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# Feasibility of Wind Energy Utilization for Sustainable Power Generation in Ilorin, Kwara State, Nigeria's North-Central Region

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***Abstract:*** *The escalating energy demands across Nigeria, especially in remote rural areas, have outpaced the capacity of the national electricity grid, necessitating the development of independent and sustainable energy sources. Among the renewable options, wind energy stands out as a promising solution. This study focuses on assessing the potential of wind energy in Ilorin, located in Kwara State, within Nigeria's north-central region. Utilizing data collected from 2007 to 2021 by the Nigerian Meteorological Agency, the research examines monthly average wind speeds at two specific coordinates in Ilorin, considering variations in air density. The study utilizes a 15-year set of monthly average wind velocities obtained from the Nigerian Meteorological Agency (NiMet) Headquarters in Abuja, measured at a height of 10 meters above ground level. By employing the 2-coefficient Weibull statistical model and extrapolation principles across different altitudes ranging from 150 to 900 meters above ground level, the study reveals distinct seasonal patterns of wind speeds ranging from 1.1 to 5.1 m/s in Ilorin. Furthermore, wind power density values ranging from 6.7 to 39.20 W/m2 are identified, with optimal wind attributes observed at altitudes exceeding 900 meters. These findings provide valuable insights for assessing the feasibility of wind energy utilization and designing efficient systems in Nigeria's north-central regions, aiding in the sustainable energy transition.*

***Keywords****: Energy Generation, Grid Integration Strategies, Meteorological Agency, Wind Energy, Wind Speed.*

## 1. INTRODUCTION

Addressing the rising global energy demand while mitigating the environmental consequences of traditional energy sources, such as fossil fuels and nuclear power, which are linked to carbon emissions, air and water pollution, and finite availability, underscores the pivotal role of renewable energy as a strategic solution [1]. Recognized as a clean and abundant resource, wind energy commands attention. In the context of the worldwide shift towards cleaner and more efficient energy systems, understanding the localized potential of wind energy becomes a crucial element. This comprehension not only optimizes energy generation but also propels sustainable development efforts, aligning with the transition toward cleaner energy models [2].

The criterion of a nation's economic advancement is intricately linked to its capability to generate and distribute power, an indispensable prerequisite for societal growth and national progress [3]. Nigeria, amid rapid development and a burgeoning population, confronts a pivotal juncture in its energy landscape. The compelling challenge of meeting escalating electricity demands, particularly in the rural areas that are underserved by the national grid, underscores the urgency of exploring alternative energy solutions. In this context, evaluating the potential of wind energy stands out as a promising approach to boost the country's energy capacity while also staying true to its dedication to environmental responsibility. Power generation becomes a linchpin in steering Nigeria towards these objectives [4]

Over the past six decades, Nigeria power system has heavily leaned on coal, oil, water, and gas for electricity production. Despite a population exceeding 200 million, the nation lags in power utilization due to an overreliance on thermal and hydroelectric power generation methods. Research indicates that renewable electricity, derived from wind, solar, biomass, and small hydro, is anticipated to increase from 13% of the total installed capacity of electricity generation in 2015 to 23% in 2025 and further to 36% by 2030, as reported by the International Trade Administrators in 2021. While traditional fuel-based fossil methods have facilitated increased energy production and the development of suitable and sustainable energy, they concurrently pose a global predicament [5].

The global acknowledgment and embrace of environmentally friendly and non-toxic methods of energy generation are evident. Nevertheless, the inherent limited capability of these methods raises concerns for the future. Renewable energy technologies rely on perpetually available primary resources [6]. Solar energy, specific biomass forms, tidal and hydropower, as well as wind energy, are examples of these sources. Originating from natural processes, they swiftly replenish themselves, ensuring an essentially boundless supply irrespective of usage rates. Their intrinsic availability, coupled with minimal environmental impact and low maintenance requirements, makes them increasingly demanded for in the electrification process. However, the initial setup costs have impeded their widespread adoption [7]

Among the renewable energy sources, wind energy stands out, surpassing conventional sources in both environmental benefits and technological advancements. Presently, wind-generated electricity serves both grid-connected and off-grid systems, powering diverse applications such as water pumps, irrigation systems, mills, and various machinery [6], [8]. Numerous studies have delved into evaluating local wind power sites, with multiple investigations conducted in Nigeria focusing on assessing wind resources. For instance, the urgent need to address environmental concerns, mitigate climate change, and ensure a secure and diversified energy supply has prompted extensive research into various methods and technologies within the realm of renewable energy. [9], [10] conducted research on feasibility of application of wind energy system for buildings in an urban environment. Ajayi et al. [11] carried research on potency of wind energy turbine in Saudi Arabia, the research discovered that installation of tall towers and large rotor diameters have made it feasible to harness wind energy in lower wind speed regions. Also, offshore wind farms along the Red Sea coast could also tap into strong and consistent winds, offering additional opportunities for wind power generation in the country. Nze-Esiaga and Okogbue [12] developed a new model to estimate daily global 339 solar radiations over Nigeria; this work evaluated the wind power potential across ten distinct locations in Nigeria's southwest region, using an in-depth cost-benefit analysis for wind power generation. authors utilized a dataset spanning 24 years from the Nigerian Meteorological Agency, focusing on wind profiles at a height of 10 meters to analyze electricity generation possibilities. The results highlighted Lagos and Oyo States as optimal areas for large-scale wind energy projects, with other sites deemed suitable for smaller-scale operations or wind farms utilizing numerous smaller turbines. The turbine compatibility analysis showed that all locations were suitable for both cut-in and rated wind speeds.

