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# DIURNAL AND NOCTURNAL WIND POWER DENSITY ASSESSMENT IN RIVERINE AND COASTAL ZONES OF NIGERIA USING ERA5 DATA

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## ABSTRACT

This study evaluated the diurnal and nocturnal wind power density across six locations in Nigeria: Port Harcourt, Lau, Kainji, Lagos, Lokoja, and Makurdi. The observed values were compared with the on-grid wind power benchmark of 100 W/m². The results reveal significant spatial and temporal variability in wind power potential. Diurnally, Lagos (117.7 W/m²) and Port Harcourt (106.8 W/m²) exceed the on-grid threshold, indicating high suitability for grid-connected wind systems. Nocturnal power density is generally lower but close to on-grid bench mark in Lagos (98.8 W/m²) and Port Harcourt (88.8 W/m²). In contrast, Lau, Kainji, Lokoja, and Makurdi fall below on-grid requirement with power densities of 77.5 (50.2), 38.1 (49.6), 22.2 (39.5), and 37.1 (59.9) W/m² respectively for diurnal (nocturnal) conditions, suggesting limited potential for large-scale applications. Generally, the mean cut-off wind speed of 3 and 4 m/s for turbine operation was achieved in all the locations. Arguably, the findings highlight the coastal advantage, clear diurnal–nocturnal asymmetry, and the necessity for site-specific planning when deploying wind energy infrastructure.

**Keywords**: Power Density, Cumulative Probability, Diurnal, Nocturnal, Wind speed

## INTRODUCTION

Nigeria possesses abundant conventional energy resources, including crude oil, natural gas, coal, and tar sands, alongside significant renewable energy potentials such as solar, hydro, wind, and biomass (Adaramola & Oyewola, 2011). Given the growing global interest in clean energy systems, wind energy has gained traction due to its maturity, environmental friendliness, and competitiveness compared to fossil-based power generation (Ayodele & Ogunjuyigbe, 2016; Ayodele et al., 2013). Therefore, accurate characterization of wind speed is essential for assessing site suitability and selecting appropriate wind energy conversion systems.

Wind energy studies commonly utilize the two-parameter Weibull distribution, a statistical model widely employed to characterize wind regimes. Adaramola *et al.* (2014) evaluated seven locations in the Niger Delta using long-term datasets and applied the Weibull distribution to assess the performance of wind turbines ranging from 35 to 500 kW. Annual energy output varied from 4.07 MWh at Ikom to 145.57 MWh at Ogoja, with the 35 kW G-3120 turbine demonstrating the highest capacity factor. Fagbenle *et al.* (2011) conducted a similar Weibull-based analysis for Maiduguri and Potiskum over 21 years, reporting mean monthly wind speeds between 3.90 and 6.33 m/s and power densities ranging from 102.54 to 360.04 W/m². Both locations were considered suitable for small- to medium-scale wind power installations.

Further contributions include the study by Udo *et al.* (2017), who examined coastal sites (Calabar, Uyo, Warri, and Ikeja), using four years of observational data. Their findings demonstrated the superiority of the Weibull distribution over the Rayleigh model based on RMSE, $\chi^2$, correlation, and Cost of Energy (COE) metrics, with Ikeja exhibiting the highest wind potential, reaching up to 8.37 m/s. Additionally, Adaramola and Oyewola (2011) provided a nationwide review of wind distribution, reporting annual mean wind speeds ranging from 2 to 9.5 m/s and power density values between 3.40 and 520 kW/m², with wind speeds generally increasing from the southern to northern regions.

Similarly, Nze-Esiaga and Okogbue (2014) analyzed 51 years of wind data from five stations in southwestern Nigeria, reporting wind speeds ranging from 1.3 to 13.2 m/s at a height of 10 meters, with seasonal averages between 3.47 and 6.94 m/s. The Weibull parameters (k = 2.99–5.32, c = 3.02–8.57) corresponded to annual power densities of 65.09 to 387.07 W/m², which improved significantly at heights above 10 meters. Ayodele *et al.* (2016) expanded the analysis to 15 locations across Nigeria's geopolitical zones, using capacity factors and present value cost metrics to assess turbine suitability and economic viability. They also highlighted persistent challenges, including poor technical data and limited high-resolution wind resource information.

Collectively, these studies emphasize that accurate wind energy assessment requires statistical models that account for variations in height, air density, seasonality, and directional patterns. However, a persistent challenge in Nigeria is the scarcity of reliable ground-based wind measurements, which has led many studies to rely on airport anemometer data located far from the target sites. Although some studies like Oluleye & Adeyewa (2016), utilized reanalysis datasets such as ERA-Interim (0.75° × 0.75°) to supplement observational data, the use of high-resolution, modern reanalysis products in localized wind assessments remains limited.

Against this background, the present study contributes by applying contemporary reanalysis data from the European Centre for Medium-Range Weather Forecasts' fifth-generation atmospheric reanalysis (ERA5), with a resolution of 0.25° × 0.25°, to evaluate wind characteristics in riverine and coastal environments where ground observations are sparse. Most importantly, the study emphasizes its application for site-specific, height-adjusted, and diurnal–nocturnal wind power analysis, which remains underexplored in Nigerian literature. Specifically, the study evaluates wind speed distribution across target locations using ERA5-derived estimates adjusted to turbine-operational hub heights (100 m). Weibull parameters (shape k and scale c) are derived to characterize the local wind regimes, and wind power density is computed to assess the practical feasibility of wind energy deployment in the study area.

## MATERIALS AND METHODS

### Study Area

The study was conducted across selected riverine and coastal-influenced locations in Nigeria, focusing on Makurdi, Lau, Port Harcourt, Lagos, Kogi, and Niger states. These areas were chosen because they lie within major river corridors such as the Benue and Niger Rivers, or along the Atlantic coastal zone, where land–water interactions strongly influence local wind regimes. The environmental diversity across these locations, ranging from humid coastal climates to inland floodplains and transitional river basins, provides an excellent natural gradient for examining variations in diurnal and nocturnal wind power potential. Their strategic geographical significance, combined with limited in-situ wind measurements, makes them ideal for evaluating the effectiveness of satellite-derived wind data in characterizing wind energy resources in Nigeria's riverine and coastal environments. The study area map is shown in Figure 1.

