ m^{-2}$)	Basrah WPD 10 m($W\ m^{-2}$)	Umm Qasr WPD 10 m($W\ m^{-2}$)	Al-Faw WPD 50 m($W\ m^{-2}$)	Basrah WPD 50 m($W\ m^{-2}$)	Umm Qasr WPD 50 m($W\ m^{-2}$)
Jan 2021	3.870	3.040	3.260	4.620	4.450	4.470	35.505	17.208	21.221	60.387	53.974	54.705
Feb 2021	7.950	6.170	7.000	9.490	8.860	9.200	307.757	143.867	210.088	523.441	425.998	476.946
Mar 2021	6.210	4.340	4.780	7.413	6.410	6.600	146.713	50.070	66.894	249.533	161.317	176.091
Apr 2021	2.215	1.880	2.100	2.644	2.530	2.740	6.659	4.070	5.672	11.325	9.919	12.600
May 2021	5.181	6.280	5.470	6.185	8.770	7.410	85.194	151.700	100.246	144.900	413.147	249.207
Jun 2021	9.183	5.160	7.020	10.961	7.120	9.300	474.296	84.150	211.893	806.695	221.078	492.669
Jul 2021	8.700	3.580	4.230	10.385	5.510	6.380	403.333	28.103	46.358	685.999	102.462	159.063
Aug 2021	8.400	3.760	4.320	10.027	5.280	6.200	363.031	32.559	49.381	617.453	90.159	145.976
Sep 2021	7.600	2.580	2.930	9.072	3.800	4.280	268.873	10.519	15.407	457.306	33.609	48.022
Oct 2021	6.400	5.710	7.010	7.640	8.430	10.010	160.563	114.029	210.989	273.090	366.935	614.339
Nov 2021	5.200	4.110	4.730	6.207	5.930	6.570	86.122	42.524	64.817	146.479	127.723	173.701
Dec 2021	3.478	2.880	3.080	4.152	4.260	4.430	25.777	14.631	17.896	43.843	47.352	53.250
Annual Mean 2021	6.199	4.124	4.661	7.400	5.946	6.466	196.985	57.786	85.072	335.038	171.139	221.381

Note: WPD calculated as $\frac{1}{2}\rho U^3$ using $\rho = 1.225\ kg\ m^{-3}$. Wind speeds at 50 m derived using power-law extrapolation ($\alpha = 0.07$ for Al-Faw & Basrah Airport; $\alpha = 0.20$ for Umm Qasr). Summer WPD may be overestimated by ~8–11 % due to reduced air density at high temperatures.

Table 3C: Monthly mean wind speed (m s^{-1}) and WPD (W m^{-2}) for 2022.

Month	Wind Speed (m s^{-1})						Wind Power Density (W m^{-2})					
	10 m Height			50 m Height			10 m Height			50 m Height		
	Al-Faw WS 10 m(m s^{-1})	Basrah WS 10 m(m s^{-1})	Umm Qasr WS 10 m(m s^{-1})	Al-Faw WS 50 m(m s^{-1})	Basrah WS 50 m(m s^{-1})	Umm Qasr WS 50 m(m s^{-1})	Al-Faw WPD 10 m(W m^{-2})	Basrah WPD 10 m(W m^{-2})	Umm Qasr WPD 10 m(W m^{-2})	Al-Faw WPD 50 m(W m^{-2})	Basrah WPD 50 m(W m^{-2})	Umm Qasr WPD 50 m(W m^{-2})
Jan 2022	4.300	4.430	5.040	5.133	6.470	6.680	48.698	53.250	78.415	82.827	165.890	182.573
Feb 2022	4.600	7.440	8.280	5.491	10.010	10.540	59.618	252.246	347.694	101.400	614.339	717.180
Mar 2022	5.300	5.330	5.700	6.326	7.800	7.960	91.187	92.744	113.431	155.094	290.663	308.919
Apr 2022	6.100	2.920	3.500	7.281	4.280	4.930	139.026	15.249	26.261	236.459	48.022	73.392
May 2022	7.200	4.290	4.380	8.594	6.070	5.900	228.614	48.359	51.467	388.834	136.985	125.795
Jun 2022	5.700	2.520	2.300	6.804	3.670	3.090	113.431	9.802	7.452	192.926	30.276	18.071
Jul 2022	4.500	3.000	3.330	5.372	4.750	4.950	55.814	16.538	22.617	94.930	65.643	74.289
Aug 2022	4.200	5.100	4.860	5.013	7.570	6.860	45.379	81.249	70.310	77.182	265.701	197.733
Sep 2022	5.300	2.990	3.490	6.326	4.450	4.980	91.187	16.373	26.036	155.094	53.974	75.647
Oct 2022	4.800	3.920	4.510	5.730	5.760	6.330	67.738	36.895	56.187	115.210	117.051	155.352
Nov 2022	3.600	2.330	2.740	4.297	2.980	3.540	28.577	7.748	12.600	48.604	16.209	27.172
Dec 2022	3.189	1.990	2.080	3.807	2.630	2.780	19.868	4.827	5.512	33.792	11.142	13.160
Annual Mean 2022	4.899	3.855	4.184	5.848	5.537	5.712	82.428	52.940	68.165	140.196	151.325	164.107

Note: WPD calculated as $\frac{1}{2}\rho U^3$ using $\rho = 1.225$ kg m^{-3}. Wind speeds at 50 m derived using power-law extrapolation ($\alpha = 0.07$ for Al-Faw & Basrah Airport; $\alpha = 0.20$ for Umm Qasr). Summer WPD may be overestimated by ~8–11 % due to reduced air density at high temperatures.