Labuschagne and Kamper [13] the wind speed characteristics and energy potential in five selected locations in the southwestern part of Nigeria were investigated using monthly mean wind speed data of 51 years obtained from the Nigeria Meteorological Agency. The data were subjected to the 2-parameter- Weibull and other statistical analyses. The outcome showed that the wind speed measured at a height of 10 m ranged from 1.3 to 13.2 m/s while the modal wind speed ranges from 3.0 to 5.9 m/s. 83.6% of the data were found to be greater than 3.0 m/s. The average monthly wind speed ranged from 2.72 to 7.72 m/s. Fagbenle et al. [14] emphasized the necessity of reliability and stability studies to ensure power system safety when connecting a wind turbine system. The paper discusses the potential for wind energy in some regions, outlining the prerequisites for connecting a wind generator to the existing grid and the associated process. Additionally, the study underscores the importance of short-circuit power at the Point of Common Coupling (PCC) in determining allowable installed power ratings for turbines.

Ahmed and Kunya [15] assessed the wind energy potential in Nigeria's North-East region, focusing on Maiduguri and Potiskum. They applied the 2-coefficient Weibull model along with other statistical techniques to analyze monthly mean wind data spanning 21 years (1987–2007). The study identified differences in average monthly wind speeds, with Maiduguri emerging as the favoured location due to its consistent monthly and seasonal variations. However, both Maiduguri and Potiskum were considered suitable for generating wind energy on a small to medium scale. Also, Adaramola and Oyewola [16] the wind speed distribution and wind energy potential are investigated in three selected locations in Oyo state using wind speed data that span between 12 and 20 years measured at 10 m height. It was found that the monthly mean wind speeds in Oyo state ranges from 2.85 m/s to 5.20 m/s. While the monthly mean power density varies between 27.08 W/m2 and 164.48 W/m2, while the annual mean power density is in the range of 67.28 W/m2 and 106.60 W/m2. Based on annual energy output, wind turbines with cut-in wind speed of about 2.5 m/s and moderate rated wind speeds will be best suited for all the sites. Garba and Al-Amin [17] investigated the wind energy resource on the basis of Weibull and Rayleigh Models in North-Eastern and Western, Nigeria, utilizing monthly average wind speed data from 1990 to 2006. The findings indicated a wind power class II for the region, with power density values exceeding 100 W/m2, suggesting favourable conditions for electricity generation from wind turbines.

Conducted in various locations and supported by detailed analyses, these studies confirm their respective conclusions. As a result, this particular study focuses on evaluating the wind resource potential in Ilorin, Kwara State, located in Nigeria's North-Central region. The evaluation aims to determine the viability of this location in generating the required electricity on a monthly, annual, and seasonal basis.

This paper makes significant contributions summarized as follows:

**i.** Specific Regional Insight: By offering a focused assessment of wind energy potential in Ilorin, this research serves as a valuable resource for policymakers, energy planners, and investors. It provides essential insights to facilitate well-informed decision-making regarding the feasibility of wind energy projects in this region.

**ii.** Data-Informed Decision-Making: Through data-driven insights, this study enables informed choices concerning the design, capacity, and optimal locations for wind farms. The research supports stakeholders in making evidence-based decisions related to the development of energy infrastructure, ensuring efficiency and effectiveness in implementation.

**iii.** Grid Integration Strategies: These rely heavily on assessing wind energy potential to develop effective plans for smoothly incorporating wind power into the current electricity grid. This process addresses issues such as intermittent power supply, grid stability, and advancements in energy storage solutions, all of which significantly contribute to enhancing overall grid management efficiency.

**iv.** Environmental Impact Awareness: By analyzing the potential of wind energy, the study lays the groundwork for further research into the potential environmental impacts of wind farms in the region. This proactive approach paves the way for implementing mitigation measures to minimize adverse effects on local ecosystems, ensuring sustainable and responsible energy development.

## 2. MATERIALS AND METHODS

The study obtained monthly mean wind speed data for a period of fifteen years (2007-2021) from the Nigeria Meteorological Agency (NiMet) in Abuja, specifically for the town under consideration, Ilorin. This data was collected at a height of 10 meters above ground level using a three-cup generator anemometer. The Weibull distribution model was utilized as a probabilistic method to estimate the wind power potential in the area. Table 1 offers a geographic overview of the selected site.

Table 1: Geographical information of the chosen site

| Station | Latitude (N)° | Longitude (E)° | Elevation (m) | Air Density ($Kgm^{-3}$) |
|---|---|---|---|---|
| **Ilorin** | 8.435951 | 4.495873 | 320 | $1.21kgm^{-3}$ |

The study utilized two coefficients, scale (c) and shape (k), to construct the Weibull Probability Density Function (PDF). Equations (1) and (2) describe the relationship between the Cumulative Density Function F(v) and Probability Density Function f(v) for the 2-parameter Weibull distribution, as referenced in [17].

$$f(v) = \left(\frac{k}{c}\right)\left(\frac{v_m}{c}\right)^{k-1} exp\left(-\left(\frac{v_m}{c}\right)^k\right) \tag{1}$$

However, the cumulative distribution function, which corresponds with the probability distribution function for observing wind speed (V), is expressed as:

$$f(v) = 1 - exp\left(-\left(\frac{v_m}{c}\right)^k\right) \tag{2}$$

Such that,
The dimensionless Weibull shape coefficient is called "k,"
The curve is c (m/s).
Equations (3) and (4) are used to solve the coefficients (k) and curve (c).

$$k = \left(\frac{\sigma}{v_m}\right)^{-1.09} \tag{3}$$

Where:
$\sigma$ = standard deviation,
$v_m$= mean wind speed

$$c = \frac{v_m}{r(1+ {}^1/_k)} \tag{4}$$

Approximately,

$$c = 1.12 * v_m \qquad For\ 1.5 \le k \ge 3.0$$

The study employed Equations (5) and (6) to determine the mean monthly wind speed and standard deviation.