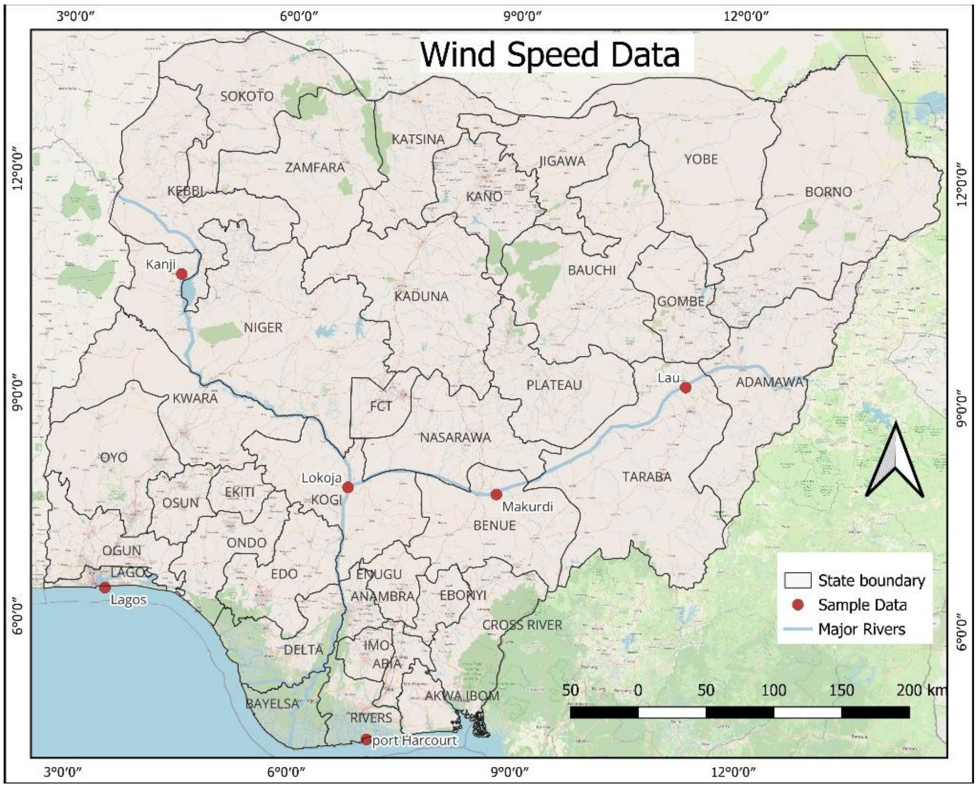


Figure 1: Study Area

### Data Collection and Pre-processing

Wind speed data were obtained from NIMET ground stations and ERA5 reanalysis products for the selected study period. All datasets underwent quality control procedures to remove missing or erroneous values. Hourly wind speeds were then grouped according to local sunrise and sunset times to calculate diurnal (daytime) and nocturnal (nighttime) averages for subsequent analysis

### Probability Distribution Analysis

The statistical distribution of wind speed was analyzed using the Weibull probability density function (PDF), which is widely applied in wind resource assessment. The two-parameter Weibull PDF is expressed as follows (Oyedepo *et al.*, 2012; Oluleye & Adeyewa, 2016):

$$f(v) = (k/c) \times (v/c)^{k-1} \times exp[-(v/c)^k] \quad (1)$$

Where v is the wind speed (m/s), k is the shape parameter estimated using the Maximum Likelihood Estimation (MLE) method, and c is the scale parameter (m/s). This function describes the likelihood of different wind speeds occurring at the study site.

### Wind Power Density Estimation

Wind power density (W/m²) represents the amount of kinetic energy available in the wind at a specific location. Using the Weibull distribution, power density is calculated as follows (Oyedepo *et al.*, 2012; Li *et al.*, 2022):

$$WP = 1/2\,\rho c^3 \times \Gamma(1 + 3/k) \quad (2)$$

Where ρ = air density (kg/m³), typically 1.225 kg/m³, and Γ = gamma function. This expression integrates the Weibull function to obtain the average power. The wind speed at turbine height (h) is given by (Oyedepo *et al.*, 2012; Li *et al.*, 2022).

$$v_h = v_{10}\left(\frac{100}{10}\right)^a \quad (3)$$

The value α = 1/7 provides a reasonable estimate in the absence of site-specific measurements (Adaramola & Oyewola, 2011)

### Nocturnal and Diurnal Wind Speed Analysis

To analyze daily variability, hourly wind speed values were divided into diurnal (daytime) and nocturnal (nighttime) periods based on local sunrise and sunset times for each location. Since ERA5 provides wind data only at hourly UTC intervals, the diurnal and nocturnal periods were approximated using the ERA5 hour closest to each day's local sunrise and sunset. This method ensures that the day/night separation accurately reflects actual solar conditions while maintaining consistency with the temporal resolution of ERA5.

$$V_d = (1/N_d)\Sigma_{i=1}^{N_d}(v_i) \quad (4)$$

$$V_n = (1/N_n)\Sigma_{i=1}^{N_n}(v_i) \quad (5)$$

$N_d$ and $N_n$ = number of daytime and nighttime observations. This allows for the assessment of boundary-layer dynamics and the influence of atmospheric stability on wind behavior.

**Wind Variance**

Wind speed variance quantifies the degree of fluctuation in wind speeds over time and is given by Katinas et al. (2018):

$$\sigma^2 = (1/(n-1)) \times \Sigma(v_i - \bar{v})^2 \quad (6)$$

Where, $\bar{v}$ = mean wind speed (m/s) The variance helps identify turbulence intensity and reliability of wind energy resources.

## RESULTS AND DISCUSSION

**Mean Wins speed over the study locations**

Figure 2 illustrates the spatial distribution of diurnal and nocturnal wind characteristics at 10 m and 100 m (turbine height). The results demonstrate clear spatial differences at both heights across the six locations, reflecting the combined influence of coastal–inland dynamics and boundary-layer processes. Figure 3 presents the annual mean distribution of diurnal and nocturnal wind characteristics at 100 m. At this height, Lagos recorded the highest diurnal wind speed of approximately 5.7 m/s, with a corresponding nocturnal speed of 5.3 m/s, indicating strong and persistent winds suitable for utility-scale wind turbines. Port Harcourt followed, exhibiting nearly equal diurnal and nocturnal speeds of about 5.3 m/s, suggesting a stable wind regime. Lau showed moderately strong winds, with diurnal and nocturnal values around 5.0 m/s and 4.8 m/s, respectively. Makurdi and Kainji exhibited moderate wind speeds, diurnal values of roughly 4.3 m/s and 4.0 m/s, compared to nocturnal speeds of 4.5 m/s and 3.8 m/s, indicating potential suitability for medium-scale or hybrid wind systems. Lokoja recorded the lowest diurnal wind speed (3.2 m/s), although its nocturnal wind speed increased to about 3.8 m/s, likely due to nighttime low-level jet activity. Wind variance also varied distinctly, with Lagos showing the highest diurnal variance of around 2.0 m/s, compared to 1.7 m/s nocturnally, while Port Harcourt, Lau, and Kainji exhibited moderate variances between 1.6 and 1.8 m/s. Lokoja again showed the lowest variance (about 1.2–1.3 m/s) during both periods, consistent with its weaker and more stable winds. Generally, the combined magnitude and variability of wind conditions identify Lagos as the most favorable site for wind turbine deployment, followed by Port Harcourt and Lau, while inland locations such as Makurdi, Kainji, and especially Lokoja offer comparatively lower but site-dependent wind energy potential.