Table 4: Summary of annual wind power density statistics and annual means used for NREL classification.

Site	Height	Mean WPD (W m⁻²)	Max. WPD (W m⁻²)	Min. WPD (W m⁻²)	Std Dev. WPD (W m⁻²)	NERL class	Suitability for wind energy	Action
Al Faw	10 m	139.289802	504.1238954	6.65872	142.3827762	Class 1	Not Suitable	Not viable
Al Faw	50 m	236.907834	857.4274535	11.3253	242.1684478	Class 2	Borderline	Consider hybrid wind-solar systems
Basrah AirPort	10 m	55.6070093	252.2463552	2.3253	62.23310972	Class 1	Not Suitable	Not viable
Basrah AirPort	50 m	160.597423	614.3393381	9.34246	159.8528915	Class 1	Not Suitable	Not viable
Umm Qasr	10 m	78.3004627	347.6939256	2.8527	86.11000194	Class 1	Not Suitable	Not viable
Umm Qasr	50 m	192.776392	717.1795967	9.34246	185.7594626	Class 1	Marginal viability	Investigate summer-only deployment

speed and power density combined with the wind profile in the atmospheric boundary layer.

Maximum instantaneous WPD values demonstrated the episodic nature of wind energy availability in the region. Al-Faw recorded peak WPD of 504.1 W m⁻² at 10 m height and 857.4 W m⁻² at 50 m height, occurring during intense Shamal wind events in November 2020. Basrah Airport reached maximum values of 252.2 W m⁻² and 614.3 W m⁻² at 10 m and 50 m heights, respectively, during February 2022. Umm Qasr exhibited intermediate maximum values of 347.7 W m⁻² (10 m) and 717.2 W m⁻² (50 m) in the same month.

Standard deviation values were notably high relative to the mean WPD at all locations, ranging from 62.2 W m⁻² to 242.2 W m⁻² depending on site and height. At Al-Faw, the standard deviation at 10 m height (142.4 W m⁻²) exceeded the mean value (139.3 W m⁻²), indicating substantial temporal variability and intermittency in wind power availability. This high variability reflects the episodic nature of Shamal wind events and the transition between active and quiescent wind periods throughout the annual cycle.

Monthly mean WPD values exhibited pronounced temporal variations throughout the year, with distinct seasonal patterns evident at all study locations (Table 3). At Al-Faw (10 m height), monthly mean WPD ranged from 6.7 W m⁻² (April 2021) to 504.1 W m⁻² (November 2020), demonstrating an approximately 75-fold variation between

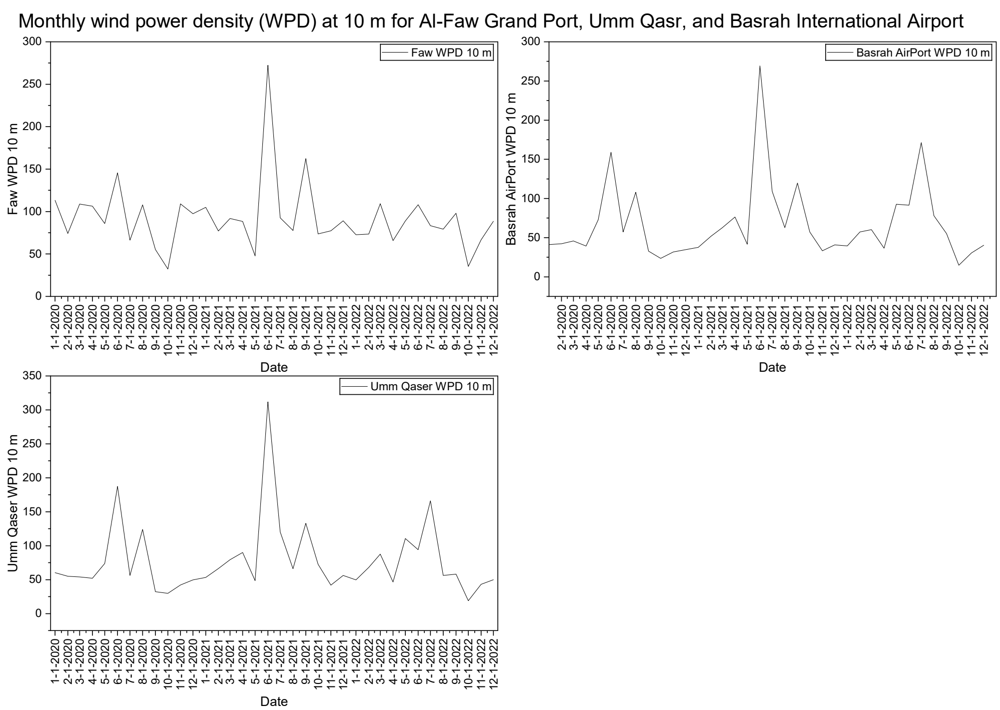

Fig. 4: Grouped box plots of monthly mean WPD by site at 10 m.

