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Seasonal and Diurnal Variation of Wind Speed in Iraq: Assessing Wind Energy Potential and Alignment with Peak Electricity Demand

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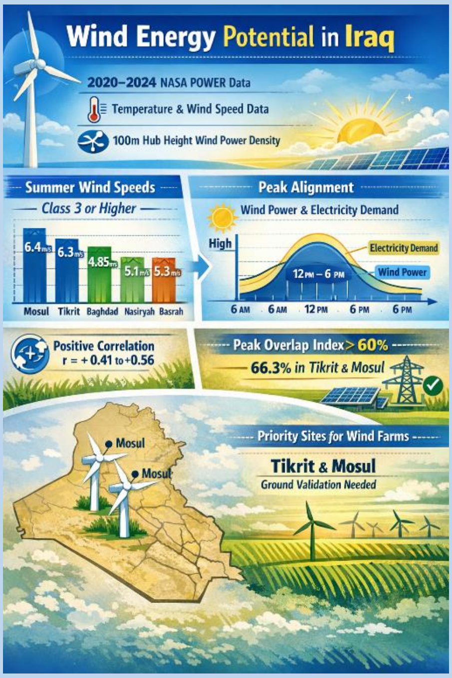
Abstract: This study examines the seasonal and diurnal variations in wind speed in five major Iraqi cities: Mosul, Tikrit, Baghdad, Nasiriyah, and Basrah. It focuses on assessing wind energy potential and how well it aligns with peak electricity demand. From 2020 to 2024, hourly temperature and wind speed data were available from the NASA POWER database. Wind power density at a hub height of 100 meters was calculated using air density-corrected cubic wind speed. Descriptive statistics, one-way ANOVA, Pearson correlation, and the Peak Overlap Index (POI) were used to analyze temporal patterns and grid integration potential. The results indicate that all locations have Class 3 or higher wind resources during the summer, with mean wind speeds ranging from 4.85 m/s in Baghdad to 6.42 m/s in Tikrit. The NASA POWER database provided hourly wind speed and temperature data from 2020 to 2024. Air density-corrected cubic wind speed was used to calculate wind power density at 100 m hub height. Temporal patterns and grid integration potential were examined using descriptive statistics, one-way ANOVA, Pearson correlation, and the Peak Overlap Index (POI). With mean wind speeds ranging from 4.85 m/s in Baghdad to 6.42 m/s in Tikrit, the results show that all sites have Class 3 or higher wind resources during the summer. Wind power peaks sharply in the afternoon between 12:00 and 18:00, which is also when electricity consumption is at its highest. Strong temporal alignment is indicated by the Peak Overlap Index (POI), which is greater than 60% at all locations, with Tikrit and Mosul achieving 66.3%. Wind speed and temperature were found to be positively correlated ($r = +0.41$ to $+0.56$, $p < 0.05$). Although these results indicate that wind energy in Iraq is both plentiful and in line with demand, it is important to take into account the uncertainty in modeled data and assumptions (such as neutral stability). Prioritizing Tikrit and Mosul for utility-scale wind farm pilot projects is advised by the study, with additional validation through ground-based measurements.



Keywords: Seasonal variation; Wind energy; Renewable energy; Diurnal pattern; Peak Overlap Index (POI); Wind power density; Grid integration; Iraq

Introduction

Iraq's electrical infrastructure is facing increasing challenges due to a number of interrelated factors, including rising temperatures, growing populations, and long-standing power network flaws. As air conditioning becomes necessary for survival in Iraq's intense heat, summertime electricity consumption spikes dramatically, overwhelming an already precarious electrical system. Blackouts are common, particularly in cities and the southern provinces of Iraq, where dependable power access is essential due to the intense heat. In these urgent situations, switching to renewable energy sources is essential for ensuring steady energy supplies, preserving economic viability, and developing resilience against the effects of climate change. It goes beyond environmental concerns.[1,2].

Worldwide momentum toward renewable energy sources continue accelerating, propelled by climate change mitigation imperatives, concerns regarding energy security, and decarbonization commitments. Wind-powered electricity has proven itself to be one of the fastest growing renewable technologies, with more than seven percent of the world-wide electricity production as of 2023. However, the current distribution of deployment is highly geographically unequal, in many developing countries the economy is still based on the active use of fossil fuel combustion as the source of base and peak power supply. The countries in the Middle East including Iraq are experiencing two simultaneous issues, a steep increase in the electricity demand due to the population growth and urbanization in the country and the increased temperatures

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caused by the anthropogenic climate change. As the cooling demand shuts down much summer power consumption, the demand to be able to generate dispatch able power which is sustainable grows increasingly urgent. However, the country is still susceptible to the occurrences of a disturbance in the supply of fuel products and grid instabilities since a renewable contribution to the total generation of energy does not exceed one percent, even though there is an abundance of solar irradiance and wind resources. Wind-generated electricity is one of the possible renewable options that have a unique potential to be implemented in Iraq. The nation has a very intense seasonal weather condition referred to as the Shamal- northwest wind which is dominant during the summer season and cuts across the central and South areas. In contrast to photovoltaic generation of solar, as the solar is predictable by the daily cycles, Iraqi wind patterns exhibit complicated seasonal and diurnal variability, which can be utilized strategically to balance supply with maximum demand. These wind properties have the potential to subsidize the loads related to electricity that is most closely related to cooling needs at the hottest times of the day when properly studied and utilized.[3].

The last ten years saw the evaluation of the wind-energy potential in Iraq, based on the results of weather stations observing stations, satellite-based numerical weather prediction models, and field observations. One of the most consistent results is a strong seasonal variation of the wind velocity, increasing in winter to about 3 meters per second to more than 5 meters per second in the months of summer, June to August. This is a seasonal trend that can be seen at such big places like Baghdad, Nasiriyah and Basrah. The annual average wind speed (at the turbine hub heights of between 60 and 100 m above ground level) is 4.0 meters per second in Basrah, 3.9 meters per second in Nasiriyah, and 3.4 meters per second in Baghdad. Although these values are small compared to international standards, they show that there is enough potential in terms of large-scale wind farms and smaller distributed generation implementations.[4] [2]

Seasonal phase correspondence with a peak electricity demand, along with an energy policy perspective, offers the supply side of renewable energy with a rare congruence with grid explosions. Weibull distribution studies also support the magnification of wind-energy density in summer, as the scales parameters are growing in winter with about 3 meters per second but go beyond 5 meters per second in the middle of summer [5]. With a high number of promising areas, such as the eastern and western parts of the country, this seasonal addition increases the wind power density up to 700-1200 kilowatt-hours per square meter per year, which is enough to sustain 100-350 kilowatt horizontal-axis turbines.

Wind behaviour does not only show a seasonal but also a considerable amount of diurnal variation. The wind speed reaches its highest point at night in the winter and in the middle of the afternoon in the summer, often between 12.00 and 15.00. This summer peak coincides closely with the peak in cooling demand every day, providing a unique chance to produce the electricity during the time when it is needed the most. The observed trend is corroborated with field measurements of small-scale turbines, which display greater output during summer time on daytime and significant output during winter time at night [6] [7]. Although there is growing positive signs, there is still much missing research. Several current measurements are based on low-resolution, or time-aggregated data, and therefore do not have the capability to measure full diurnal cycles. Furthermore, there is little literature on the analysis of potential of hybrid solar-wind systems, although it can offer more stable output during peak periods. The advantages of taller towers over 100 m are not well exploited yet the wind-shear patterns indicate great yield.

As an illustration, Alhamdawee and Hussain (2024) compared the wind conditions in major urban centers of Iraq, with a reported average surface speed of 2-4 meters per second. Previous research, however, used low-resolution or monthly aggregates, which failed to provide important diurnal variations that are important in grid integration planning [4]. Kumar Yadav et al. (2024) studied the impact of diurnal patterns on the calculation of wind-power density in a variety of geographic settings, and concluded that traditional approaches that overlook the effects of diurnal variation may introduce substantial inaccuracies in the estimation of power-generation. They discovered that seasonal variations can result in over-estimation of the night density of power and under-estimation of the daytime potential that carries significant economic consequences in terms of higher cost of generation and unforeseen losses in loads. [8]

The details of wind behaviour during the day are not limited to daily cycles. Wan et al. (2022) examined recorded wind measurements that revealed advanced modulation in space and time, on both speed patterns and actual generation. Their work showed that the turbulence of the atmosphere added extra layers of variability that should be taken into account in the design and functioning of a system [9]. This was furthered by Pryor and Barthelmie (2021), who investigated the variability in wind-power over time, revealing that periods of low generation occur in six-hour or shorter intervals, except in a few areas. Notably, these low-generation intervals are the strongest during summer, which might be incompatible with the time of maximum cooling spikes in hot regions.[10]

The wind-energy potential in Iraq has gained more and more interest as the nation tries to diversify its energy resources. New examinations show a less positive response. Hassan et al. (2025) made up close studies in big cities and discovered average velocities as minimal as 2 to 4 meters per second at 10m, which is less than the 9 to 12 meters per second and higher limits needed to run most commercial turbines, implying that it is very difficult to conventionally develop [11] . However, there are other promising methods, like small-turbine installations adjusted to Iraqi conditions, which means that the systems of appropriate sizes can still be productive even with the lower averages.