$$v_m = \frac{1}{n}\sum_{i=1}^{n} v_i \tag{5}$$

$$\sigma = \frac{1}{n-1}\sum_{i=1}^{n}((v_i - v_m)^2)^{\frac{1}{2}} \tag{6}$$

Where:
$v_i$=individual velocity, $v_m$= average wind velocity, and $n$ = number of measurements

The most likely wind speed $(v_{mp})$ and the wind speed with highest energy capacity are the two other important wind speeds for estimating wind energy capacity in addition to the average wind speed $(v_{emax})$. They can be expressed using Equations (7) and (8), respectively.

$$v_{mp} = c\left(\frac{k-1}{k}\right)^{\frac{1}{k}} \tag{7}$$

$$v_{emax} = c\left(\frac{k+2}{k}\right)^{\frac{1}{k}} \quad (8)$$

According to [13], the power density (Pd) and energy density (Ed) per unit area for a cross-sectional area (A) perpendicular to the direction of wind moving at a speed of $v_m$ are expressed as follows:

$$pd = \frac{p}{A} = \frac{1}{2}\rho V m^2 (W m^{-2}) \quad (9)$$

Also, the energy per unit area is given as:

$$Ed = \frac{E}{A} = \frac{1}{2}\rho V m^3 x\tau \ (W h m^{-2}) \quad (10)$$

Where,

$\tau$ is the total active hours.

Wind energy potentials can be categorized based on average wind speed and power density attributes [19]. The wind data from NIMET were collected at a 10-meter height. Equation (11) is applied to standardize the recorded wind speeds to match the wind turbine hub height. Additionally, Equations (9) and (10) were utilized to extrapolate the wind profile features to these heights, given that the wind turbine tower hub heights exceeded 10 meters [20].

$$v_{ref} = v_0\left(\frac{h_{ref}}{h_0}\right)^{\alpha} \quad (11)$$

Where:

$v_{ref}$ = wind speed at the reference height, $v_0$= wind speed at 10m height, $h_{ref}$= reference height, $h_0$ =10m height, and α = surface roughness coefficient

Equation (12) can be applied to compute the surface roughness coefficient, which is assumed to be 0.143, consistent with the 1/7th power law used in previous research [21].

$$\alpha = \frac{(0.37 - 0.088 ln v_0)}{1 - 0.088 ln\left(\frac{h_0}{i_0}\right)} \quad (12)$$

## 3. RESULTS AND DISCUSSION

Table 2 offers a detailed summary of the variation in the wind speed data collected at the site throughout the entire observation period, highlighting a monthly average wind speed ranging from 1.1 to 5.1 m/s. Figures 1, 2, and 3 further clarify the wind speed patterns across different time scales: monthly, seasonal, and yearly, covering the span from 2007 to 2022. Figure 1 indicates noticeable variability in monthly average wind speeds, with peaks in March and lows in November. Across the months from January to December, wind speeds fluctuate between 2.2 m/s and 3.7 m/s, showcasing seasonal variations annually. Figure 2 outlines the yearly wind speed distribution, illustrating fluctuations between 2.1 and 3.8 m/s over the observed years.

Table 2: Variations in wind speed at 10 meters above ground level

| YEAR | JAN | FEB | MAR | APR | MAY | JUN | JUL | AUG | SEPT | OCT | NOV | DEC | AVERAGE |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 2007 | 3.4 | 3.8 | 4.6 | 4.1 | 3.2 | 3.7 | 4.7 | 4.2 | 3.4 | 3.4 | 3.3 | 3.3 | 3.8 |
| 2008 | 4.9 | 3.6 | 5.1 | 3.8 | 3.7 | 3.9 | 3.5 | 4.2 | 3.5 | 2.9 | 2.8 | 3.2 | 3.8 |
| 2009 | 3.7 | 4.6 | 4.3 | 4.0 | 3.6 | 3.5 | 3.6 | 3.6 | 2.5 | 3.5 | 2.8 | 2.6 | 3.5 |
| 2010 | 2.6 | 4.7 | 3.8 | 4.7 | 3.3 | 3.2 | 3.8 | 4.1 | 3.3 | 3.0 | 2.9 | 2.3 | 3.5 |
| 2011 | 1.9 | 3.3 | 3.7 | 4.7 | 3.6 | 3.1 | 3.5 | 4.2 | 3.7 | 2.7 | 2.2 | 3.1 | 3.5 |
| 2012 | 1.4 | 2.9 | 3.1 | 3.0 | 2.5 | 2.1 | 2.0 | 2.7 | 2.0 | 2.2 | 1.1 | 1.5 | 3.3 |
| 2013 | 1.5 | 2.1 | 3.0 | 2.5 | 2.2 | 1.9 | 2.2 | 1.9 | 1.6 | 2.4 | 1.6 | 1.7 | 2.2 |
| 2014 | 1.5 | 2.1 | 3.0 | 3.9 | 2.8 | 2.7 | 2.7 | 2.9 | 2.2 | 2.4 | 1.8 | 1.8 | 2.1 |
| 2015 | 1.5 | 2.6 | 2.8 | 2.8 | 2.2 | 2.6 | 2.0 | 3.1 | 2.1 | 2.4 | 2.2 | 1.8 | 2.5 |
| 2016 | 1.6 | 2.9 | 2.9 | 2.9 | 2.7 | 2.6 | 3.4 | 3.2 | 2.2 | 2.0 | 2.3 | 2.2 | 2.3 |
| 2017 | 2.2 | 3.1 | 4.1 | 3.4 | 3.3 | 3.3 | 3.9 | 3.4 | 2.5 | 2.1 | 1.8 | 2.0 | 2.6 |
| 2018 | 2.7 | 3.5 | 3.8 | 3.9 | 3.2 | 3.0 | 3.2 | 3.4 | 2.7 | 2.7 | 2.3 | 2.3 | 2.9 |
| 2019 | 2.4 | 3.6 | 3.7 | 3.2 | 3.6 | 3.8 | 3.1 | 4.0 | 3.1 | 1.6 | 1.7 | 2.3 | 3.1 |
| 2020 | 2.5 | 3.3 | 3.7 | 3.6 | 3.1 | 3.0 | 3.2 | 3.4 | 2.7 | 2.5 | 2.2 | 2.3 | 3.0 |
| 2021 | 3.1 | 3.8 | 4.0 | 4.0 | 3.3 | 3.2 | 3.5 | 3.7 | 3.0 | 2.8 | 2.5 | 2.5 | 3.0 |
| Average | 3.1 | 3.8 | 4.0 | 4.0 | 3.3 | 3.2 | 3.5 | 3.7 | 3.0 | 2.8 | 2.5 | 2.5 | 3.3 |