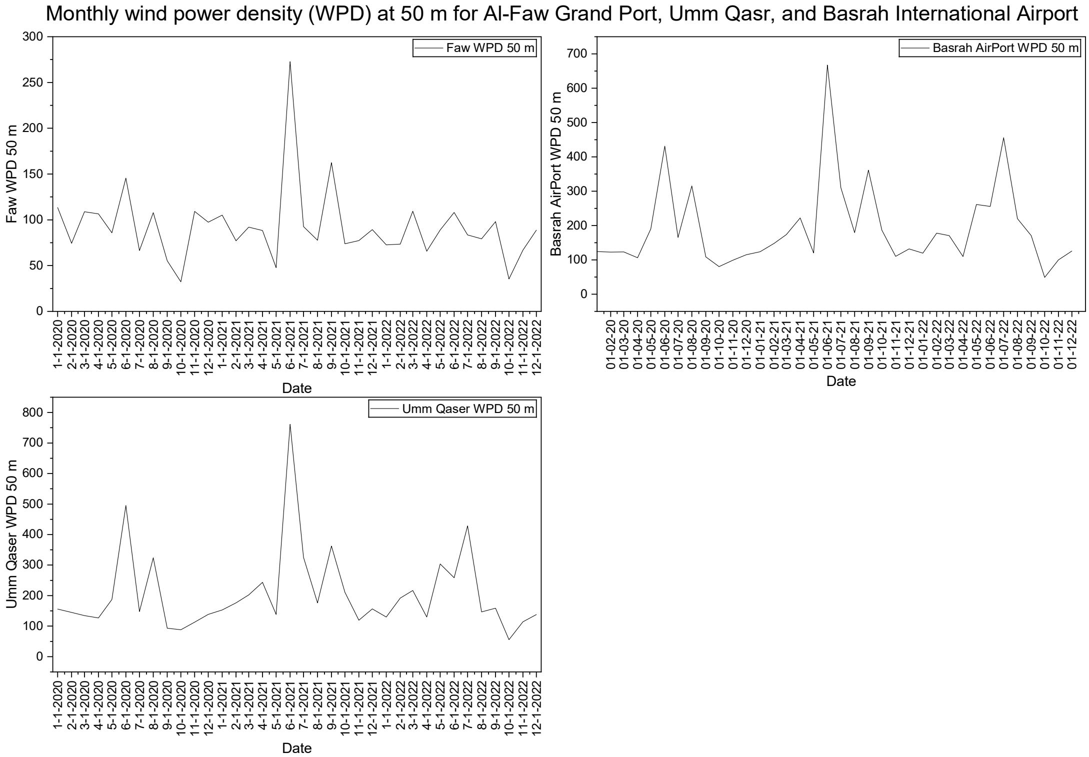

Fig. 5: Grouped box plots of monthly mean WPD by site at 50 m.

minimum and maximum monthly conditions. The November 2020 peak corresponded to an exceptionally strong and persistent Shamal wind event that produced sustained high wind speeds throughout the month, as shown in Figs. 4 and 5.

Table 5 gives the seasonal means throughout the study period, where Summer months generally displayed elevated WPD values, though substantial inter-annual variability was observed. June exhibited consistently high WPD across all three years, with Al-Faw recording values of 25.7 W m^{-2} (2020), 474.3 W m^{-2} (2021), and 113.4 W m^{-2} (2022) at 10 m height. July showed similar patterns with values of 26.4 W m^{-2} (2020), 403.3 W m^{-2} (2021), and 55.8 W m^{-2} (2022). This inter-annual variability highlights the influence of year-to-year differences in synoptic circulation patterns affecting Shamal wind intensity and persistence, as shown in Figs. 6 and 7. At 50 m, Al-Faw achieves 236.9 W m^{-2} (97 % of the Class 2 threshold), making it the only site with marginal potential. However, high variability (CV = 1.02) and low capacity factor (CF = 0.18) limit commercial viability.

Winter months demonstrated moderate to high WPD values during years with active winter Shamal conditions. At 10 m height, January mean WPD at Al-Faw ranged from 35.5 W m^{-2} (2021) to 170.7 W m^{-2} (2020), while December values varied from 19.9 W m^{-2} (2022) to 467.7 W m^{-2} (2020). February exhibited the greatest interannual range, with WPD values spanning from 14.5 W m^{-2} (2020) to 307.8 W m^{-2} (2021), reflecting the episodic nature of winter Shamal events. At 50 m height, these values were significantly amplified, with January WPD ranging from 60.4 W m^{-2} (2021) to 290.3 W m^{-2} (2020), December values varying from 33.8 W m^{-2} (2022) to 795.5 W m^{-2} (2020), and February values spanning from 24.6 W m^{-2} (2020) to 523.4 W m^{-2} (2021).