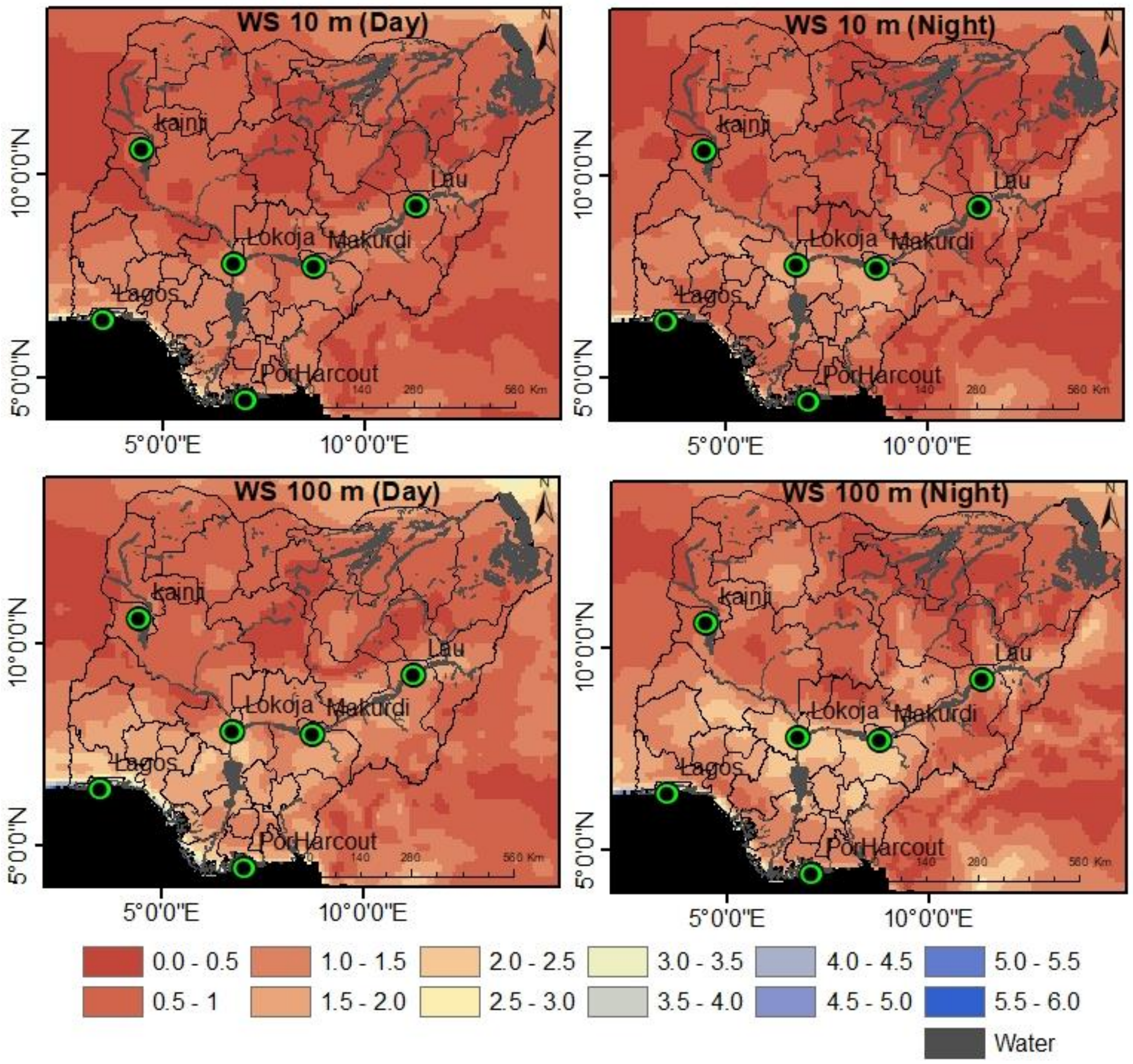


Figure 2: Spatial distribution of the diurnal and nocturnal wind characteristics at 10 and 100 m

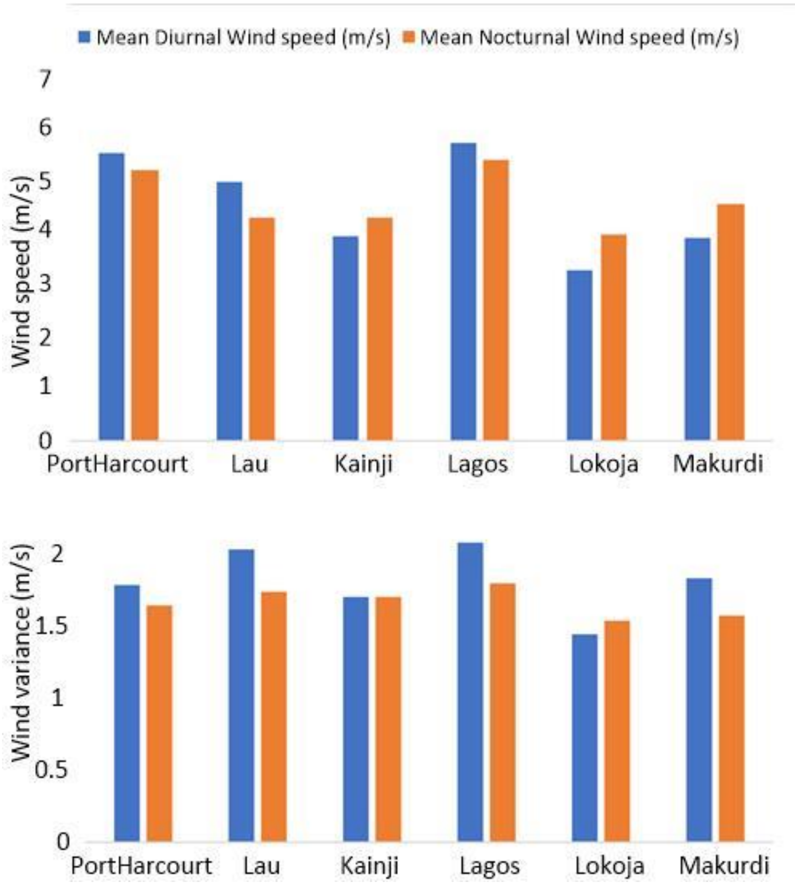


Figure 3: Annual mean distribution of the diurnal and nocturnal wind characteristics at 100 m