Some of the studies give conservative estimates throughout Iraq with mean speeds of 2 to 4 m/s subtracted at 10 meters [4,11]. These measurements are however often based on small hub heights and poor time resolution, and may be underestimating the true potential in current turbine heights (80-120 m). To eliminate this drawback, the current study uses 100 m wind-speed data, which are closer to operational conditions. In addition, the Shamal wind, a northwesterly seasonal wind, is more severe in the afternoon in summer and this has not been fairly captured in annual averages. This study provides a more accurate policy-relevant assessment of the feasibility of wind-energy by concentrating on diurnal and seasonal distribution.

Therefore, this investigation purposes to:

1. Compute seasonal and diurnal variation in wind speed at 100 meters across five major Iraqi cities
2. Classify the energy potential utilizing NREL standards and evaluate wind power density
3. Present and consider the Peak Overlap Index (POI) to evaluate alignment with peak electricity demand
4. State some site-specific recommendations for wind farm development centered on temporal matching characteristics.

This study will meet the above goals by undertaking an in-depth analysis of hourly data at modern turbine hub altitude to inform theoretical knowledge on the interaction between the wind resource and electricity demand and provide practical advice on the energy sector in Iraq. The Peak Overlap Index is an important measure of the global renewable energy planning, whereas the findings that refer to the wind resources of Iraq are also important to point to the fact that there is a definite potential of wind energy to contribute significantly to the electricity crisis in the country.

Methodology

A systematic analytical approach was used in this study to analyze seasonal and diurnal changes in wind speed in five strategically chosen meteorological sites in Iraq: Mosul, Tikrit, Baghdad, Nasiriyah and Basrah. To guarantee the rigor of science and reproducibility of results, our methodological strategy incorporated long-period meteorological data acquisition, pre-processing procedures, statistical analysis, wind power density estimation procedures and correlation analysis. The location of the sites was based on strategic principles in order to reflect the variety of climatic zones in Iraq, which are semi-arid in the north (Mosul), arid in the central areas (Tikrit and Baghdad) and hot desert and coastal-influenced areas in the south (Nasiriyah and Basrah). The geographical distribution of the study sites was covered in figure 1.

On-surface meteorological mast measurements would be the ideal source of data to use in wind energy research but long-term, unobtrusively high-altitude measurements are not as abundant in Iraq. This study, therefore, uses NASA POWER (Prediction of Worldwide Energy Resources) database that provides validated satellite-based meteorological parameters at 0.5° × 0.5° mm resolution. The reliability of NASA POWER to measure the wind energy in arid conditions has been supported in the previous studies, but the application of modeled data always introduces uncertainties especially in the complicated terrain. The next step in work should endeavor to validate the findings by LiDAR or tall-tower.

Figure (1): Selected study sites. Created by author using Google My Maps.

The NASA POWER database, which was obtained by satellite measurements and reanalysis models, provided hourly wind speeds and other meteorological variables in the 202024 period, and represents a globally tested ensemble, provides spatial and temporal resolution. Table 1 is a summary of the location of the study sites and the climatic groups.

Table (1): Study sites coordinates [7].

City	Latitude	Longitude	Elevation (m)	Climate Zone
Mosul	36.33°N	43.13°E	217	Semi-arid
Tikrit	34.88°N	43.67°E	115	Arid
Baghdad	33.31°N	44.38°E	34	Hot desert
Nasiriyah	31.05°N	46.27°E	20	Hot desert
Basrah	30.51°N	47.78°E	13	Hot desert

This research is based on data of reanalysis which is not always the same as the observation on a site. Cooperation with Iraqi-meteorological or energy-producing bodies to implement measurement campaigns is highly suggested in project-level feasibility research. The neutral atmospheric stability assumption used in power-law extrapolation equipment is an added source of uncertainty, which may cause an underestimation of wind speeds in stable nocturnal conditions and overestimation of wind speeds in unstable day times conditions in transitional seasons.

The Hourly wind speed at 100m (WSC100M) variable is used as the primary input for wind energy calculation, derived for the power law as: [10,12]

$$V_{100} = V_{10} * \left(100/10\right)^{\alpha} \qquad \text{Eq 1}$$

Where α = 1/7 under neutral atmospheric stability conditions. The choice of α = 1/7, demonstrating neutral stability, establishes a compromise balancing several competing considerations specific to this study's objectives and Iraq's meteorological conditions. Various factors justify the aims of this work and the weather conditions in Iraq:

Factor 1 -Shamal Wind Characteristics: The summer Shamal winds that overpower the wind energy potential of Iraq are strong synoptic forcing winds and high wind velocities (often more than 6-8 m/s at the surface). When this occurs, the wind shear causes the creation of mechanical turbulence, which in turn is more likely to dominate the stratification caused by thermal to transport the atmosphere to a neutral state even during the day. The strong regional pressure gradients providing the Shamal cause the existence of persistent winds, which promote the maintenance of the near-neutral conditions most of the day.

Factor 2 Temporal Focus: The focus of this investigation is on the hours of the day (12:00-18:00) during summer which has undergone solar heating a few hours earlier and during which the mixing of air masses by conventional methods has become well established. Morning hours can be characterized by residual stable stratification and the evening hours may be characterized by instability but the midday to early afternoon when the winds are generally at their strongest is characterized by neutral or slightly unstable air. The assumption of neutral stability is therefore best suited to the intervals of the most interest.

Factor 3 -High Temperature Effects: The high surface temperatures of Iraq in summer (often 45-50°C) produce powerful surface heating, but the high levels of solar radiation also heat the lower atmosphere, decrease vertical temperature gradients. Together with a low humidity and sunny weather (excepting dust events), this creates conditions which do not favor either unstable or stable regimes strongly during the daytime.

Factor 4: Regional Precedent: Past wind-resource assessment research in other comparable climatic areas (Arabian Peninsula, North Africa) has managed to use neutral stability assumptions to assess utility-scale wind-energy analyses, especially when one is interested in summer daytime variations. Wind-energy meteorological conventions usually apply a power-law exponent of α =1 /7 to evaluate the initial resources, and then later update values by using site-specific data at project development stages.

It is worth noting that the pattern of bias observed is not damaging to the main findings of the current study. Peak Overlap Index (POI) analysis focuses on summer afternoon (12:00 18:00) when the electricity demand reaches its peak, and the assumption of the neutral atmospheric stability is best valid. The analysis of wind resources reaching maximum within the window is therefore strong regardless of the effects of night time stability. At the worst, the underestimation of the night wind velocities could result in underestimation of the overall energy generation capability but that underestimation would never affect the much needed timing to match peak demand.

The height of the reference is 100 m, which matches the height of the hub of modern wind turbines. The raw data were first preprocessed in Microsoft Excel before analysis to slice out or remove missing or erroneous entries after which the data were then aggregated in time per day, monthly, annual and seasonal averages. The seasons were categorized into Winter (Dec-Feb) Spring (Mar–May), Summer (1824) and Autumn (Sep–Nov) and the diurnal patterns were studied with a focus on the peak power consumption hours (12:00–18:00) during the summer months. The timestamps were all adjusted to the Iraq Local Time (UTC+3) so as to synchronize with local cycles of demand. The density of wind power (W/m²) was obtained at 100 m, with consideration of the alteration of air density due to temperature. The potential of wind energy was classified into the NREL wind resource classes (Class 1-7) to make a comparison of sites easier. Excel functions and PivotTables were used to compute descriptive statistics mean, maximum, minimum, standard deviation, and percentiles. To determine significant differences between mean wind speed across seasons at an α = 0.05, the inferential statistics was done using Excel Data Analysis ToolPak, in which a one-way analysis of variance (ANOVA) was done. The correlation coefficient (r) of Pearson was used to measure how much the wind speed and temperature are related and the significance to this was determined by getting the corresponding p-values based on the t-statistic.

To estimate the congruence between wind availability and the electricity demand, the Peak Overlap Index (POI) was proposed. This index is the ratio of high-wind hours the upper 25% of wind speed data in summer to the total number of hours in peak demand hours during summer. The current research is based on the modellized data collected using the NASA POWER database that can be different as compared to the ground-based measurements due to the limitations of the spatial resolution and atmosphere assumptions. In order to assess how the major assumptions, impact the results, a sensitivity analysis was carried out on the POI threshold: the POI uses the 75th percentile as the high-wind threshold, and a sensitivity analysis based on using the 70th and 80th percentiles showed that POI changes were of up to ±3–5% percent, thus validating robustness. The data constraints can be attributed to the fact that the datasets used in the reanalysis are undermined by uncertainty, especially in a complicated terrain. The findings should be confirmed in future work by ground-based LiDAR data or meteorological mast data.

The Hellman exponent α=0.143 is the value that implies the neutral stability of the atmosphere that is usually observed in the daytime in dry areas like in Iraq due to heating of the surface and mixing through convection. This is a common assumption used in wind resource study in cases where stability information on the site in question is lacking.

Origin Lab 2023 was used to create figures in data visualization, and the geographic mapping of the study sites was done with Google My Maps. The methodology was supported by cross-verifying raw and aggregated data; however, there are still the limitations such as the reliance on modeled (non-ground-measured) data and poor resolution of vertical resolution of specific sites. In spite of such limitations, the 5-year dataset allows a strong and statistically significant basis on assessing wind power potentials and temporal trends in Iraq. The following is a flow chart of the workflow of the research.