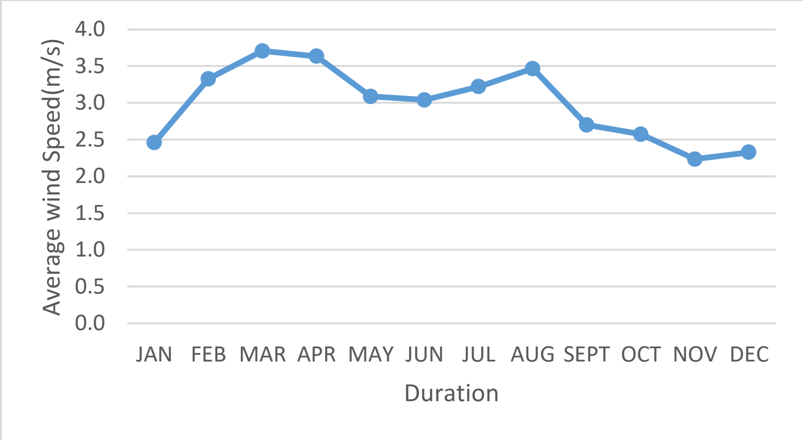

Figure 1: Plot showing monthly wind speed variation

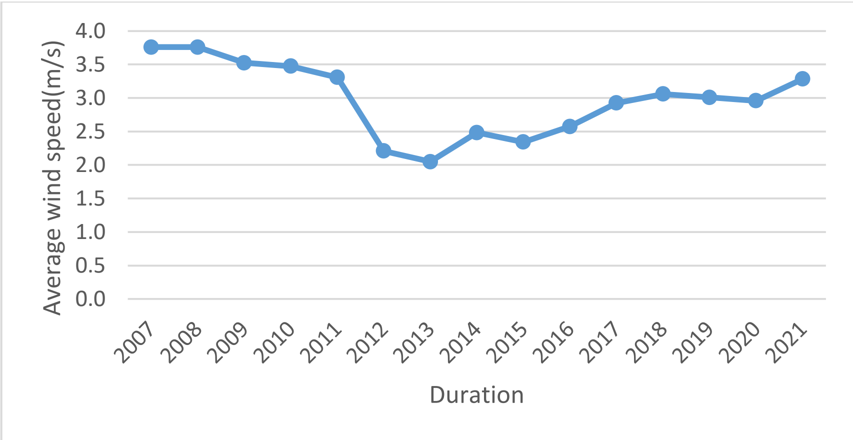

Figure 2: Plot showing annually wind speed variation

Figure 3 illustrates the wind speed trends throughout both the wet (April to September) and dry (October to March) seasons in Ilorin. Remarkably, the wind speed profiles remain relatively stable between these two seasons. The average wind speeds recorded during these periods range from 2.2 to 3.7 m/s and 2.7 to 3.6 m/s, respectively, as shown in the mean distribution data. Additionally, Table 3 details the Weibull coefficients (c and k), average monthly wind speed, standard deviation, and power density for Ilorin, providing further statistical insights into the area's wind characteristics. Figures 4 and 5 complement this analysis by depicting Probability Density Function (PDF) and Cumulative Distribution Function (CDF) plots, offering graphical representations of wind speed distribution and cumulative probability. This comprehensive analysis of wind speed data, along with statistical metrics and graphical representations, offers valuable insights into Ilorin's wind climate, facilitating assessments for various applications such as renewable energy generation and urban planning.

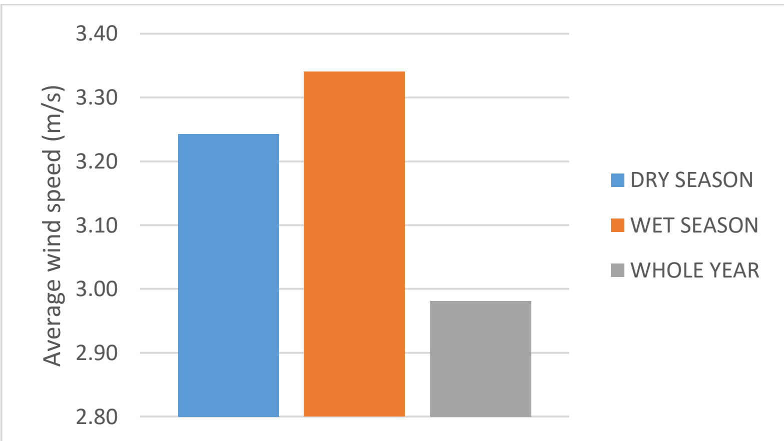

Figure 3: Plot showing seasonal wind speed variation

 