**Cumulative Probability**

Figures 4 and 5 show the Weibull probability density and cumulative probability distributions for diurnal and nocturnal winds. The results reveal that the Weibull probability density and cumulative distribution functions provide an excellent representation of both the diurnal and nocturnal wind-speed regimes across the six sites, as demonstrated by the close alignment between the empirical histograms and the fitted Weibull curves. During the daytime, Kainji's wind-speed distribution peaks at approximately 4.5 m/s, with most values ranging between 2 and 7 m/s, while Lau exhibits a stronger peak near 5.0 to 5.5 m/s. Lagos records the highest daytime densities, with a broad peak centered around 6.5 to 7.0 m/s, indicating its superior wind resource. Lokoja and Makurdi show more moderate distributions, with peak daytime probabilities occurring around 4.0 to 5.0 m/s, whereas Port Harcourt displays a more skewed distribution with a prominent peak close to 6.0 m/s. The corresponding daytime cumulative probability plots show that Kainji, Lokoja, Makurdi, and Lau reach 80 to 90% cumulative probability by 7 to 8 m/s, while Lagos and Port Harcourt extend this threshold to 9 to 10 m/s, highlighting their higher wind-energy potential. At night, the distributions maintain similar shapes but with slightly more concentrated (narrower) peaks: Kainji, Lokoja, and Makurdi retain their maxima around 4.5 to 5.0 m/s; Lau's peak shifts toward 4.0 to 5.0 m/s; and Lagos and Port Harcourt continue to dominate with peaks between 6.0 and 7.0 m/s. The nighttime cumulative curves again show a strong match between empirical and Weibull-modeled probabilities, with inland stations reaching 90% probability at 7 to 8 m/s, and coastal stations (Lagos and Port Harcourt) doing so near 9 to 10 m/s. Overall, the strong agreement between actual and Weibull-fitted distributions across all sites confirms that the Weibull model reliably characterizes wind-speed behavior at 100 m, providing a robust basis for estimating wind-energy potential during both day and night.

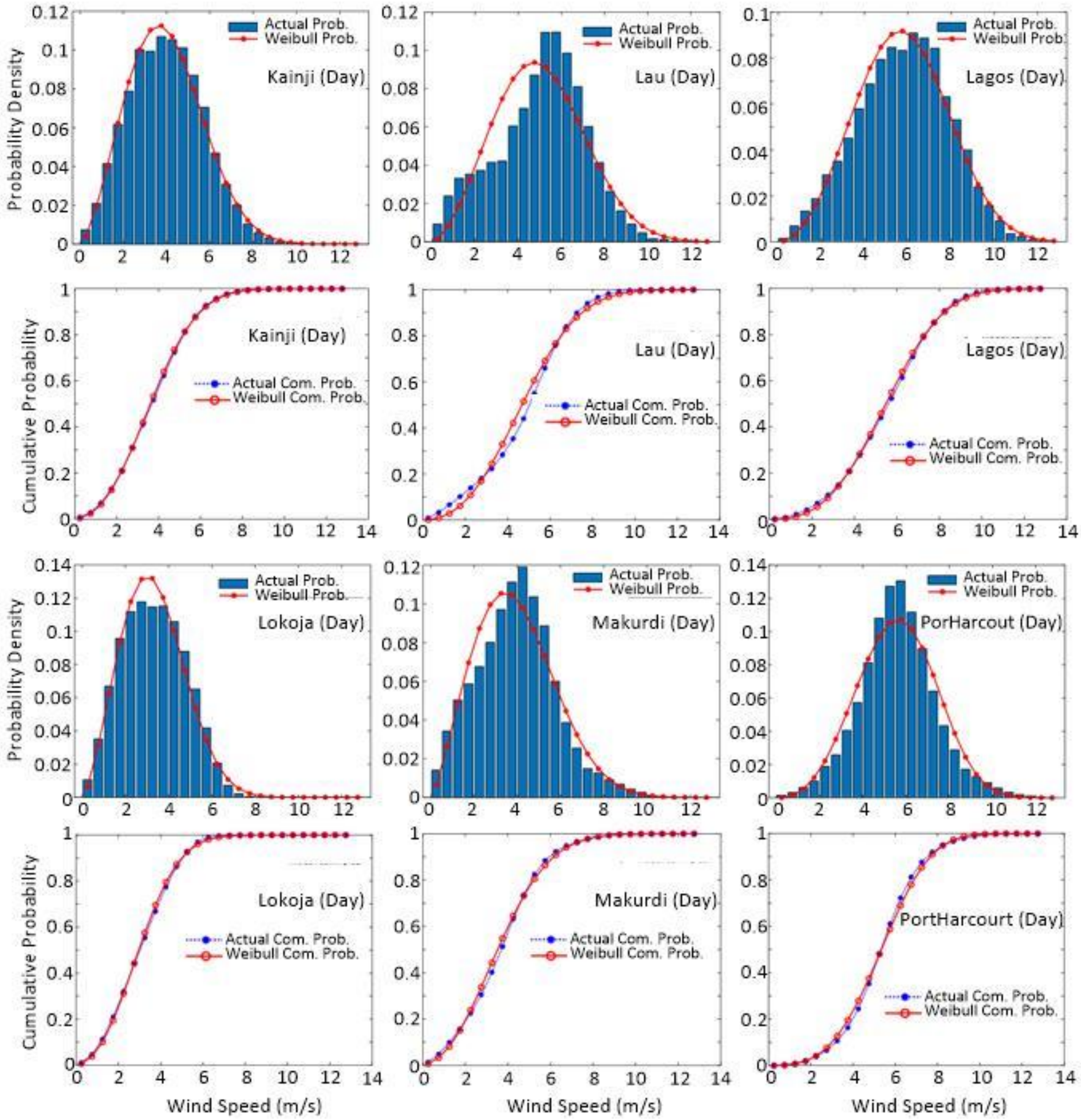


Figure 4: Weibull Probability density and cumulative probability for diurnal winds