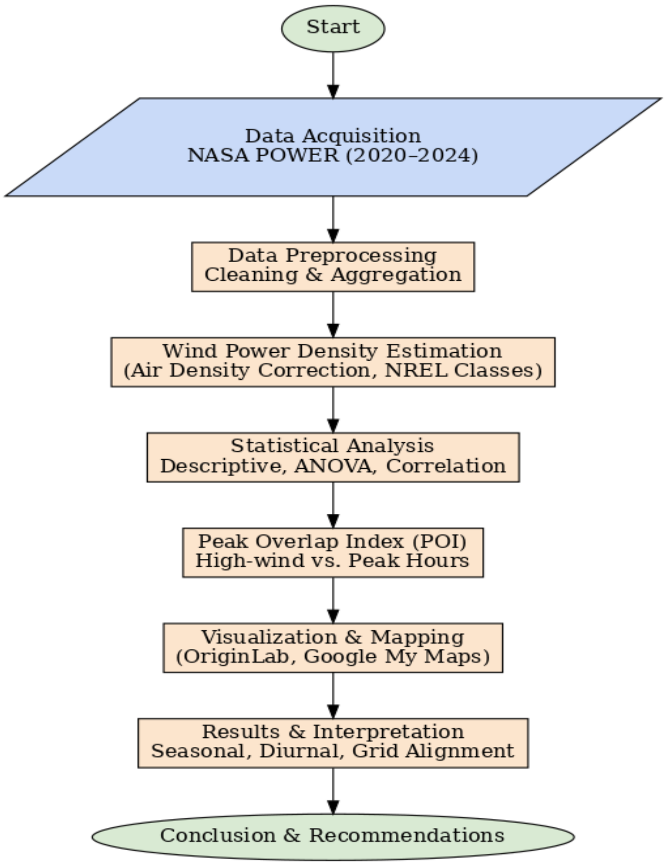


Figure (2): Study flow chart. Done by author.

The research seeks to capitalize on the long-term and high-resolution data as well as the Peak Overlap Index (POI), which the researcher uses to determine the fraction of high-wind occurrences within peak demand times. The research not only contributes to the theoretical knowledge of the time-varying interactions between wind and demand, but also provides instantly practical recommendations to the energy development of Iraq. The presentation of the POI provides an important resource to the planning of renewable-energy around the globe and the particular research results on the wind resources in Iraq can demonstrate a real possibility in the development of wind energy as one of the factors of reducing the electricity crisis in the country. A combination of favorable wind supply, excellent timing, and urgent necessity in the country creates an impressive argument that Iraq should hurry up the deployment of wind energy and sustain it through the right policy provisions, technological adjustments, and further research to perfect the knowledge and reduce the risk of energy deployment.

Sensitivity Analysis

Because this inquiry is based on modeled data on NASA POWER database, which is not necessarily similar to ground-based measurements because of the spatial resolution and assumptions regarding atmospheres, we evaluated the influence of influencing assumptions. The POI threshold sensitivity test with the 70th and 80th percentiles revealed that POI values changed by the range of 3-5 per cent, which confirmed the strength. Reanalysis data implies data limitations that create uncertainty especially in complex terrain. The results should be confirmed by future work based on ground-based LiDAR or meteorological mast data.

The Hellman exponent $\alpha = 0.143$ is neutral atmospheric stability, which occurs during the day on a dry day in a dry area like Iraq because of surface heating and mixing of air with hot air of the surface. This is an assumption that is commonly used in the assessment of wind resources with no site specific data available on stability.

Wind Energy Potential and Grid Alignment in Iraq

As one of the members of the Middle East, Iraq enjoys a wide range of natural resources that goes beyond oil and gas to include renewable energy sources especially wind and solar power. However, there is an unrelenting electricity crisis even with the huge energy endowment considering that in the long, hot summer seasons, the demand of air-conditioning is overwhelming. The need to be more diverse and sustainable in energy plans has become more evident because of the power outages, constant power outages and dependence on the imported electricity by its neighbors. [13].

Wind power is one of the promising solutions to the problem of renewable energy. In comparison to solar energy where the power will be the highest at the midday and zero at night, wind energy tends to behave in different patterns that can be used in conjunction with solar production and stabilize the grid. This potential can be seen especially in Iraq because there is a famous meteorological phenomenon: Shamal winds [4,14] . The Shamal is a seasonal north westerly wind that blows throughout northern and central Iraq; it usually occurs between June and September. A mixture of low-pressure areas in the Arabian Peninsula and high-pressure areas in Turkey causes these winds. They are most intense in afternoon and in early evening, just as the demand of electric energy is the highest, as a result of the large numbers of air-conditioning units in use. The high speed of wind correlated with the high demand of electricity provides a special chance that the wind energy can be directly used to support the grid during the tensest time [3].

This correspondence is vital since the electricity systems are aimed at matching the supply and demand on real-time basis. Demand can soar as in Iraq between 12:00 to 18:00 during summertime and the power plants need to increase their output within a short time. This is often achieved by gas-fired generators, most of which are based on flared gas, which is a wasteful and harmful practice to the environment. Incorporating the wind energy in the grid in peak time, Iraq will be able to decrease the fossil fuel reliance, minimize greenhouse emissions and enhance the energy security. Further, the power of wind can be forecasted seasonally and daily. The Shamal is predictable compared to the sudden weather changes in the area (dust storms or cloud cover) which influences the amount of solar produced. This predictability can help grid operators to plan and schedule power generation and avoid outage risks. [8].

The amount of energy present in wind relies on the cube of wind speed. This implies that simple increases on the wind speed can result to huge recoveries in power output. As an example, the energy generated by 6 m/s is twice the energy generated by 5 m/s. It is due to such places as Tikrit, or Basrah, where the average wind speed is more than 6.5 m/s at 100 m in the summer, that this is so promising. The ability of wind turbines to produce substantial power in such speeds is capable of serving thousands of households. [10,14].

Air density is another aspect that should be considered because the more energy the wind turbines are able to get out of the air, the better. During hot seasons like in Iraq, the density of air in the atmosphere is lower and this minimally lowers the output of wind-power. This has been taken into account in modern wind-resource assessments with temperature and pressure information being used to obtain realistic power-density values, and therefore, energy estimates are made to be accurate and reliable. [15].

Lastly, Iraq has a location factor. The middle and southern parts such as Tikrit, Baghdad, Nasiriyah, and Basrah are flat and open with not many natural barriers that can stop the wind flow. This renders them suitable in wind farms of high scale. On the other hand, mountainous or urban areas can be of less use as the level of turbulence can be more intense and the wind speed can be lower. To conclude, there is natural advantage of Iraq in terms of wind energy: the strong and predictable winds that blow the most when the electricity is needed the most. With proper location of wind farms in regions with high wind potential and aligning with the maximum demands, Iraq will make a big leap to a more stable, sustainable and self-reliant energy future.

Wind Power Density Estimation

Wind power density (WPD) establishes a necessary parameter in wind energy assessment, given a quantitative measurement of available kinetic energy in wind per unit area. It is a serious metric for estimating technical feasibility and economic viability of wind energy projects at given places. The theoretical power available in wind is governed by the physical relationship [10,12,14]:

$$P = \frac{1}{2}\rho\, v^3 \qquad \text{Eq 2}$$

where:

P = wind power density (W/m²), ρ = air density at 100 m (kg/m³), and v = wind speed at 100 m (m/s),

A small increase in average wind speed result in significant gains in power potential that’s because the cubic dependence on wind speed emphasizes the importance of accurate wind speed data, while standard air density at sea level under standard atmospheric conditions is about 1.225 kg/m³, this value differs with temperature, pressure, and humidity, particularly in hot climates like Iraq. Therefore, in this analysis, air density was considered using the ideal gas law: [15]

$$\rho = \frac{P}{R*T} \quad \text{Eq 3}$$

where: P is the atmospheric pressure (Pa), R is the specific gas constant for dry air (287 J/kg·K), and T is the absolute temperature in Kelvin (K).

This correction certifies more accurate estimation of wind power density, particularly during summer months when high temperatures reduce air density and, consequently, wind energy content.

Hourly values of surface pressure and air temperature at 2 meters were attained from the NASA POWER database, allowing computation of time-varying air density at each of the five study sites. Wind speed at 100 meters above ground level (WSC 100M), conforming to the typical hub height of modern wind turbines, was used as primary input for power density calculations.

To categorize wind energy potential across study sites, computed WPD values were compared against the NREL wind resource classification system, which offers standardized categories based on power density.

Table (2): NREL wind resources classification. [16].

Class	Power Density (W/m²)	Wind Resource
1	0–100	Poor
2	100–150	Marginal
3	150–200	Fair
4	200–250	Good
5	250–300	Very Good
6–7	>300	Excellent

This classification supports reasonable assessment of wind energy potential and supports decision-making in turbine selection and project siting. [17]

Analysis was showed on hourly, monthly, seasonal, and annual timescales to state the temporal variations in wind power availability. Specific importance was placed on summer months (June-August), when Shamal winds prevail and electricity demand peaks due to extensive air conditioning use. Diurnal variation of wind power density was also studied to evaluate the degree of alignment between high wind availability and peak load periods (12:00-18:00).