Table 5: Seasonal mean WPD (W m^{-2}) by site and height.

Season	Al Faw WPD 10 m	Basrah Airport WPD 10 m	Umm Qasr WPD 10 m	Al Faw WPD 50 m	Basrah Airport WPD 50 m	Umm Qasr WPD 50 m
Winter	127.788	76.538	106.422	217.346	213.368	239.929
Spring	99.043	50.047	56.466	168.455	149.692	149.028
Summer	177.910	39.718	58.072	302.593	120.917	153.748
Autumn	152.418	56.126	92.222	259.237	158.412	228.400

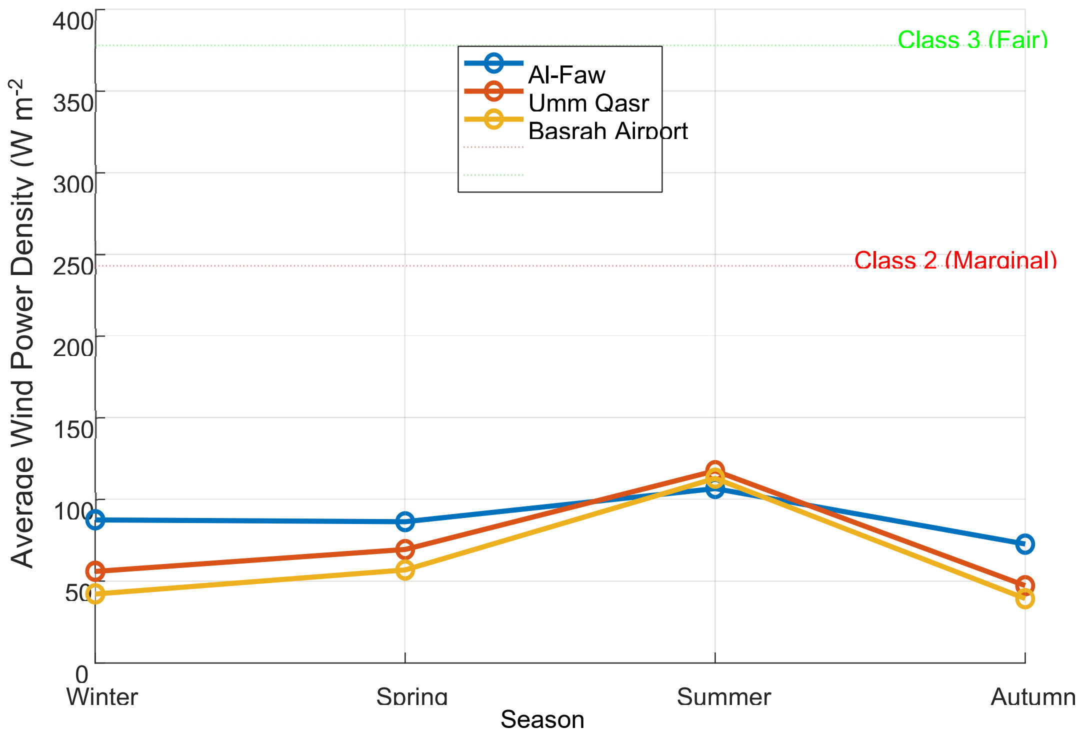

Fig. 6: Seasonal mean WPD (W m⁻²) at 10 m by season and site for 2020–2022.