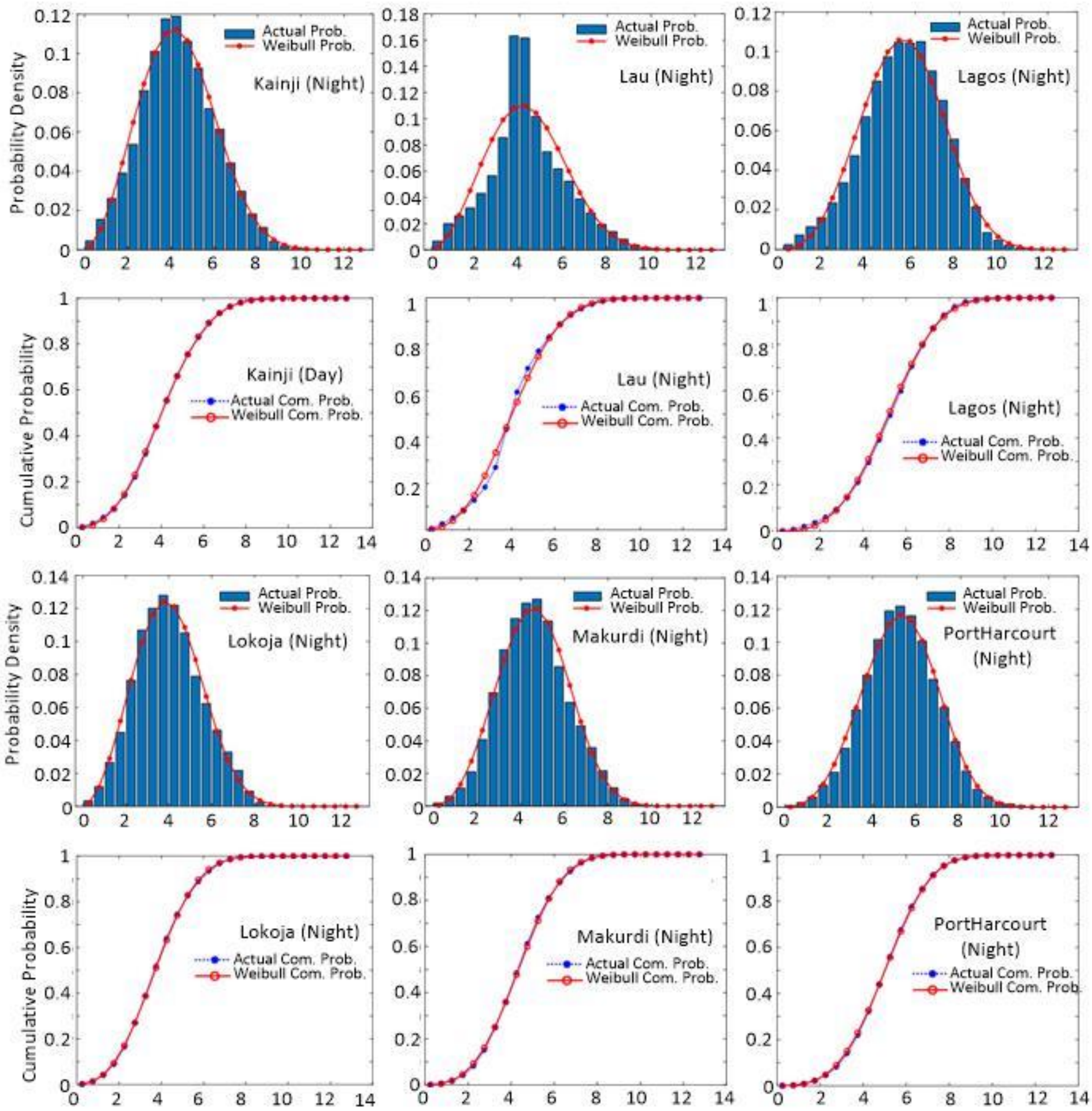


Figure 5: Weibull Probability density and cumulative probability for nocturnal winds

**The Weibull shape and scale parameters**

The Weibull parameter results (Table 1) reveal distinct diurnal and nocturnal variations across the six locations, reflecting differences in wind regime stability and intensity at a 100 m hub height. During the day, Lagos and Port Harcourt exhibit the strongest winds, with scale parameters (c) of 6.46 m/s and 6.21 m/s, respectively, and shape parameters (k) of 3.03 and 3.46, indicating relatively stable and high-energy winds. Kainji and Makurdi show moderate daytime scale values of 4.47 m/s and 4.43 m/s, with corresponding shape factors of 2.49 and 2.27, reflecting broader variability. Lau and Lokoja display slightly lower scale parameters at 5.65 m/s and 3.73 m/s, with shape values of 2.66 and 2.46, respectively. Model performance during the day is strong across all sites, with very low RMSE values (e.g., 0.0037 in Kainji, 0.0049 in Lagos) and high Kolmogorov–Smirnov D-statistics, specifically 0.99 in Kainji and 0.98 in Lagos, confirming a good Weibull fit. At night, the wind regime becomes more uniform and better structured, as reflected in higher k values at several sites, including Makurdi (k = 3.22), Lokoja (k = 2.84), and Kainji (k = 2.76). Nighttime scale parameters decrease slightly at most locations, for example, Lagos reduces from 6.46 m/s (day) to 6.07 m/s, Port Harcourt from 6.21 m/s to 5.84 m/s, and Lau from 5.65 m/s to 4.88 m/s, consistent with the typical nocturnal stabilization of the boundary layer. Despite this, nighttime Weibull model performance improves markedly, with RMSE values dropping as low as 0.0029 in Port Harcourt and D-values exceeding 0.99 in Port Harcourt, Lokoja, Kainji, and Makurdi, indicating near-perfect correspondence between observed and fitted distributions. Overall, the findings show that Lagos and Port Harcourt maintain the highest wind-energy potential, while all sites exhibit excellent Weibull model performance, especially at night when the distributions become smoother and more stable.