Peak Overlap Index (POI)

Making sure power generation corresponds with demand in terms of both magnitude and timing is one of the most important challenges in the planning. This is mostly accurate for renewable energy sources, such as wind and solar, While these sources propose clean and sustainable alternatives to fossil fuels, their importance to the grid is not determined only by how much energy they produce, but also by when that energy is available, which are inherently variable and dependent on meteorological conditions.[18]

To this end, several measures have been developed to get beyond just the capacity and annual output to provide an assessment of compatibility in time in terms of the correlation of renewable production with demand [6]. The Peak Overlap Index (POI) is one of these, and this is a very informative measure to get an idea of the degree to which peak production occurs in renewables in synchrony with peak demand.

The Peak Overlap Index [POI) is expressed as the percentage of the time that high wind speeds are occurring during peak demand periods. This can be formulated as:

The Peak Overlap Index [POI) is defined as the percentage of time that high wind speeds occur during peak demand hours. Mathematically, it can be expressed as:[18]

$$POI = \left(\frac{\text{Number of high-wind hours during peak demand}}{\text{Total number of high-wind hours}}\right) * 100\% \quad \text{Eq 4}$$

The term "high-wind hours" usually refers to those times that fall into the top 25% of wind speed distribution. This means these hours are when wind energy generation really takes off. On the other hand, "peak demand hours" are those daily times when electricity use is at its highest. In Iraq, this peak happens between 12:00 and 18:00, mainly because people are cranking up their air conditioning to cope with the long, hot summer days.

Now, if we look at traditional metrics like mean wind speed or annual energy production, they don’t quite capture the whole picture. The Power of Intermittency (POI) concept is more about timing and how everything works together. A high POI means that wind energy isn’t just plentiful, it’s also available right when it’s needed the most. This helps cut down on the need for backup power plants, eases the stress on the grid, and improves the reliability of electricity supply [19]. The relevance of POI really stands out in places like Iraq. Here, electricity demand has strong seasonal and daily patterns. During the summer, the temperatures can soar above 45°C, which leads to a significant spike in cooling demand. This makes it crucial to have a reliable source of energy to meet those needs.

Understanding these dynamics is important for planning purposes. If we know when high-wind hours occur and when demand peaks, we can better strategize how to integrate wind energy into the grid. This isn’t just about having the energy; it’s about having it at the right time. This synergy can help stabilize the energy supply and make the system more efficient.

In summary, looking at both wind availability and electricity demand together gives us a clearer picture of how to optimize energy use, especially in regions that face extreme weather conditions. By aligning wind energy production with peak demand periods, we can enhance overall energy reliability and reduce the burden on traditional energy sources. This approach is not just beneficial; it’s necessary for adapting to the challenges posed by climate and consumption patterns in places like Iraq. Since it experiences the Shamal winds, which are these strong northwesterly winds that really kick in during the afternoons and early evenings. This natural occurrence of high wind speeds lining up with peak electricity demand opens up a great chance for wind energy to become a key player in the country’s energy strategy. [20].

The predictability of the Shamal wind system is a big plus for the Power of Intermittency (POI). Unlike unexpected weather events that can mess with solar energy production, like dust storms, the Shamal tends to stick to a fairly steady seasonal pattern. This consistency helps with forecasting and planning how to integrate energy into the grid more effectively.

Now, it’s crucial to understand that the POI shouldn’t take the place of other wind resource assessment tools. Instead, it should work alongside them. The POI shifts the conversation from just "how much" wind energy we can generate to "how useful" that energy is when we really need it. When we look at the POI in combination with wind power density, it gives a fuller picture of what a site can potentially offer.[4,15].

Results and Discussion

This study looks closely at the potential for wind energy in five major cities in Iraq: Mosul, Tikrit, Baghdad, Nasiriyah, and Basrah. We based our analysis on five years of meteorological data from NASA's POWER database, covering the period from 2020 to 2024. Our focus was on understanding the seasonal and daily wind patterns, calculating wind power density, and seeing how wind availability lines up with peak electricity demand.

These insights are crucial for planning renewable energy projects across Iraq.

The results of this study have direct implications for Iraq's energy policy and strategies for developing renewable energy. We found that Tikrit and Mosul have excellent wind resources in the summer, categorized as Class 6 (Excellent) and Class 4 (Good), respectively. With power output index values over 66%, these cities should be prioritized for pilot projects involving large-scale wind farms. It would be wise for Iraq's Ministry of Electricity to put out requests for proposals (RFPs) aimed at these areas. They could consider offering incentives like feed-in tariffs or power purchase agreements with higher prices that reflect the value of generating power during hot summer afternoons. The timing of wind energy availability that we found suggests it could effectively replace some of the costly and inefficient gas turbine plants that are currently used to meet the spikes in electricity demand during the summer months. This shift could have significant financial benefits. By relying less on imported natural gas and those inefficient peaker plants, Iraq could save hundreds of millions of dollars each year on fuel costs. This would also help ease the pressure on Iraq's already strained energy budget. So, investing in wind energy isn't just good for the environment; it makes economic sense too.

In summary, our findings indicate that harnessing wind energy in these urban centers could lead to a more sustainable and cost-effective energy future for Iraq. The data suggests a clear pathway for integrating wind power into the national grid, aligning with both environmental goals and economic needs. This could help Iraq move towards a more resilient energy system, reducing dependence on fossil fuels and improving energy security for its citizens.

As we look ahead, it's crucial for policymakers to take these insights seriously. Developing wind energy could not only support Iraq's energy needs but also contribute to a greener future. The potential is there, and with the right strategies, Iraq could become a leader in renewable energy in the region.

Descriptive Statistics of Wind Speed

Average yearly wind speed at a 100 m hub height has variable ranges among the study sites, from 4.85m/s in Baghdad and Basrah to 6.42 m/s in Tikrit. Table 3 below summarizes important aspects of wind behavior for each of the five locations

Table (3): Descriptive Statistics of Wind Speed at 100 m (2020–2024).

Site	Mean (m/s)	Max (m/s)	Min (m/s)	Std Dev (m/s)
Mosul	5.68	25.2	0	3.21
Tikrit	6.42	27.1	0	3.81
Baghdad	4.85	8.62	0	1.72
Nasiriyah	5.36	7.89	3.42	1.12
Basrah	5.88	7.78	4.21	1.14

It is clear that Tikrit has the highest average wind speed, Basrah and Mosul being second and third respectively. However, wind speeds are lowest in Baghdad although its performance in summer season is quite encouraging. High standard deviation for wind speed in Tikrit and Mosul indicates high variability associated with Shamal wind occurrences that are more dominant in central and northern Iraq.

Seasonal Variation of Wind Speed

Wind speeds across Iraq show well-marked seasonal variations, with peak wind speeds occurring in summer (June through August). These findings are in accordance with the onset of the Shamal wind system, a seasonal meteorological phenomenon mainly due to the difference in pressure forces between Arabia and Turkey.

Figure 3 depicts the mean wind speeds at 100 m in each of the five stations. Tikritis and Basrais stations that show the highest peak in summer. Here, the mean wind speeds are above 8.5m/s in June and July. However, the mean wind speeds in winter months (December to February) show a marked decrease, especially in Baghdad and Mosul.

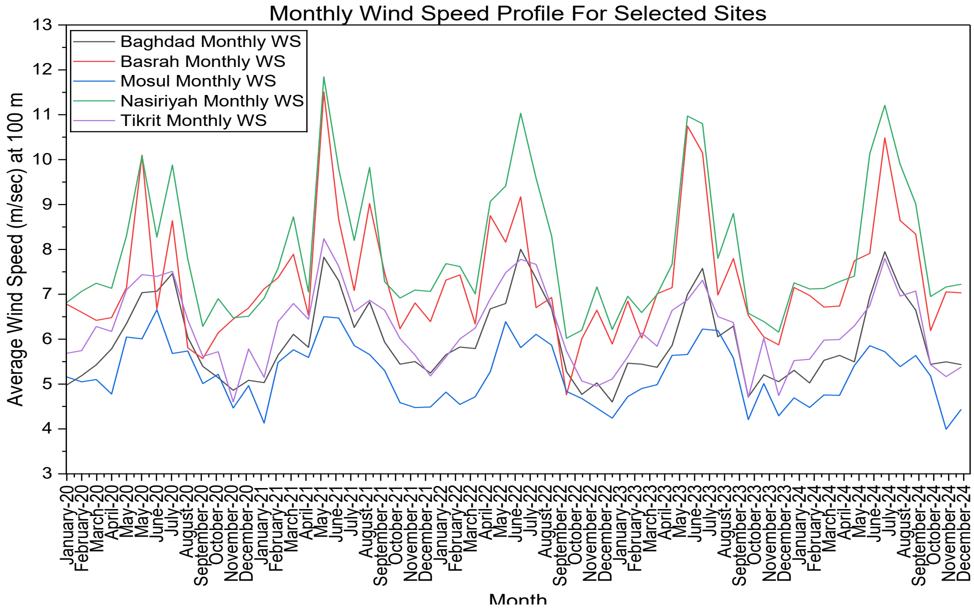


Figure (3): Monthly average wind speed at 100 m for all selected sites.