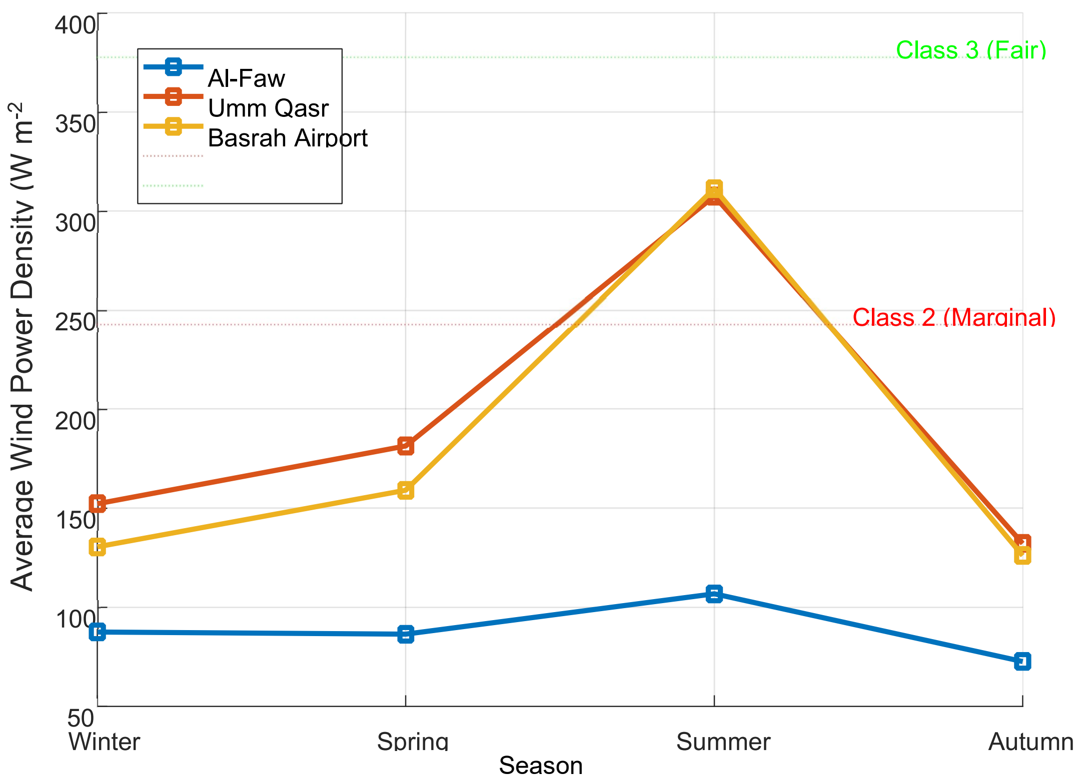

Fig. 7: Seasonal mean WPD (W m⁻²) at 50 m by season and site for 2020–2022.

Spring and autumn months generally produced lower WPD values, with April and October frequently recording the annual minima. At Basrah Airport, April mean WPD values at 10 m height were consistently low across all years: 52.2 W m⁻² (2020), 4.1 W m⁻² (2021), and 15.2 W m⁻² (2022) (compared to 168.2 W m⁻², 9.9 W m⁻², and 48.0 W m⁻² at 50 m height, respectively). Similarly, October displayed reduced wind power availability at 10 m, with values of 22.4 W m⁻² (2020), 114.0 W m⁻² (2021), and 36.9 W m⁻² (2022) (compared to 175.4 W m⁻², 273.1 W m⁻², and 115.2 W m⁻² at 50 m height, respectively).

3.1.3. Spatial Gradient Analysis

A methodical analysis of wind power density (WPD) at the three study sites shows a consistent coast-to-inland gradient, with higher WPD closer to the Arabian Gulf (Fig. 8). Annual average WPD at 10 m height decreased from Al-Faw (coastal) to Umm Qasr (intermediate, approximately 5 km inland) and then to Basrah Airport (inland, approximately 80 km inland). A clear coastal-inland gradient is observed: WPD at 10 m decreases from 139.3 W m⁻² (Al-Faw, coastal) to 78.3 W m⁻² (Umm Qasr, ~5 km inland) and to 55.6 W m⁻² (Basrah Airport, ~80 km inland). However, with only three sites, linear trends are not statistically justified.

The spatial gradient at 50 m height was slightly weakened but remained substantial. Mean annual WPD values of 236.9 W m⁻² (Al-Faw), 192.8 W m⁻² (Umm Qasr), and 160.6 W m⁻² (Basrah Airport) specified a 32 % reduction from coast to inland. The reduced gradient magnitude at higher elevations proposes that marine boundary layer effects influencing coastal wind speeds decrease with increasing height above the surface.

The spatial gradient demonstrated temporal variability, with the coastal advantage most marked during strong Shamal wind events and reduced during calm periods. During November 2020, when intense northwesterly winds prevailed, Al-Faw recorded WPD values 2.2 times greater than Basrah Airport at 10 m height. On the contrary, during April 2021, a outstandingly calm month, the spatial differences were minimal, with Al-Faw exhibiting only 1.6 times the WPD of Basrah Airport.

Monthly grouped box plots revealed the distribution characteristics of WPD at each location. Al-Faw displayed the widest distribution range and highest median values, with occasional extreme outliers exceeding 400 W m⁻² at 10 m height during intense wind events. Basrah Airport showed the narrowest distribution with the lowest median values, reflecting its inland position and greater surface roughness effects. Umm Qasr exhibited intermediate characteristics,