**Table 1: Weibull parameters at 100 m (turbine height) for diurnal and nocturnal wind conditions**

| | Location | Weibull parameters | | Error metrics | |
|---|---|---|---|---|---|
| | | Shape, k | Scale, c | RMSE | $R^2$ |
| Day | Port Harcourt | 3.463345 | 6.212811 | 0.008768 | 0.962544 |
| | Lau | 2.655193 | 5.649563 | 0.014084 | 0.842017 |
| | Kainji | 2.494823 | 4.467305 | 0.003723 | 0.991855 |
| | Lagos | 3.033561 | 6.458881 | 0.004861 | 0.978214 |
| | Lokoja | 2.457418 | 3.732424 | 0.006159 | 0.983955 |
| | Makurdi | 2.272822 | 4.431847 | 0.009294 | 0.944773 |
| Night | Port Harcourt | 3.543473 | 5.835828 | 0.002862 | 0.996127 |
| | Lau | 2.706016 | 4.884484 | 0.017616 | 0.853424 |
| | Kainji | 2.758866 | 4.863033 | 0.00367 | 0.991995 |
| | Lagos | 3.337558 | 6.065969 | 0.004056 | 0.988942 |
| | Lokoja | 2.837847 | 4.502605 | 0.003594 | 0.993588 |
| | Makurdi | 3.224936 | 5.141900 | 0.004299 | 0.990801 |

**Wind Power**

Table 2 presents the wind power and corresponding power density at 100 meters. Across the six locations, daytime wind conditions generally exhibited higher wind speeds and power outputs compared to nighttime values. During the day, Lagos recorded the highest mean wind speed at 5.77 m/s, with a corresponding power density of 117.69 W/m², closely followed by Port Harcourt at 5.59 m/s and 106.81 W/m². Lau maintained moderate daytime winds of 5.02 m/s and 77.54 W/m², while Makurdi and Kainji had lower values of 3.93 m/s and 37.06 W/m², and 3.96 m/s and 38.14 W/m², respectively. Lokoja exhibited the weakest daytime winds at 3.31 m/s and 22.22 W/m². At night, wind speeds slightly decreased at most locations: Lagos dropped to 5.44 m/s with 98.84 W/m², and Port Harcourt to 5.25 m/s with 88.84 W/m². Lau and Kainji experienced nighttime mean speeds of 4.34 m/s and 4.33 m/s, producing 50.21 W/m² and 49.65 W/m², respectively. Makurdi also showed moderate nighttime winds of 4.61 m/s with a power density of 59.89 W/m², while Lokoja again remained the lowest at 4.01 m/s and 39.54 W/m². Generally, daytime winds demonstrated stronger generation potential, with Lagos and Port Harcourt emerging as the most promising sites for wind energy development under both diurnal conditions.

**Table 2: Wind Power and Power Density**

| | Location | Weibull statistics and power | | | |
|---|---|---|---|---|---|
| | | Mean, v (m/s) | Std (m/s) | Wind Power (W) | Power Density (W/m²) |
| Day | Port Harcourt | 5.587 | 1.785 | 838876.115 | 106.809 |
| | Lau | 5.021 | 2.036 | 609026.942 | 77.544 |
| | Kainji | 3.963 | 1.699 | 299519.507 | 38.136 |
| | Lagos | 5.771 | 2.076 | 924349.810 | 117.692 |
| | Lokoja | 3.310 | 1.438 | 174503.750 | 22.219 |
| | Makurdi | 3.926 | 1.829 | 291048.411 | 37.057 |
| Night | Port Harcourt | 5.254 | 1.644 | 697784.512 | 88.845 |
| | Lau | 4.344 | 1.732 | 394340.591 | 50.209 |
| | Kainji | 4.328 | 1.696 | 389968.969 | 49.652 |
| | Lagos | 5.444 | 1.798 | 776320.588 | 98.844 |
| | Lokoja | 4.011 | 1.532 | 310522.374 | 39.537 |
| | Makurdi | 4.607 | 1.569 | 470413.377 | 59.895 |

Across the six locations, wind power density exhibits significant spatial and diurnal variability when compared to the on-grid generation standard of 100 W/m², as shown in Figure 6. Lagos demonstrates the highest potential, with a diurnal mean of 117.7 W/m² and a nocturnal value of 98.8 W/m², making it the only site that consistently meets or closely approaches the grid threshold. Port Harcourt follows, with a diurnal power density of 106.8 W/m², slightly above the standard, although its nocturnal value decreases to 88.8 W/m². All other sites fall well below the grid requirement: Lau records 77.5 W/m² (day) and 50.2 W/m² (night); Kainji yields 38.1 W/m² (day) and 49.7 W/m² (night); Lokoja shows very low densities of 22.2 W/m² (day) and 39.5 W/m² (night); while Makurdi produces 37.1 W/m² (day) and 59.9 W/m² (night). Overall, only Lagos and, to a lesser extent, Port Harcourt demonstrate wind power densities compatible with on-grid electricity generation, whereas the remaining locations are more suitable for small-scale or off-grid wind applications.