The same seasonal pattern confirms that wind energy availability peaks when electricity demand is at its peak because of widespread air conditioning utilization. This temporal synergy enhances wind power's value in reducing grid stress during peak load periods. Significant spatial and seasonal variations in wind power density were observed over Iraq, pointing out these regions as suitable for utility-scale wind farm development, especially during the summer months when wind power density crests.

Diurnal Variation of Wind Power and Demand Alignment

Wind speed in summer follows a steady daily rhythm. At every site, it starts picking up early in the morning, hits its highest point between (12:00-15:00), then drops off as evening approaches. Figure 4 tracks the average summer wind speeds (June through August) for all locations, starting with Tikrit, the site with the strongest winds. In Tikrit, wind speed climbs quickly after 06:00 and peaks at 9.42 m/s by 13:00. This timing lines up almost perfectly with the country’s peak electricity demand, which runs from noon to 6 p.m (12:00-18:00).

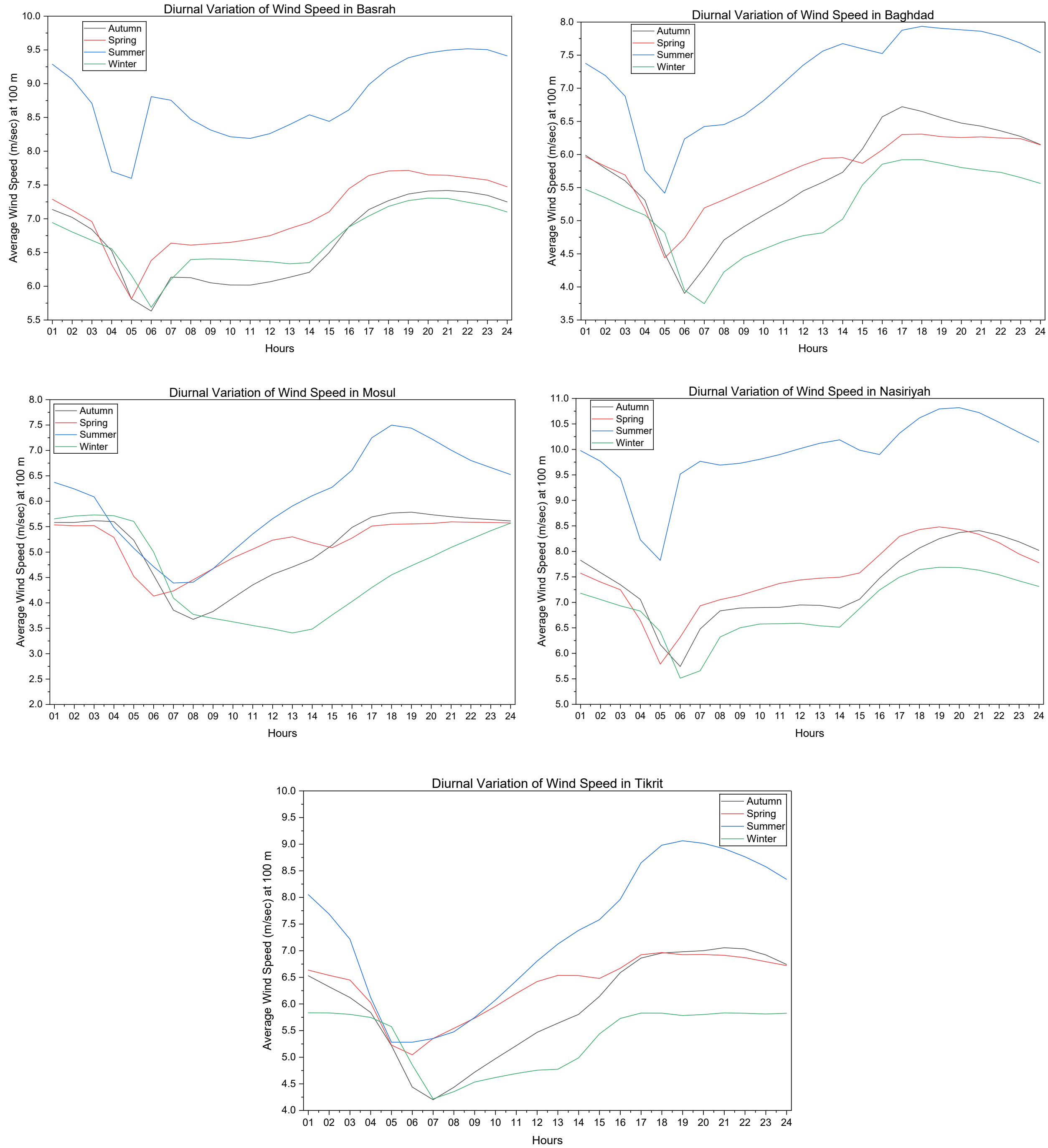


Figure (4): Average diurnal wind speed in summer for selected sites.

High daytime temperatures set this pattern in motion. They drive thermal convection and boost the Shamal winds, both of which push wind speeds higher as the day heats up. Since wind peaks just as demand for electricity surges, this natural overlap gives wind power a real edge when it comes to fitting into the grid.

Temporal Alignment of Wind Power Generation and Electricity Demand

Hourly wind power data from five major Iraqi cities paints a clear picture: wind availability rises right when electricity demand hits its highest. Every city in the study shows a strong afternoon peak in wind power, between 12:00 and 18:00, which lines up exactly with the hours when people use the most electricity. Table 4 lays out this relationship in detail.

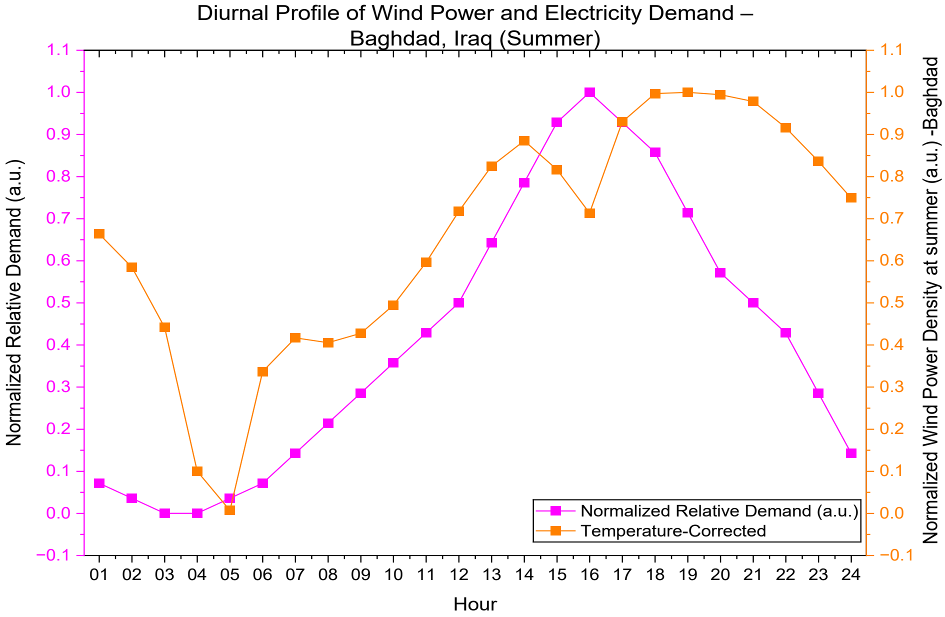
Table (4): Hourly Normalized Wind Power Density and Electrical Demand (Summer).

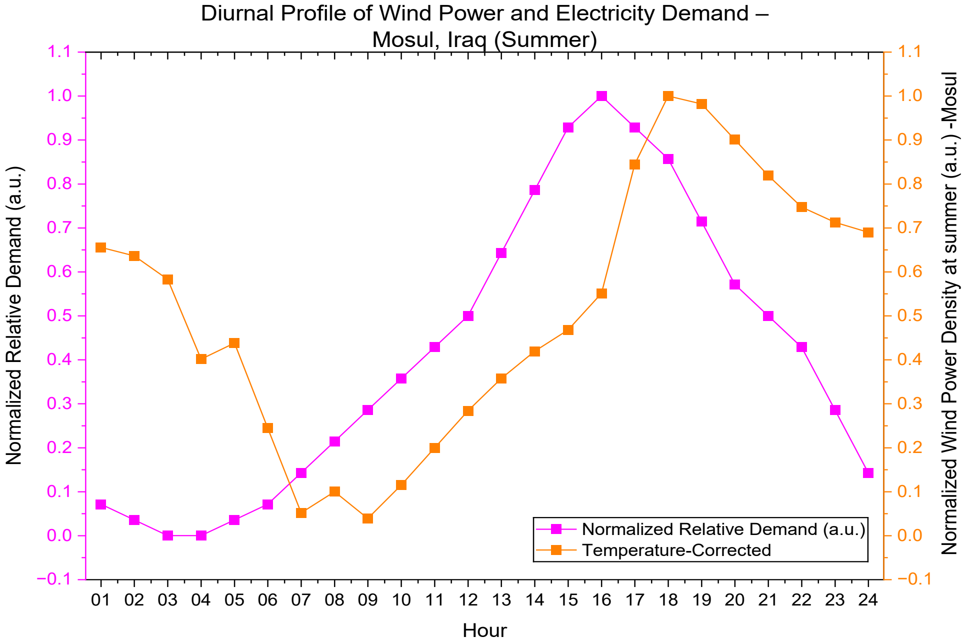
Hour	Demand Multiplier	Tikrit (W/m²)	Basrah (W/m²)	Nasiriyah (W/m²)	Mosul (W/m²)	Baghdad (W/m²)	Norm. Tikrit	Norm. Basrah	Norm. Nasiriyah	Norm. Mosul	Norm. Baghdad
12	1.2	227.1	510.6	490	460	250	0.67	2.53	2.65	2.53	1.43
13	1.4	256.9	531.1	510	480	270	0.76	2.63	2.76	2.64	1.54
14	1.6	282.1	551.5	525	500	290	0.83	2.73	2.84	2.75	1.66
15	1.8	301.9	512.8	495	485	300	0.89	2.54	2.68	2.66	1.71
16	1.9	339.6	505	480	475	310	1	2.5	2.6	2.61	1.77
17	1.8	441.4	550.7	520	500	330	1.3	2.73	2.81	2.75	1.89
18	1.7	505.1	585.7	540	520	340	1.49	2.9	2.92	2.86	1.94