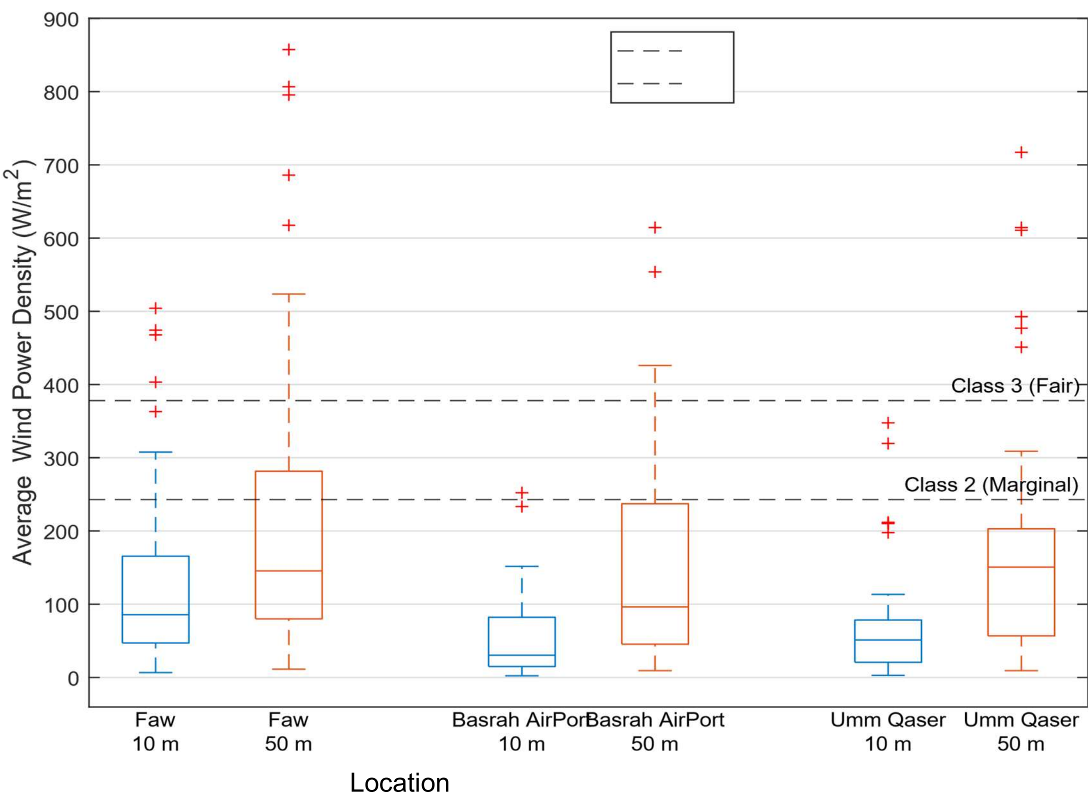

Fig. 8: Distribution of monthly mean WPD by site and height. Outliers represent rare extreme events, such as the November 2020 Shamal event.

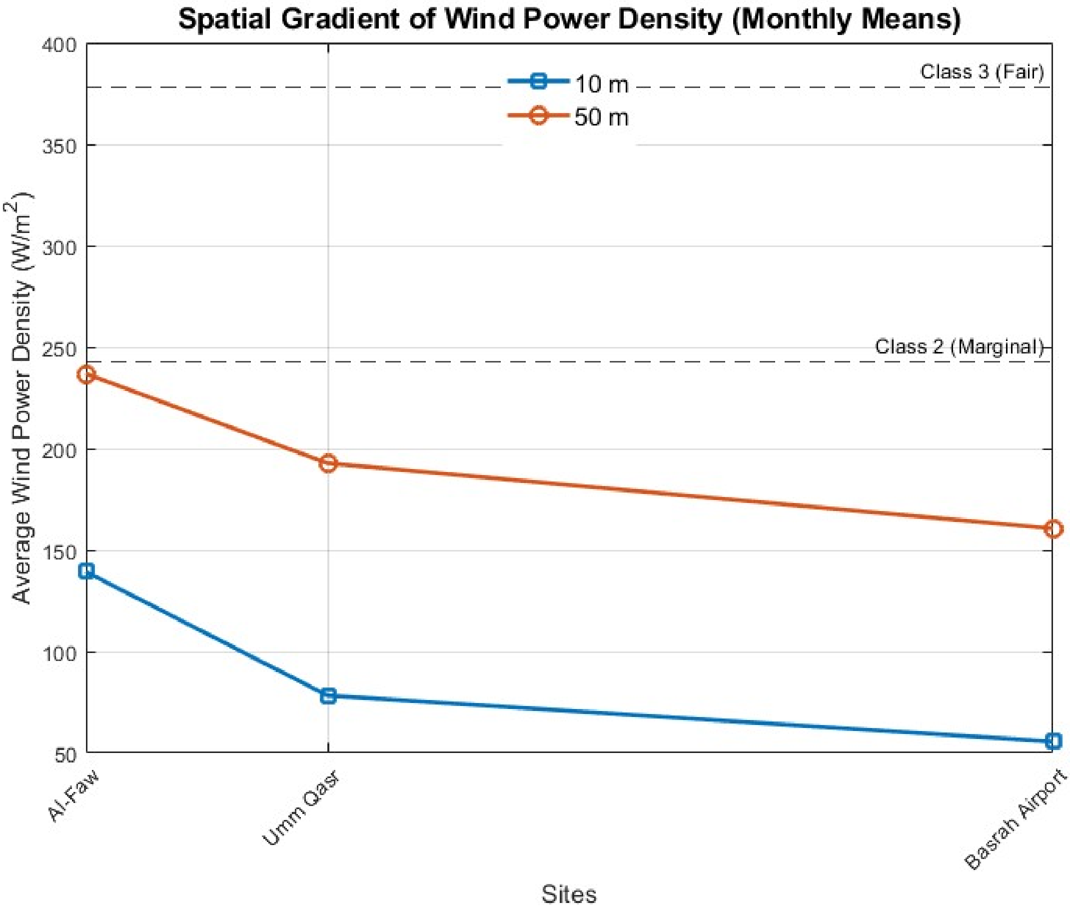

Fig. 9: Spatial gradient of monthly mean wind power density.

with distribution parameters falling consistently between the coastal and inland extremes.