Table 3: Weibull coefficients (c and k), standard deviation, power density, and monthly average wind speed for Ilorin

| PERIOD | Vm ($ms^{-1}$) | δ(m/s) | k-shape | c-scale (m/s) | (PD) ($Wm^{-2}$) | (ED) ($kWhm^{-2}$) |
|---|---|---|---|---|---|---|
| **JANUARY** | 3.1 | 1.0 | 2.7 | 2.8 | 9.0 | 78.9 |
| **FEBRUARY** | 3.3 | 0.8 | 5.0 | 3.6 | 22.3 | 195.1 |
| **MARCH** | 3.7 | 0.7 | 6.5 | 4.0 | 30.8 | 269.9 |
| **APRIL** | 3.6 | 0.7 | 6.4 | 3.9 | 29.0 | 254.2 |
| **MAY** | 3.1 | 0.5 | 7.3 | 3.3 | 17.8 | 155.9 |
| **JUNE** | 3.0 | 0.6 | 6.0 | 3.3 | 17.0 | 148.9 |
| **JULY** | 3.2 | 0.7 | 5.0 | 3.5 | 20.2 | 176.9 |
| **AUGUST** | 3.5 | 0.7 | 6.2 | 3.7 | 25.2 | 220.8 |
| **SEPTEMBER** | 2.7 | 0.6 | 5.0 | 2.9 | 11.9 | 104.3 |
| **OCTOBER** | 2.6 | 0.5 | 5.8 | 2.8 | 10.3 | 90.3 |
| **NOVEMBER** | 2.2 | 0.6 | 4.4 | 2.5 | 6.7 | 59.0 |
| **DECEMBER** | 2.3 | 0.5 | 4.9 | 2.5 | 7.6 | 66.8 |
| **DRY SEASON** | 3.2 | 0.7 | 5.5 | 3.6 | 20.63 | 180.74 |
| **WET SEASON** | 3.3 | 0.3 | 15.5 | 3.7 | 22.54 | 197.47 |
| **WHOLE YEARS (2007-2021)** | 3.0 | 0.6 | 6.3 | 3.2 | 16.0 | 140.4 |

**Vm, average wind speed; δ, standard deviation k, dimensionless Weibull shape coefficient; c, Weibull scale coefficient; PD, mean wind power density; ED, mean energy density.**

Figures 4 and 5 provide a visual representation of the cumulative distribution patterns of wind profiles across various time periods, including monthly, seasonal, and annual data series. These plots reveal that the cumulative distribution curves for different periods exhibit a consistent pattern, indicating uniformity in the distribution of wind speeds over time. Notably, the observed patterns align well with findings from previous research studies conducted by [14], [15], and [16]. This consistency in cumulative distribution patterns underscores the reliability and robustness of the data analysis methodologies employed in this study.

Additionally, differences in the shape (k) and scale (c) parameters of the Weibull distribution led to variations in the forms of the cumulative distribution function (CDF) and probability distribution function (PDF) plots. Figures 4 and 5 effectively illustrate these differences, highlighting how changes in the Weibull coefficients impact the distribution of wind speeds across different time periods. Moreover, Table 3 complements the graphical representations by providing a comprehensive statistical analysis of the wind speed data using Weibull's statistical framework. This analysis includes the estimation of Weibull coefficients and other relevant parameters, offering valuable insights into the characteristics of the wind climate in the study area.

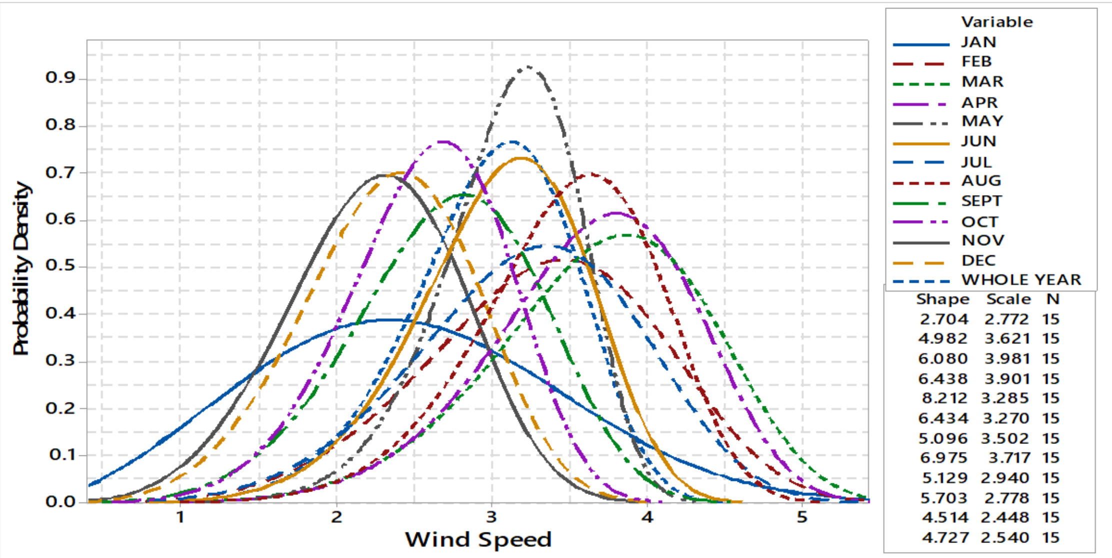

Figure 4: Plot showing monthly probability density function for Ilorin at 10 m height.