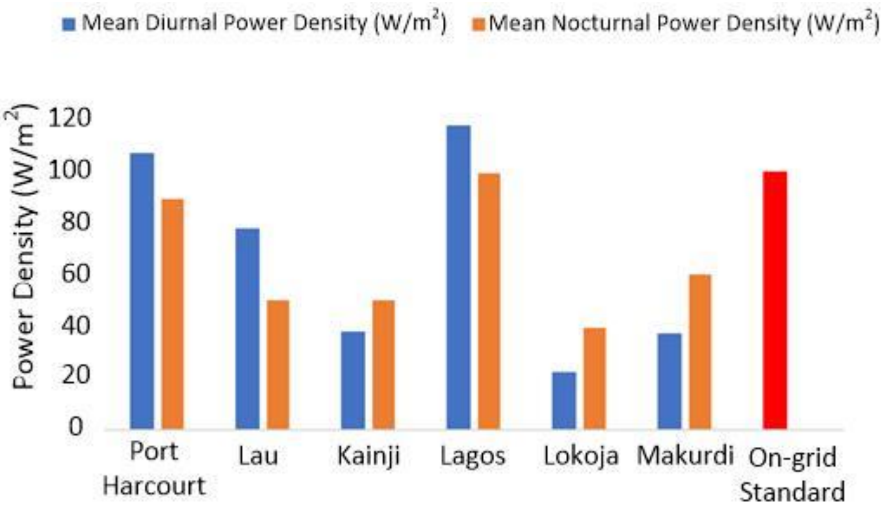


Figure 6: Power density comparison with On-grid standard

**Comparison of Satellite data with Ground Measurements**
The validation results demonstrate a reasonable level of agreement between the satellite-derived wind speeds and ground measurements, although the strength of this agreement varies across locations. The Taylor diagram (Figure 7) shows that Lagos exhibits the closest match overall, with the lowest centered RMS difference (0.80) and the highest standard deviation (0.96), indicating that the satellite data more effectively captures both the variability and magnitude of the observed winds there. Makurdi also shows good correspondence, with a centered RMS difference of 0.56 and a correlation of 0.70, suggesting that the satellite estimates closely follow the temporal pattern of the ground observations, even though the variability is slightly lower (standard deviation 0.78). In contrast, Port Harcourt presents a weaker match, as reflected by a higher centered RMS difference (0.76) and a lower correlation (0.40), implying that the satellite data does not track the observed fluctuations as well in this coastal environment. Despite these differences, the overall validation indicates that the satellite dataset can reliably approximate ground-based wind speed characteristics, particularly in inland locations, and is therefore suitable for wind resource assessment in areas where meteorological stations are sparse or unavailable.

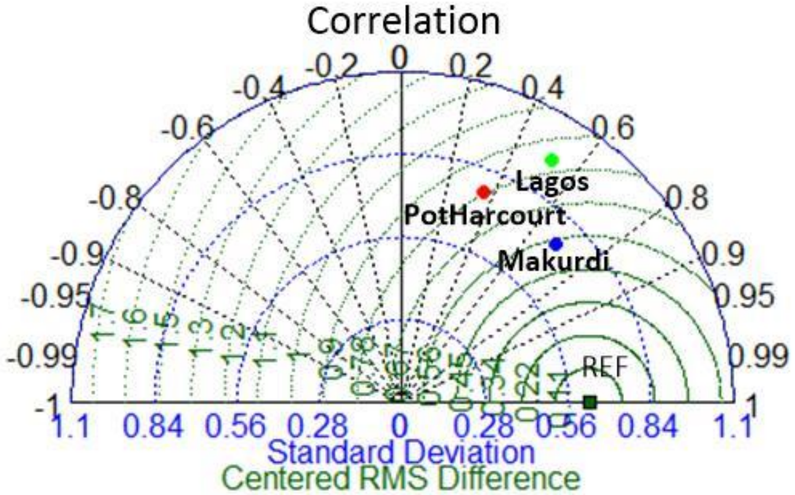


Figure 7: Tailor diagram showing comparison between satellite data and ground measurements

**Discussion**
In this study, ERA5 reanalysis wind data were utilized to estimate wind speed and wind energy potential at a turbine hub height of 100 meters, particularly in regions where long-term ground-based observations are limited or difficult to obtain. Among the six selected locations, only Makurdi and Port Harcourt and Lagos had available ground-measured wind data for validation. The comparison demonstrated that ERA5 reasonably reproduced the temporal patterns of observed wind speeds, indicating general agreement between the datasets. However, consistent with previous studies reporting that reanalysis products tend to underestimate near-surface wind speeds in tropical regions (e.g., Ayodele *et al.*, 2016; Adaramola & Oyewola, 2011; Oluleye & Adeyewa, 2016), ERA5 values were lower than ground observations at both locations. This underestimation may be attributed to the coarse spatial resolution of reanalysis data, smoothing of local terrain effects, and the model's limited ability to capture microscale atmospheric processes, especially in complex surface environments. Despite this bias, ERA5 remains a reliable alternative where measured data are unavailable, and its use at 100 meters height is advantageous for modern wind energy assessments, as wind speeds at this height better represent turbine performance.
The analysis of wind characteristics across the study area revealed patterns broadly consistent with earlier findings on Nigeria's wind energy potential. In this study, annual mean wind speeds generally fell within moderate ranges, aligning

with the national pattern reported by Adaramola and Oyewola (2011), who documented values between 2 and 9.5 m/s, with lower speeds in the south and progressively higher speeds toward the north. Our findings similarly show spatial variations favoring northern locations, reinforcing the established north–south wind gradient. The computed Weibull parameters (k and c) also fell within expected ranges for Nigerian wind regimes. For example, the scale parameter (c) values obtained in this work correspond well with those reported by Nze-Esiaga and Okogbue (2014), who found 3.02 ≤ c ≤ 8.57 for five southwestern stations, indicating comparable variability of wind resources at our sites, particularly during the wet season when wind speeds increased. Olu reported wind speeds in Enugu, Owerri, and Onitsha as 5.42, 3.36, and 3.59 m/s at 10 m height, whereas the 10 m day (night) annual wind speeds in the present study for Port Harcourt, Lau, Kainji, Lagos, Lokoja, and Makurdi were 2.99 (2.82), 2.69 (2.33), 2.12 (2.32), 3.09 (2.92), 1.77 (2.15), and 2.10 (2.47) m/s, respectively. Similarly, Eboibi et al. (2017) reported annual mean wind speeds of 3.3, 3.3, 4.4, 3.4, 3.5, and 3.7 m/s for Asaba, Benin, Calabar, Port Harcourt, Uyo, and Warri, while in Makurdi, Audu et al. (2019) documented wind speeds ranging between 3.0 and 4.0 m/s.

The seasonal variation in wind speed observed in this study corroborates earlier findings. As reported by Nze-Esiaga and Okogbue (2014), who documented seasonal mean wind speeds ranging from 3.47 to 6.55 m/s during the dry season and 3.83 to 6.94 m/s during the wet season, our dataset similarly reflects stronger winds during the wet period. This indicates a persistent climatological influence of monsoonal flow on Nigeria's wind field. The nocturnal–diurnal cycle identified in Section 3.3 revealed higher nighttime wind speeds compared to daytime values, an outcome consistent with boundary-layer characteristics described in similar energy assessments in tropical regions. However, this pattern is notably absent in turbine-height measurements from temperate climates, such as those studied by Bilir et al. (2015) in Turkey.