The spatial gradient in WPD was maintained throughout most months, with Al-Faw consistently exhibiting higher values than Umm Qasr and Basrah Airport. However, the magnitude of this gradient varied temporally. During strong Shamal events, the coastal advantage of Al-Faw was most pronounced, with WPD values 3–5 times greater than inland locations stated in Fig. 9. During calm periods, the spatial differences diminished, though Al-Faw retained a modest advantage due to reduced surface roughness effects near the coastline.

3.1.4. NREL Wind Power Classification

Applying the NREL wind power classification to annual average WPD values provided an objective evaluation of wind power capacity at every site under study and height (Table 4). All three sites were in Class 1 (0–243 W m^{-2}), at 10 m above the ground, which is a poor wind resource that cannot sustain commercial development of wind energy. Although Al-Faw had the largest 10 m WPD (139.3 W m^{-2}), it was still well below the 243 W m^{-2} threshold for Class 2 marginal viability. Lower values for Basrah Airport (55.6 W m^{-2}) and Umm Qasr (78.3 W m^{-2}) were observed, remaining within Class 1.

While summer monthly WPD exceeds 243 W m^{-2} (e.g., 307 W m^{-2} in June), the annual mean remains below Class 2. Thus, the site is classified as NREL Class 1 (Not Suitable) for utility-scale projects. Seasonal peak potential does not override annual viability, as shown in Fig. 10.

Basrah Airport remained in Class 1, with a WPD of 160.6 W m^{-2}, which clearly shows that the site remains unsuitable for wind-power development even at higher turbine-hub elevations. The 50 m WPD is merely 66 % of the lowest Class 2 limit, indicating that tremendous height gain or major technological progress would be necessary to make the inland site economically viable.

Umm Qasr was in a borderline position with 50 m WPD of 192.8 W m^{-2}, which remains Class 1 but approaches the Class 2 threshold. This mid-coastal site has potential for marginal wind-energy applications, especially at high-wind

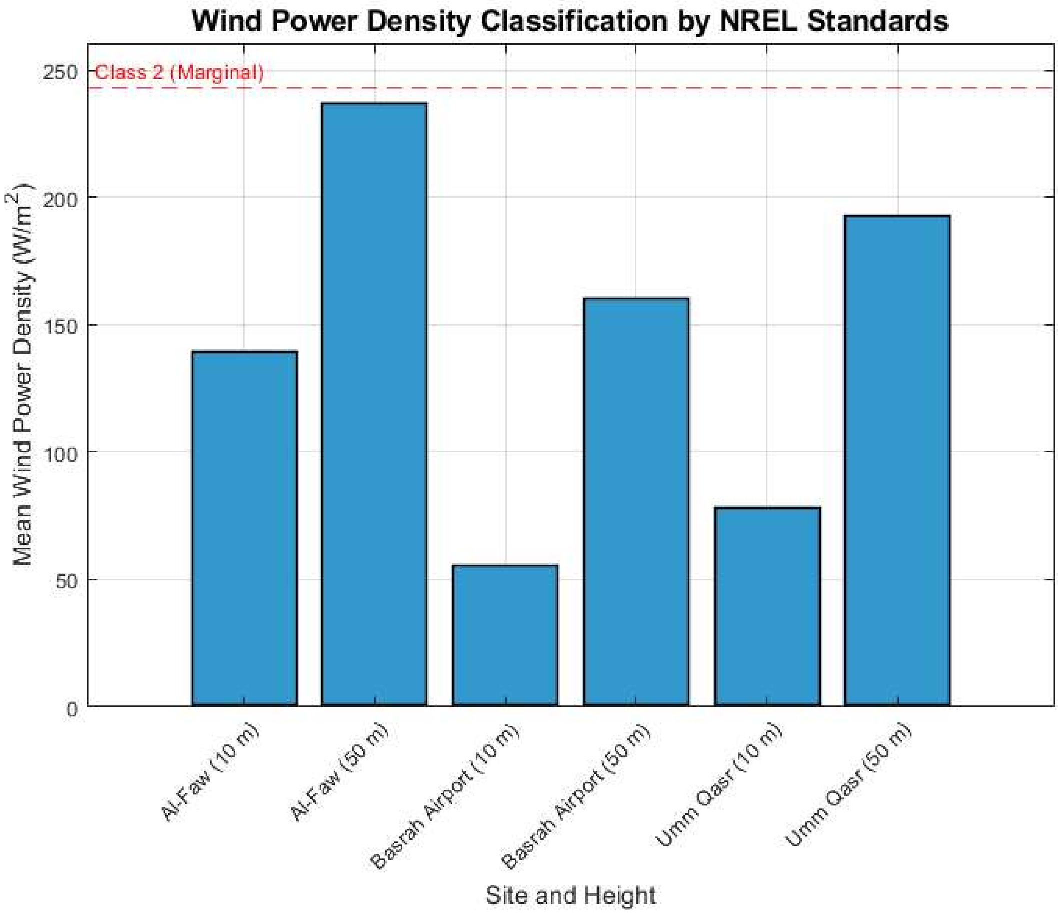

Fig. 10: Wind power density classification according to the adopted NREL thresholds.