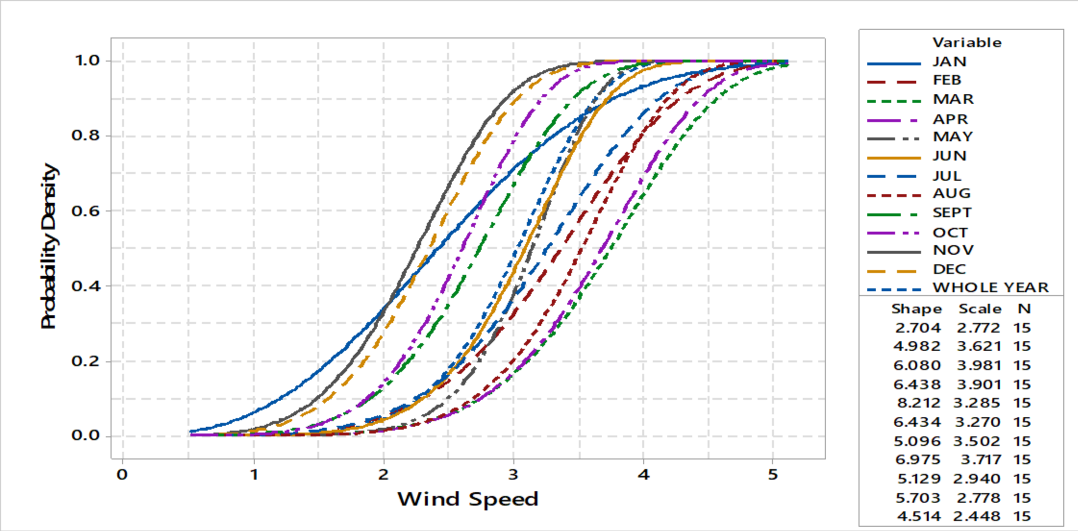


Figure 5: Plot showing monthly cumulative density function for Ilorin at 10 m height.

The analysis shows that the parameters k (representing shape) and c (representing scale) of the Weibull distribution demonstrate significant variability throughout the observed period. Specifically, the values of k fall within the range of 2.7 to 8.6, while the values of c range from 2.3 to 4.2. These findings indicate a wide variability in wind speed characteristics, with higher values of k and c suggesting a distribution that closely resembles a normal distribution and exhibits good uniformity with minimal scatter, as noted in previous studies [17], [18]. Furthermore, the effectiveness of wind energy production is intricately tied to wind power density, which directly impacts the electricity generation potential of an area. Wind power density is directly related to the potential energy output, with higher densities signifying greater potential for generating electricity. Hence, surges in wind speed leading to elevated k values contribute to heightened wind power density and, consequently, increased potential for electricity generation.

Figures 6 and 7 illustrate the monthly/seasonal and yearly variations in power density and energy density distribution for the study site, Ilorin city, respectively.

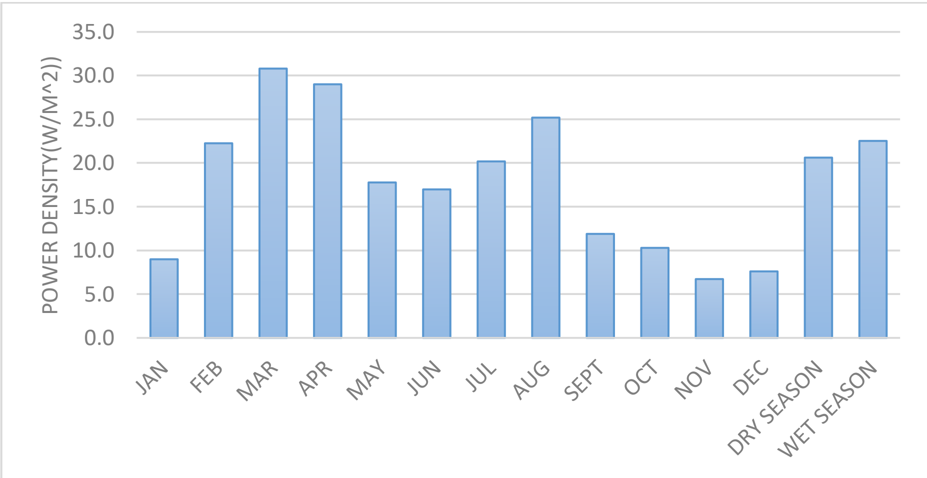


Figure 6: Power density variation plot for Ilorin at 10 m height

According to the Pacific Northwest Laboratory (PNL) classification system [27], the variability in wind speed and power density observed in Ilorin falls within class 1 (PD ≤ 100) at a height of 10 meters above ground level. However, despite this classification, there is significant potential to effectively utilize wind energy resources, particularly through the deployment of windmills to support community water supply, livestock watering, and reliable irrigation systems.

Evaluating a site's wind potential for power generation extends beyond simply assessing the wind power capability at that site. It necessitates a comprehensive analysis of two key wind speed parameters crucial for determining the wind speed rating specific to wind turbines. These parameters encompass the maximum energy-carrying wind speed ($v\_emax$) and the most probable wind speed ($v\_mp$) [28]. By applying equations (9) and (10) in combination with the information provided in Table 4 and Figure 7, we were able to calculate monthly, seasonal, and annual wind speeds spanning from 2007 to 2021.