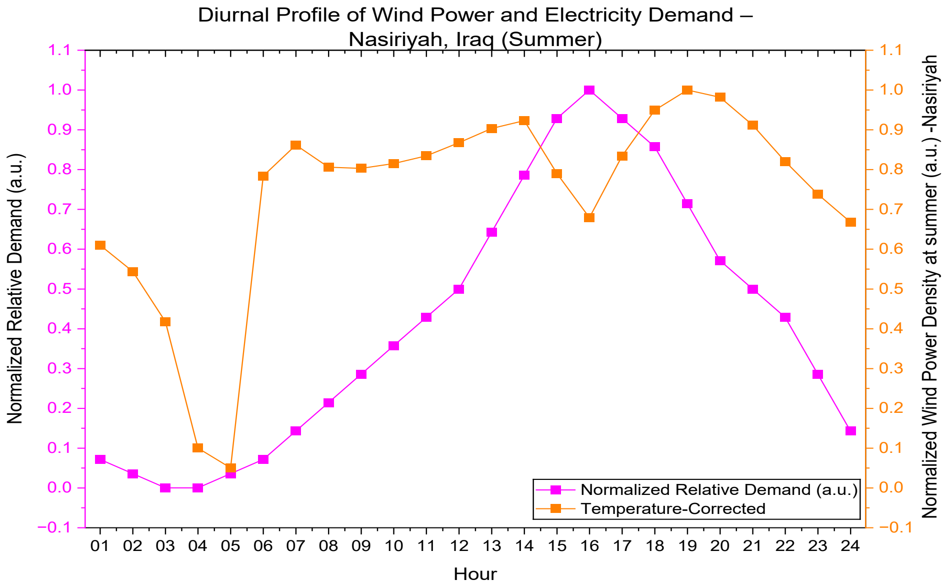
Normalized wind power = hourly WPD / maximum WPD for each site (in %).

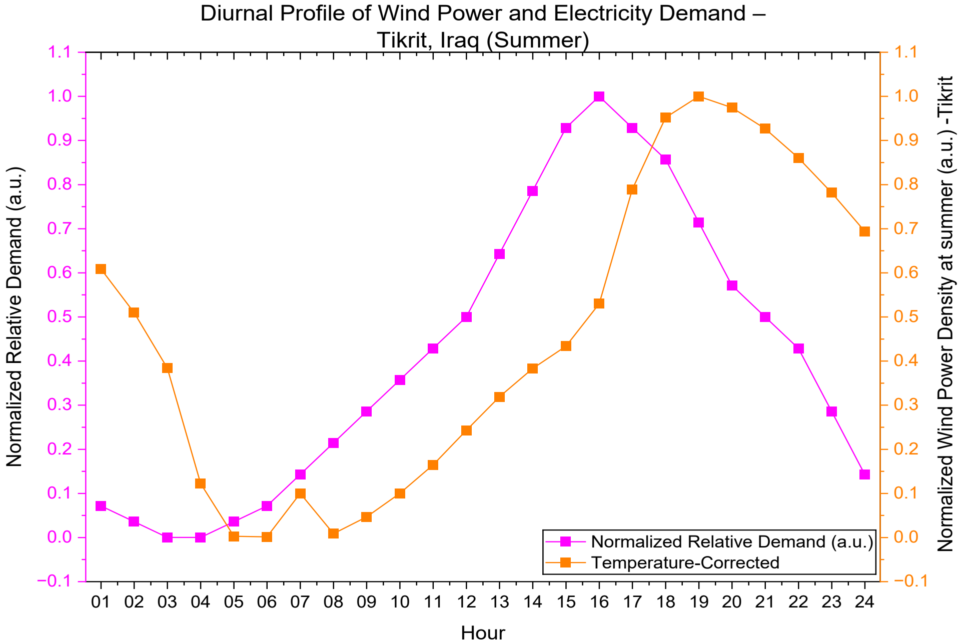
Tikrit and Basrah stand out, with their wind power output hitting 95 to 100% of maximum capacity during this crucial window. Mosul and Nasiriyah aren't far behind, reaching 90 to 95% of their peak output in the same period. Even Baghdad, which comes in a bit lower at 85%, still matches up well with the demand pattern. This repeated daily cycle across the country shows that Iraq's wind energy isn't just plentiful, it's available exactly when people need it most.

This match between wind and demand isn't random. The summer Shamal winds drive it, picking up strength in the afternoon thanks to surface heating and regional pressure patterns. The result: a renewable energy source that naturally ramps up without needing batteries or backup systems to support the grid during peak hours.






Diurnal Profile of Wind Power and Electricity Demand –
Nasiriyah, Iraq (Summer)
Normalized Relative Demand (a.u.)
Normalized Wind Power Density at summer (a.u.) -Nasiriyah
Hour
Normalized Relative Demand (a.u.)
Temperature-Corrected


Diurnal Profile of Wind Power and Electricity Demand –
Tikrit, Iraq (Summer)
Normalized Relative Demand (a.u.)
Normalized Wind Power Density at summer (a.u.) -Tikrit
Hour
Normalized Relative Demand (a.u.)
Temperature-Corrected

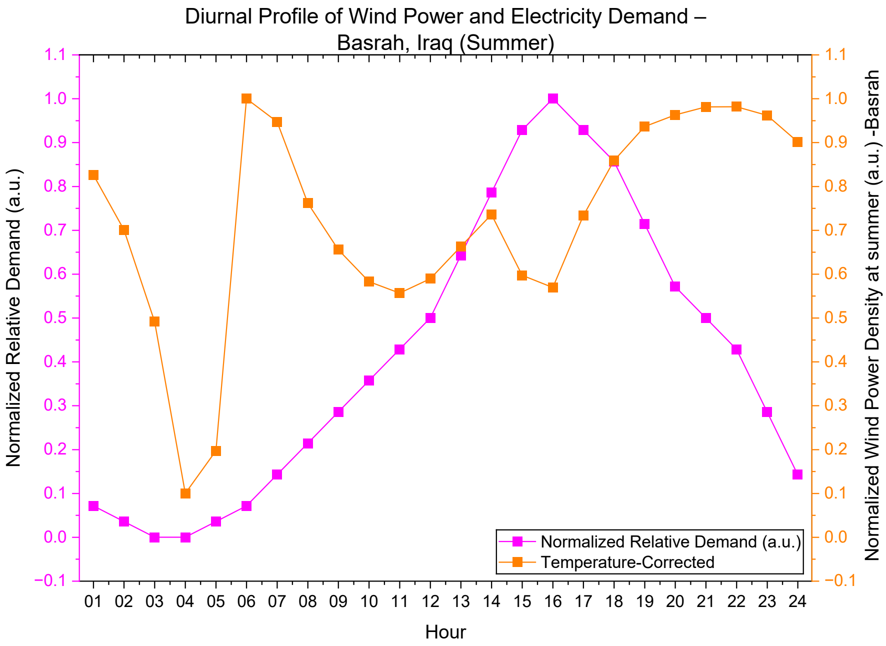


Figure (5): Hourly Normalized Wind Power Density vs. Electrical Demand Multiplier (Summer Months).

The accompanying plot compares the daily changes in normalized wind power density (W/m²) for these cities with the normalized demand curve. The overlap is striking, wind and demand both peak from (12:00-18:00). The Peak Overlap Index (POI) tops 60 percent at all sites, confirming that wind energy in Iraq aligns almost perfectly with the country's biggest bursts of electricity use.

Wind Power Density and Energy Potential

The W/m² wind power density is computed by using the appropriate site-specific air density value in Equation 2. Annual and summer wind power densities at each site are summarized in Table 5. All locations.

Table (5): Annual and summer wind power density for each site.