The wind power density (WPD) values derived from this study also fall within the broad national ranges. While Adaramola and Oyewola (2011) reported a national range of 3.40 to 520 W/m², our computed WPD values cluster more closely within the low-to-moderate category observed in previous Nigerian studies. For example, Nze-Esiaga and Okogbue (2014) reported mean annual power densities between 65.09 and 387.07 W/m², which align with the moderate WPD values from our results. This suggests that the study area possesses wind resources suitable for small-scale wind applications but is marginal for large grid-scale projects. Similarly, the seasonal pattern observed in our WPD analysis mirrors the findings of Bilir et al. (2015), who recorded the highest wind power density in winter and the lowest in autumn; in our case, peak values also corresponded to periods dominated by stronger synoptic-scale weather systems. Additionally, Oyedepo et al. (2012) reported annual mean power densities of 96.98, 23.23, and 28.34 W/m² at 10 m for Enugu, Owerri, and Onitsha, respectively. The report by Eboibi et al. (2017) indicated average wind speeds of 3.3 m/s, 3.3 m/s, 4.4 m/s, 3.4 m/s, 3.5 m/s, and 3.7 m/s for Asaba, Benin, Calabar, Port Harcourt, Uyo, and Warri, respectively, with corresponding mean power densities of 21.8 W/m², 21.4 W/m², 35.8 W/m², 23 W/m², 25.2 W/m², and 30.8 W/m². Another study by Omonigho et al. (2019), which corroborates our findings, reported a wind power density of 174.69 W/m² in Ikeja at 100 m. Audu et al. (2019) reported a power density of 86.85 W/m².

The Weibull distribution proved to be an effective tool for modeling wind speed behavior in this study, consistent with its widespread application in Nigeria and beyond. As emphasized by Adaramola et al. (2014), proper Weibull analysis is essential for selecting the most appropriate wind energy conversion system (WECS). Our results similarly highlight the importance of the shape (k) and scale (c) parameters in predicting power output. The shape parameter (k) values obtained indicate relatively stable wind regimes, aligning with earlier findings by Nze-Esiaga and Okogbue (2014) and Fagbenle *et al.* (2011), who reported k values typically between 2 and 5 for Nigerian environments. This reflects moderate turbulence characteristics and suggests that turbines designed for relatively steady winds may perform optimally in these locations.

Bias-corrected wind speed data used in this study further enhance the reliability of the results, particularly given the persistent discrepancies between station measurements and reanalysis datasets such as ERA5. This approach aligns with global assessments that advocate for the harmonization of observational and reanalysis data prior to applying probabilistic models. The strong dependence of power density on wind speed, following the cubic relationship highlighted by Carta and Mentado (2007), underscores the necessity of accurate local calibration—an issue that has historically impeded wind energy development in Nigeria due to insufficient site-specific measurements, as documented by Ayodele *et al.* (2016).

The implications of these results for wind energy development in Nigeria are significant. Sites with moderate wind power density (WPD) values, such as those identified in this study, are ideal for small-scale or community-based wind systems. This aligns with the feasibility demonstrated by Adaramola et al. (2014), where certain turbine models (e.g., G-3120) performed well even at moderate wind speeds. Our findings confirm that, with appropriate turbine selection, particularly models designed for medium wind regimes, wind energy can serve as a viable supplement to local power supply. This supports the broader national renewable energy agenda outlined by Ayodele et al. (2016), who emphasized the urgent need to diversify Nigeria's energy mix amid rising energy poverty and insufficient generation capacity.

The validation results indicate that Makurdi exhibits the highest correlation between ERA5 data and ground measurements, followed by Lagos and then Port Harcourt. This difference is primarily attributed to terrain and local meteorological conditions. Makurdi, located inland along the Benue River, features relatively flat terrain and limited urban development, allowing ERA5 (approximately 31 km resolution), to capture regional wind patterns more accurately. In contrast, Lagos and Port Harcourt are coastal and more urbanized, where land-sea breeze circulations, urban roughness, and local turbulence generate wind variations at scales smaller than ERA5 can resolve. Additionally, the placement of wind measurement stations may influence the correlation; Makurdi stations are likely more exposed and representative of grid-scale winds, whereas coastal and urban stations in Lagos and Port Harcourt experience stronger sub-grid variability.

In general, the findings of this study align well with the existing body of research, highlighting the persistent spatial and seasonal patterns of wind resources in Nigeria. They also reaffirm the applicability of Weibull analysis and power density modeling for assessing wind energy potential. These results strengthen the evidence base necessary for site selection, turbine selection, and the broader investment framework for renewable energy deployment across Nigeria.

**Limitations of the Study**

While ERA5 reanalysis data provide comprehensive and spatially continuous wind information, several limitations affect the precision and applicability of the results in the tropical and coastal regions of Nigeria. Jiang et al. (2021) and Hassler and Lauer (2021) have reported systematic biases in ERA5 over tropical regions, which may affect the accuracy of wind and boundary-layer estimates in such climates. First, ERA5 has a horizontal resolution of approximately 31 km, which limits its ability to capture small-scale wind variations caused by complex terrain, local topography, and urban structures. Consequently, coastal and riverine areas influenced by strong land-sea breezes, local turbulence, or mangrove and creek systems may experience under- or overestimation of wind speeds. Second, validation is constrained by the limited availability of ground-based measurements, with reliable observational data only from Makurdi and Port Harcourt. While Makurdi shows good agreement with ERA5, Port Harcourt exhibits a lower correlation ($r \approx 0.4$), likely due to coastal dynamics, urban effects, and site-specific conditions not resolved by the reanalysis. Third, ERA5 represents grid-cell averages, which may differ from point measurements at meteorological stations, particularly in areas with high spatial variability in wind speed. Finally, diurnal/nocturnal separation and height extrapolation rely on approximations, such as using the nearest hourly data to sunrise and sunset and applying a general power-law exponent ($\alpha = 1/7$) for hub-height estimation. Collectively, these factors indicate that the results reflect regional-scale wind patterns rather than precise local measurements. Further studies incorporating dense in situ observations and finer-scale modeling would enhance the reliability of site-specific wind assessments.

## CONCLUSION

The assessment reveals that only a few stations, particularly Lagos and Port Harcourt, have diurnal wind power densities that consistently meet or exceed the on-grid standards required for efficient grid-connected wind energy generation. The predominance of diurnal power density across all stations indicates that daytime wind regimes contribute most significantly to the energy potential. Inland locations such as Lokoja, Makurdi, and Kainji exhibit substantially lower values, suggesting that wind resources in these areas may be more suitable for small-scale or hybrid renewable systems rather than large utility-scale installations. These spatial disparities also explain the influence of coastal–inland climatic gradients on Nigeria's wind energy distribution. Therefore, wind energy development in the country should prioritize high-yield coastal regions while exploring complementary renewable options for inland areas.

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