Table 4: Pacific Northwest laboratory (PNL) classification scheme [19]

| Wind power Class | Average Wind speed at 10m (m/s) | Wind Power Density at 10m (W/m$^2$) |
|---|---|---|
| **1** | 0 – 4.4 | 0 – 100 |
| **2** | 4.4 – 5.1 | 100 – 150 |
| **3** | 5.1 – 5.6 | 150 – 200 |
| **4** | 5.6 – 6.0 | 200 – 250 |
| **5** | 6.0 – 6.4 | 250 – 300 |
| **6** | 6.4 – 7.0 | 300 – 400 |
| **7** | 7.0 – 9.5 | 400 -1000 |

The data presented in Table 5, along with the graphical representations, highlight fluctuations in power density across different months and seasons. Specifically, months such as February, April, May, June, July, and August exhibit better wind power density variation, with the highest values observed in March. Additionally, the examination of seasonal fluctuations indicates that the wet season offers a more favourable perspective regarding wind power density when contrasted with the dry season. Monthly power density figures vary from 6.7 to 30.8 W/m², with seasonal shifts ranging from 20.63 W/m² (dry season) to 22.54 W/m² (wet season).

**Table 5:** Calculation of the most probable wind speed ($v\_mp$) and maximum energy-carrying wind speed($v\_emax$)

| Months/Period | Wind Speed (m/s) | $v_{mp}$ (m/s) | $v_{emax}$ (m/s) |
|---|---|---|---|
| **JANUARY** | 3.1 | 2..4 | 3.5 |
| **FEBRUARY** | 3.3 | 3.5 | 3.9 |
| **MARCH** | 3.7 | 3.9 | 4.2 |
| **APRIL** | 3.6 | 3.8 | 4.1 |
| **MAY** | 3.1 | 3.2 | 3.4 |
| **JUNE** | 3.0 | 3.2 | 3.5 |
| **JULY** | 3.2 | 3.4 | 3.8 |
| **AUGUST** | 3.5 | 3.6 | 3.9 |
| **SEPTEMBER** | 2.7 | 2.8 | 3.2 |
| **OCTOBER** | 2.6 | 2.7 | 2.9 |
| **NOVEMBER** | 2.2 | 2.3 | 2.7 |
| **DECEMBER** | 2.3 | 2.4 | 2.8 |
| **DRY SEASON** | 3.2 | 3.5 | 3.9 |
| **WET SEASON** | 3.3 | 3.6 | 3.8 |
| **WHOLE YEARS (2007 to 2021)** | 3.0 | 3.1 | 3.4 |

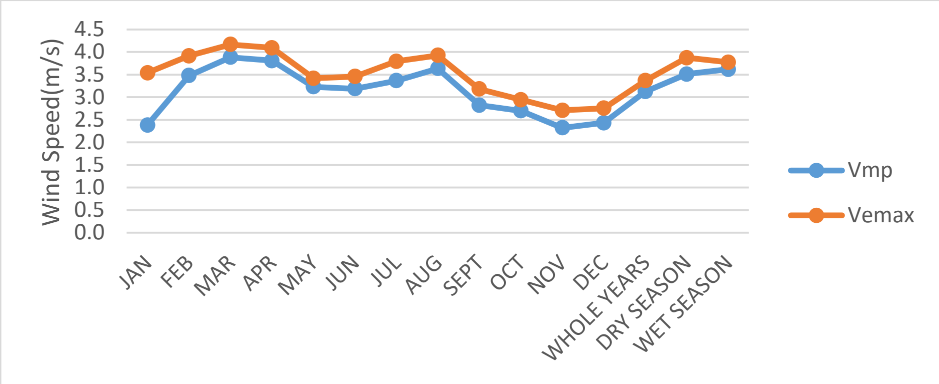


Figure 7: Graph illustrating the fluctuations in the most probable wind speed ($v\_mp$) and maximum energy-carrying wind speed ($v\_emax$) for Ilorin.

In the context of enhancing the power density of the Ilorin wind site, Equation 13 was employed in conjunction with Equations 9 and 10 to conduct vertical extrapolation on the wind speeds. This approach aimed at augmenting the power density of the area by considering wind resources at varying heights above ground level. Figures 8 and 9 provide graphical representations depicting the range of extrapolated wind power densities at the Ilorin wind site, showcasing the potential for increased power generation through vertical extrapolation. It is crucial to examine the potential for wind-generated electricity in elevated areas like highlands and hilltops that surpass 10 meters in height. This study delved into the potential for wind-generated electricity at altitudes ranging from 150 to 900 meters above ground level (AGL), in increments of 150 meters. By examining wind resources at different elevations, the study aimed to assess the feasibility and viability of harnessing wind energy from elevated locations to further enhance power density and electricity generation capacity.

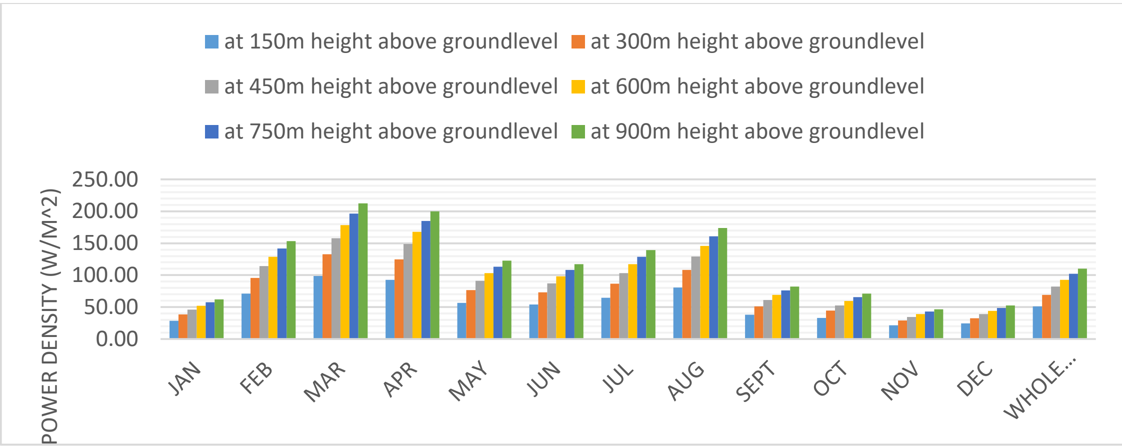


Figure 8: Plot of the monthly variation of Ilorin's power density at extrapolated heights