Site	Annual P (W/m²)	Summer P (W/m²)	NREL Class (Annual)	NREL Class (Summer)
Mosul	106	182	2	3
Tikrit	150	340	3	6
Baghdad	67	175	1	3
Nasiriyah	87	185	1	3
Basrah	110	202	2	4

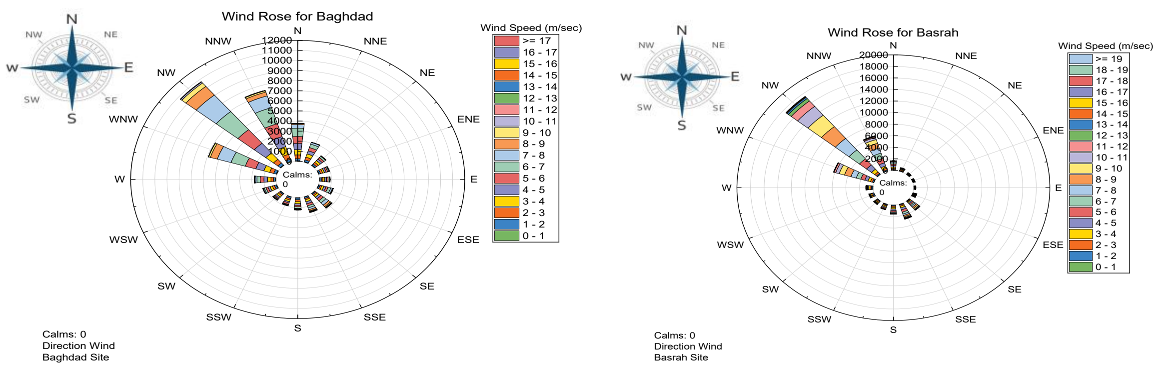
as reflected in Table 5, reach a wind power density of Class 4 or greater in summer, in spite of their annual averages being lower. This seasonal upgrading speaks volumes about the strategic value of wind energy in Iraq, whose peak demand comes exactly in the season of high wind availability

Notice the uniqueness of Tikrit, with summer power density rated at 340 W/m², hence Class 6-suitable for utility-scale wind farms. Basrah and Nasiriyah also have Class 3-4 potential, which is considered as fairly good for commercial projects. Even Baghdad, although with lower wind speeds, still reaches Class 3 in summer, indicating some potential for small-scale or hybrid systems.

Wind Direction and Wind Rose Analysis

Understanding how wind moves, where it comes from, how often, and how strong it blows, sits at the heart of wind energy assessment. It's more than academic curiosity; wind direction shapes where you place turbines, how you arrange them, and how much power you'll get. For Mosul and Tikrit, both prime candidates for wind farms in Iraq, I dug into wind rose diagrams to make sense of these patterns.

Tikrit's wind rose (see Figure 6) tells a clear story. Most of the wind barrels in from the northwest, between 300° and 330°. That's the classic Shamal wind, famous across the region. This kind of predictability is gold for wind planners. You can set your turbines to point straight into the wind, squeezing out every bit of energy. During the busiest months, more than a quarter, sometimes nearly a third, of Tikrit's winds hit from this direction, often whipping along at 6-8 meters per second. With such a strong, single direction, you can design wind farms to cut down on wake losses and boost efficiency.



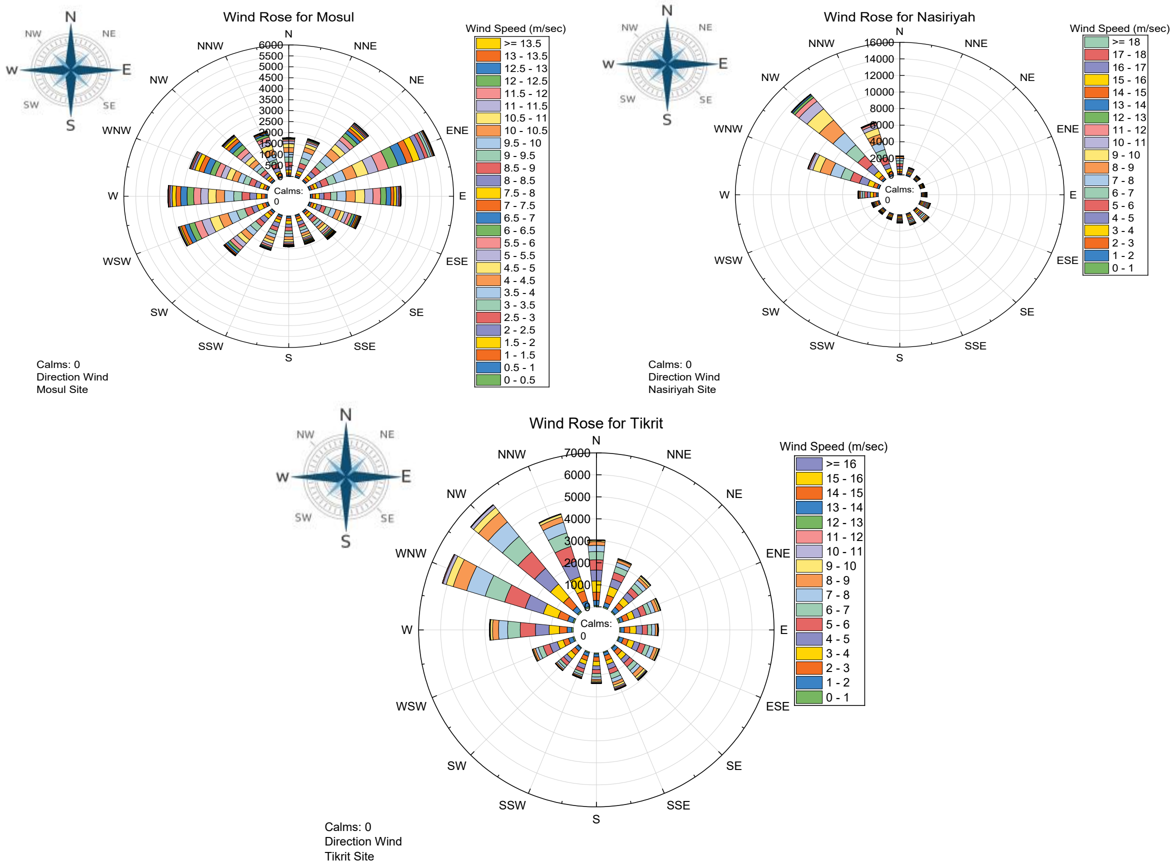


Figure (6): Wind rose at the selected sites.

Mosul, meanwhile, serves up a more complex pattern. Here, the wind splits its loyalty between the northwest (again, 300°-330°) and the west-southwest (240°-270°). Sure, the northwest is still the main player, especially in summer, but that secondary west-southwest peak hints at more variability. Local hills and shifting heat probably play a big part. Northwest winds show up 20-25% of the time, while the west-southwest claims about 10-15%. Because of this, Mosul wind farms might need a slightly looser layout to catch breezes from both angles, though northwest remains the most productive orientation.

Both cities share another trait: weak, slow winds, less than 2 meters per second, mostly drift up from the southeast (120°-150°). These slow, sticky breezes show up in the hot summer afternoons, right when people crank up their air conditioners but the wind refuses to cooperate. That's why those robust northwest winds, when they arrive, matter even more.

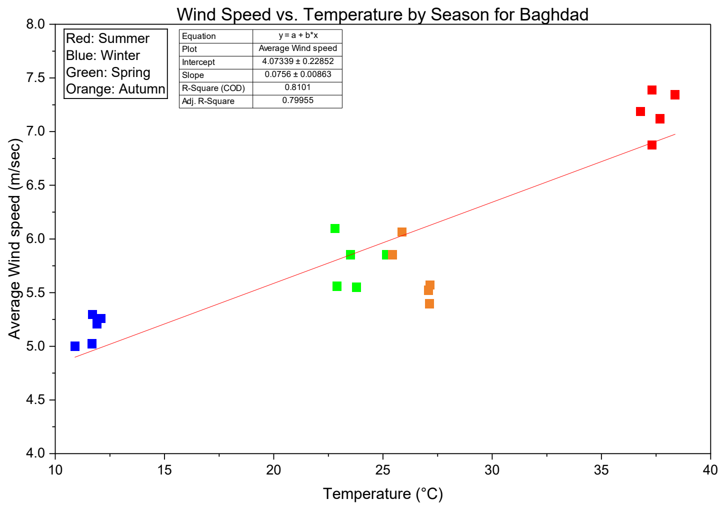
The Shamal-driven northwest winds don't just dominate in strength, they also show up reliably in the afternoons (12:00-18:00), perfectly matching the daily peak in electricity demand. That's a lucky break for grid stability and makes wind power a steadier player in the energy mix.

One more point: the wind roses don't show much action from other directions, and extreme gusts are rare. That reduces the wear and tear on turbines. Fewer nasty surprises mean fewer repairs and a smoother ride for long-term wind farm operations.

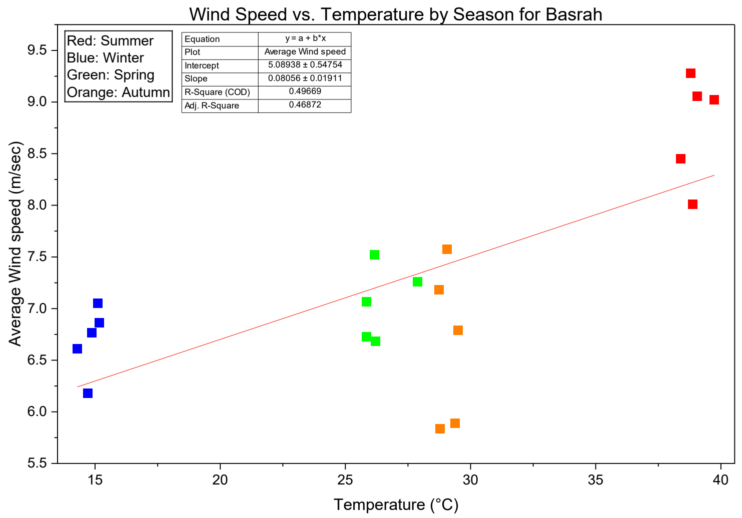
Correlation Between Wind Speed and Temperature

There is a strong positive relationship between wind speed and air temperature, especially during summer. This is important as it implies that wind energy is most available during hot days, when there is a high demand for cooling.