summer periods when instantaneous WPD is often Class 2, and sometimes Class 3. The possibility of seasonal or hybrid wind-solar facilities at Umm Qasr may be considered due to the maximum wind speed in the summer, which is the period when the solar radiation is at its maximum in the area.

Analysis of monthly WPD values relative to the NREL classification thresholds indicated that all three locations occasionally reached Class 2 or above during high-wind periods. At 50 m, Al-Faw exceeded the Class 2 threshold (243 W m^{-2}) in 12 of the 36 study months and reached Class 3 (378 W m^{-2}) or higher in 4 months during particularly strong Shamal events. Basrah Airport reached Class 2 in only 3 months, associated with extreme winter Shamal events. Umm Qasr reached Class 2 in 6 months, mainly during summer and occasional high-wind events in winter.

The temporal variability in classification status suggests that, although annual mean conditions do not meet commercial viability thresholds, the wind resource may support supplemental generation during favorable periods. This pattern indicates that wind energy facilities in southern Iraq may be better suited to hybrid renewable-energy systems or seasonal ancillary generation than to baseload generation. At 10 m, Al-Faw remains in Class 1 with an annual mean WPD of approximately 139.3 W m^{-2}. At 50 m, the annual mean WPD increases to 236.9 W m^{-2}, which approaches but does not meet the 243 W m^{-2} Class 2 threshold. Thus, Al-Faw remains Class 1 on an annual-mean basis, although its proximity to the Class 2 threshold suggests that site-specific techno-economic assessment at greater hub heights may be warranted.

The analysis confirms that wind-energy potential improves with height; however, the annual mean WPD at 50 m remains below the Class 2 threshold and well below the Class 3 level generally associated with more favorable wind-farm development conditions.

4. CONCLUSIONS

This comprehensive three-year assessment of wind power density (WPD) across the coastal zone of southern Iraq reveals that the regional wind resource remains marginal according to global standards, though it exhibits specific characteristics that could facilitate the strategic integration of renewable energy under favorable conditions.

Crucially, none of the three evaluated stations are currently suitable for standalone, commercial utility-scale wind energy generation. Based on annual mean WPD, Al-Faw (236.9 W m^{-2} at 50 m) approaches but does not meet the NREL Class 2 threshold (243 W m^{-2}), while Umm Qasr (192.8 W m^{-2} at 50 m) and Basrah Airport (160.6 W m^{-2} at 50 m) remain within Class 1. Although Al-Faw and Umm Qasr at 50 m periodically exceed Class 2 thresholds during peak summer months (June–August), and Al-Faw occasionally reaches Class 3 during intense Shamal events, these are seasonal peaks rather than sustained annual resources. Consequently, any potential for supplemental or hybrid wind-solar applications remains contingent upon future site-specific techno-economic analyses.

The analysis confirms a distinct coastal-to-inland gradient, with WPD declining by approximately 60 % from coastal Al-Faw (139.3 W m^{-2} at 10 m) to inland Basrah Airport (55.6 W m^{-2}) over an approximately 80 km transect. Extrapolating to a 50 m hub height yields significant vertical amplification (factors of 1.7–2.9×), bringing Al-Faw close to the marginal viability threshold. Nevertheless, no site achieves the Class 3 threshold typically required for commercially viable wind farms.

Seasonal analysis indicates that peak WPD values (>300 W m^{-2} at 50 m at coastal sites) occur during the summer, coinciding with Iraq's peak electricity demand driven by air-conditioning loads. While this temporal alignment offers a strategic advantage for grid support, the high temporal variability, evidenced by standard deviations exceeding the mean values, reflects the episodic nature of the Shamal wind regime. This high intermittency presents inherent challenges for grid integration, necessitating robust energy storage or reserve capacity.

Ultimately, the marginal nature of the resource implies that standalone wind farms are not economically viable under current conditions. However, hybrid systems combining wind and solar photovoltaics could potentially mitigate intermittency issues due to complementary generation patterns. Furthermore, the significant WPD improvement observed when extrapolating from 10 m to 50 m suggests that modern turbines with hub heights of 80 to 100 m might achieve improved classifications, particularly along the coast.

As the first multi-height, multi-site comparative evaluation of WPD in Iraq's coastal region, this study provides essential baseline data to support evidence-based renewable energy planning. While southern Iraq's wind resources fall below optimal global thresholds, strategic approaches, such as hybrid system deployment, hub-height optimization, and seasonal energy planning, could enable the region to make meaningful contributions to Iraq's renewable energy portfolio and broader energy security goals.

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