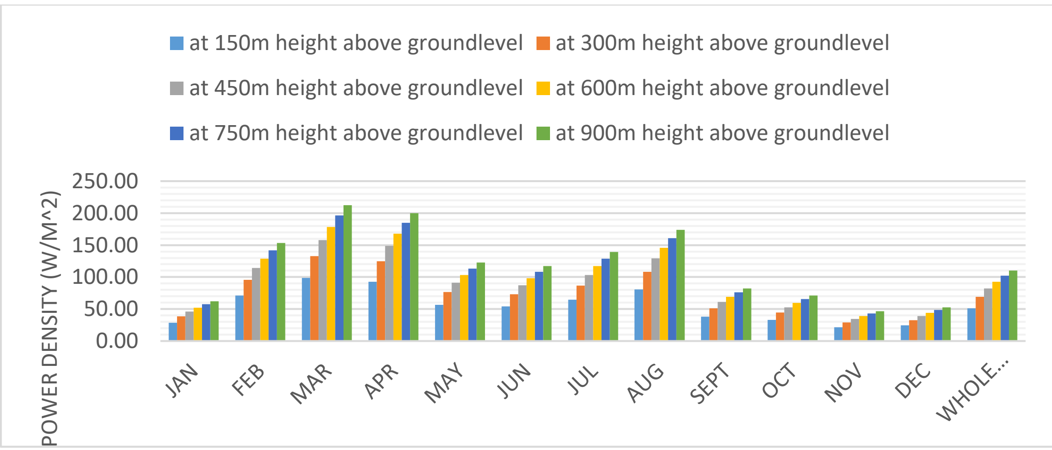


Figure 9: Plot of the monthly variation of energy density for Ilorin at extrapolated heights

The wind power density classification system by the Pacific Northwest Laboratory (PNL) designates wind speeds at elevations up to 150m as class 1, indicating their unsuitability for electricity generation. However, by extrapolating wind speed data and estimating power density at higher altitudes, such as 300m AGL, distinct classifications emerge for different months. Specifically, wind conditions at 300m AGL are classified as class 2 in March, April, and August, while other months remain in class 1. As altitude increases to 450m AGL, wind classifications evolve further: March and April are classified as class 3, indicating more favourable conditions for electricity generation. February, July, and August are class 2 months, while the rest remain class 1. At 600m AGL, March, April, and August transition to class 3, with February, May, and July in class 2, and the rest in class 1. Moving higher to 750m AGL, wind classifications continue to vary: March, April, and August are class 3, February, May, June, and July are class 2, and the rest are class 1.

At 900m AGL, wind conditions show increased potential for electricity generation: March and April are class 4, February and August are class 3, and May, June, and July are class 2. The remaining months are class 1. On average for the year, elevations from 150m to 750m AGL mainly fall under class 1, indicating limited electricity generation potential. However, at 900m AGL, wind power density leans slightly towards class 2, suggesting improved prospects for power production.

## 4. CONCLUSION

This research focused on evaluating the wind energy potential for electricity generation in Ilorin, Kwara State, Nigeria. Utilizing the validated Weibull statistical distribution model, monthly mean wind speed data collected over a fifteen-year period from the Nigeria Meteorological Agency (NiMet) were analyzed. The primary objective was to assess the wind resources available at the site for generating electricity. The main outcomes and implications of the study are outlined below:

- **i.** The Weibull parameters k and c demonstrated fluctuation, with values ranging between $2.7 \leq k \leq 8.6$ and $2.3 \leq c \leq 4.2$ respectively. These parameters play a vital role in defining wind speed distributions and evaluating wind energy potential.
- **ii.** The analysis revealed fluctuations in monthly wind power density and energy density, ranging between 67.94 to 30.8 W/m² and seasonally between 20.63 (dry season) to 22.54 W/m² (wet season). Additionally, mean wind speeds ($v\_mp$) varied from 2.3 to 3.9 m/s throughout the year (January to December) and were recorded at 3.5 m/s (dry season), 3.6 m/s (wet season), and 3.1 m/s annually. Furthermore, maximum energy-carrying wind speeds ($v\_emax$) ranged from 2.7 to 4.2 m/s across the year (January to December), with readings of 3.9 m/s (dry season), 3.8 m/s (wet season), and 3.4 m/s annually.
- **iii.** Applying the Pacific Northwest Laboratory (PNL) system to classify Ilorin's wind potential resulted in a class 1 classification, indicating limited suitability for wind energy generation at a height of 10 meters above the ground surface.
- **iv.** By extrapolating wind power densities at elevations between 150 and 900 meters, different classifications ranging from class 1 to 4 were identified on both monthly and yearly scales. However, the potential for wind power generation may be more effectively utilized at heights, surpassing 900 meters above ground level. Installing windmills for purposes such as community water supply, livestock watering, and agricultural irrigation could lead to more advantageous results.
- **v.** Extrapolation principles indicate that harnessing wind energy for power generation could be more efficient by installing turbines at heights surpassing 900 meters above ground level.

Considering the measurement height of 10 m in this study, employing scale-up formulas could provide insights into wind speeds at heights beyond 10 m. Hence, installing a taller measuring mast could offer a more comprehensive understanding of wind shear at the site and the overall potential for power generation. In conclusion, this study underscores the importance of comprehensive wind resource assessment methodologies and highlights the need for further exploration and deployment of wind energy technologies to tap into Ilorin's wind energy potential for sustainable electricity generation.

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