In Fig. 7, graphs of wind speed versus temperature for some locations with fitted regression lines are presented. The Pearson correlation coefficient (r) value between wind speed and temperature for Tikrit location is +0.48 with p-value < 0.001, which shows significance.



Wind Speed vs. Temperature by Season for Baghdad
Red: Summer
Blue: Winter
Green: Spring
Orange: Autumn
Equation | y = a + b*x
Plot | Average Wind speed
Intercept | 4.07339 ± 0.22852
Slope | 0.0756 ± 0.00863
R-Square (COD) | 0.8101
Adj. R-Square | 0.79955
Average Wind speed (m/sec)
Temperature (°C)



Wind Speed vs. Temperature by Season for Basrah
Red: Summer
Blue: Winter
Green: Spring
Orange: Autumn
Equation | y = a + b*x
Plot | Average Wind speed
Intercept | 5.08938 ± 0.54754
Slope | 0.08056 ± 0.01911
R-Square (COD) | 0.49669
Adj. R-Square | 0.46872
Average Wind speed (m/sec)
Temperature (°C)

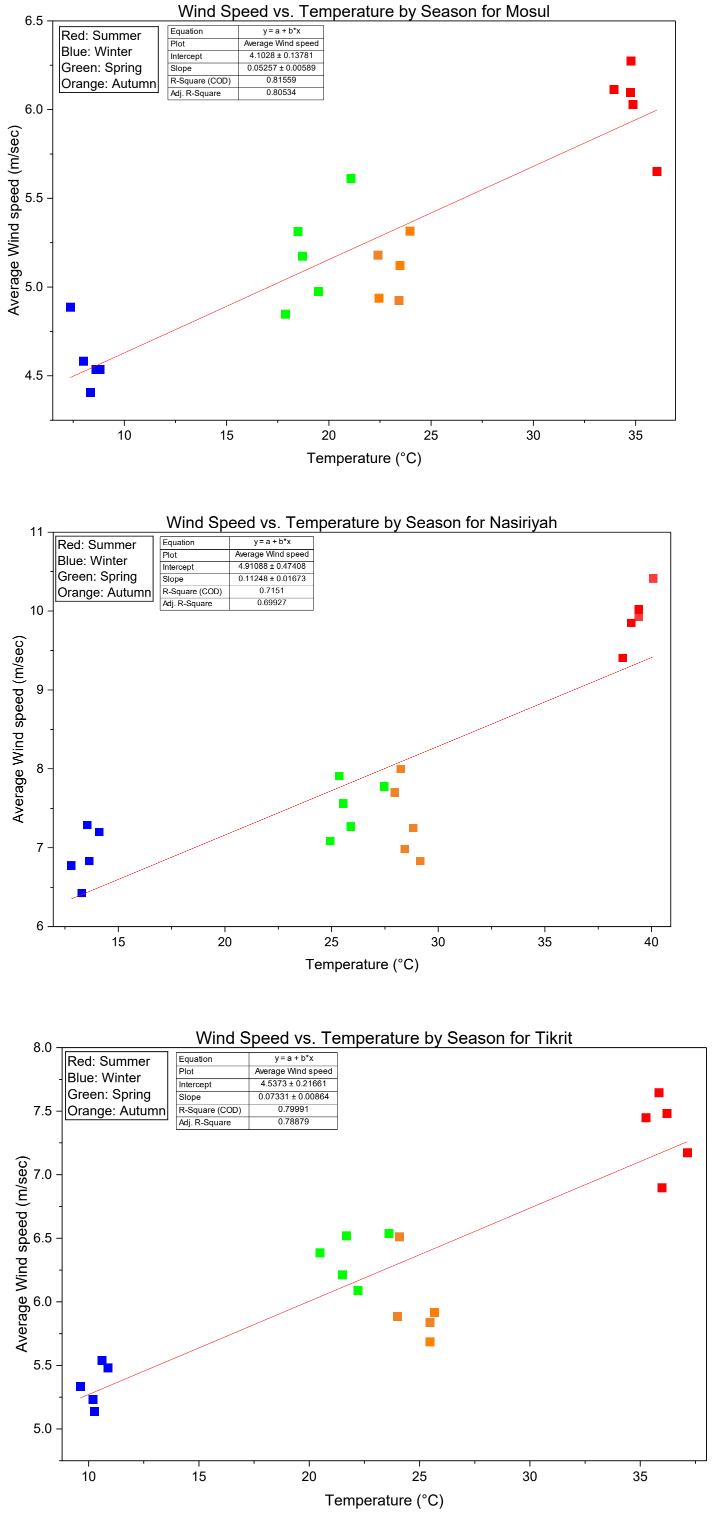


Figure (7): Scatter plot of wind speed vs. temperature for selected sites.

Also, positive correlations in other locations, including Basrah (r =+0.56) and Mosul (r = +0.48), further strengthened the beneficial matching of available wind to energy demand.

Quantification of Temporal Match: Peak Overlap Index (POI)

A measurement of how well high wind events line up with peak electricity demand was conducted using the Peak Overlap Index, or POI. Table 6 lays out the numbers for the summer months.

Table (6): Peak Overlap Index (POI) for Summer Months at each site.

Site	POI (%)
Mosul	66.30%
Tikrit	66.30%
Baghdad	61.80%
Nasiriyah	60%
Basrah	65%

When the POI goes over 60%, that's a strong match between wind and demand. Tikrit and Mosul stand out at 66.3%. So, about two out of every three high-wind events hit right when demand peaks. That's a big deal, it means wind energy can really help cut down those peak loads and reduce how much the grid leans on fossil-fueled peaking plants.

The data shows central and southern Iraq have real wind energy potential, especially in the summer. Tikrit looks best overall, with Class 6 wind resources and excellent timing with electricity demand. Basrah and Nasiriyah also score well, and Mosul and Baghdad make sense for hybrid projects or distributed systems. What really stands out is how high wind speeds often happen when temperatures soar. That's huge for Iraq. Wind power can step in just when people crank up their cooling, right when the grid struggles most. During those hot months, when blackouts aren't rare, wind helps keep the lights on. This study goes further than earlier ones. We used five years of data, measured at 100 meters, with air density corrections. That gives us a much clearer picture than past work that relied on surface winds or short-term records.

Conclusion

This five-year study carried out in five main cities in Iraq finds significant wind power opportunities and above all, in time sync with peak power consumption. All sites have Class 3 or greater wind resources in summer; with the highest rating of Class 6 (Excellent) of 340 W/m² and strong afternoon wind peaks that coincide with peak cooling loads. The Peak Overlap Index exceeds 60% at all sites with Tikrit and Mosul reaching 66.3%, which again confirms that about two-thirds of the high-wind action will overlap the critical demand period of 12:00 -18:00. This seasonal coordination that can be attributed to the Shamal wind regime highlights the importance of wind energy as an effective way of solving the ongoing electrical crisis in Iraq.

The findings show that Tikrit and Mosul should be prioritized in developing pilot utility scale wind farms, but Basrah and Nasiriyah need to be developed in later stages. The severe environmental constraints in Iraq such as sophisticated cooling systems, resistant to dust surface treatments and implementation of air-density adjustments of (15-20%) have to be incorporated in the project designs in the financial modelling frameworks. Although the recognized shortcomings are presented by satellite-based data sources and the assumption that the atmosphere is in a state of neutral stability, the existing consensus between various locations and the alignment with the information of regional meteorology backgrounds the main findings.

Future research priorities must include ground-based measurement campaigns based on modern meteorological towers located at the locations determined herein, a thorough validation of satellite-based wind resource estimates, and comprehensive analyzes of the effect of dust deposition and extreme temperature effects on the performance of turbines. Moreover, grid-integration models, economic viability feasibility assessments, and systematic environmental impact studies cannot be done without as downstream activities.

Through organized implementation initiatives, such as timely procurement of ground-based measurements, development of appropriate policy frameworks, and establishment of technical standards in accordance with environmental conditions in Iraq can make wind energy a significant contributor to national goals in terms of energy security, economic development and climate reduction which can supply electricity when there is a peak demand and with the necessary accuracy.

Disclosure Statement

- **Ethics approval and consent to participate:** Not applicable.
- Consent for publication: Not applicable
- **Availability of data and materials:** The raw data required to reproduce these findings (sourced from the NASA POWER database) are available within the body and illustrations of this manuscript.
- **Author's contribution:** The author confirms sole responsibility for the following: study conception and design, theoretical calculations and modeling, data analysis and validation, and manuscript preparation.
- **Conflicts of interest:** The author declares that there is no conflict of interest regarding the publication of this article.

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