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Wind Speed Characteristics and Energy Potentials in Lafia, Nasarawa State, Nigeria

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Abstract

Renewable energy, specifically wind power, is vital for reducing fossil fuel dependency, greenhouse gas emissions, and improving energy security. With advancements in technology, wind energy has become cost-effective and competitive. Wind energy research in Lafia is essential to developing solutions in harnessing its potential as a significant renewable energy source for Nigeria, which has abundant but untapped wind energy resources. This study investigates the wind energy potential in Lafia, Nasarawa State, using daily averaged wind speed data from MERRA-2 measured at 2, 10 and 50-*metre* altitudes. The Weibull distribution function was applied to determine Lafia's wind energy potential, and the outcomes revealed that the highest yield for wind harvest occurred during the peak of the dry season in February, while the lowest yield for wind harvest occurred during the beginning of the dry season in October. Moreover, the monthly mean power densities peaked in February, 2001 at 341.87 W/m^2 (Class 3: $300<P_D\leq399$), indicating moderate potential, and in January, 2002 at 454.12 W/m^2 (Class 4: $400<P_D\leq499$), indicating good potential. However, the peak monthly mean power densities in December, 2003 and February, 2004 were poor and marginal, respectively, according to the Wind resource Potential (WRP) classification. Furthermore, at 50 *metres* altitude, the recorded wind speeds were above the recommended minimum (3.00 – 4.00 *m/s*) for most wind turbines to start producing electricity. The findings indicate significant wind resource potential at high altitudes (50 *metres*) in Lafia, which suggests great potential for wind energy generation.

Keywords: Atmosphere, mean energy density, Weibull distribution function, wind power density, wind speed

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Introduction

The numerous renewable energy sources in Nigeria are hydropower, solar power, and wind power but still there are persistent electricity supply deficits which are epileptic in nature and attributed to the under-utilization of these abundant natural resources thereby, becoming a bottleneck to socio-economic development of its economy [1]. The need for energy diversification is paramount because of the increasing population of Nigeria which is responsible for the high energy demands and to meet such demands; there should be an exploration of moderate wind energy to complement the existing National grid in the country [2].

Wind energy like other renewable energy sources is abundant, inexhaustible, affordable, clean by nature, recyclable and environmentally preferable due to its zero discharge of greenhouse gases (e.g. emission of carbon dioxide) into the atmosphere thereby, reducing global warming unlike fossil fuels [3]. The renewable energy source that is the fastest-growing today, both in developed and developing nations is wind energy [4]. The windmills and wind turbines generate energy that is used to produce electricity, pump water, saw wood, hammer seeds, and grind grains depending on their capacity [5].

In analysing wind data, there have been various statistical methods (e.g. Weibull and Rayleigh distribution models) and mathematical models (e.g. normal and lognormal). Over other statistical functions, the Weibull probability distribution function (two-parameter type) is more preferable because it indicates a better fit for wind distribution [3].

Classification of wind power using WPD

Based on its Wind Power Density (WPD) (in Wm^{-2}), the Battelle-Pacific Northwest Laboratory (PNL) has formulated a wind classification zone. As shown in Table 1, this classification was made for three varying heights (10, 30, and 50 *metres*) and classified wind power into seven distinct classes. Wind power Class 1 areas are unsuitable for investment in wind energy, Class 2 and Class 3 areas are deemed marginal and moderate for the development of wind power projects respectively, whereas Class 4 or higher areas are generally regarded as appropriate for small and large-scale generation [6].

Table 1: Classification of wind power by PNL [7]

Wind Power Class	Wind Power Density (WPD) at 10*m* (Wm^{-2})	at 30*m* (Wm^{-2})	at 50*m* (Wm^{-2})	Resource Potential
1	0 – 99	0 – 159	0 – 199	Poor
2	100 – 149	160 – 239	200 – 299	Marginal
3	150 – 199	240 – 319	300 – 399	Moderate
4	200 – 249	320 – 399	400 – 499	Good
5	250 – 299	400 – 479	500 – 599	Very Good
6	300 – 399	480 – 639	600 – 799	Excellent
7	400 – 1000	640 – 1600	800 – 2000	Superb

The majority of research studies investigated Nigeria's wind energy potential by conducting statistical Weibull parameter analyses of wind characteristics as a substitute energy resource in various regions. At the Nigeria's south-eastern region, Oyedepo reported the yearly mean wind speeds of 5.42 *m/s* for Enugu, 3.36 *m/s* for Owerri, and 3.59 *m/s* for Onitsha, respectively, with yearly average power densities of 96.98, 23.23 and 28.34 W/m^2 [4]. Also they decoded that the most likely wind speed has yearly average values for Enugu, Owerri, and Onitsha were 5.47, 3.72 and 3.50 *m/s*, respectively while the wind speed carrying maximum energy has yearly values of 6.48, 4.33 and 3.90 *m/s*. Asiegbu [29] used 1994 to 2003 wind speed data in Umudike, South-East, Nigeria to duly examine the availability of wind resources. They discovered that for the siteto be economically viableat a 65 *m* above ground (hub height), its yearly mean wind speed must be around 5.36 *m/s* [8].

In the South-western zone of Nigeria, Fadare [9] statistically conducted a wind energy potential analysis in Ibadan using a Weibull distribution function on 1995 to 2004 daily wind speed data. The findings revealed that the city's average wind speed and power density were 2.947 *m/s* and 15.484 W/m^2, respectively. According to Agbetuyi [10], the existing grid has not been linked to wind power electricity production. Before concluding, they provided information on Nigeria about the potential (wind speed), the prerequisites for connecting a wind generator to the main grid (electricity network), and how to go about making the connection. Ajayi [11] evaluated the potential in wind energy at ten (10) chosen spots in the South-western zoneof Nigeria for 20 *years* (1987-2010). At 10 *metres*, data (wind speed) extracted from the Nigerian Meteorological Agency were used to arrange the sites' wind profiles for electricity generation and reportedly has wind potential particularly in the states of Lagos and Oyo, with average wind speeds of 2.9 and 5.8 *m/s*, respectively. Nze-Esiaga [12] used data (monthly average wind speed) from the Nigeria Meteorological Agency (NiMET) to analyse the features of wind speed and energy potential (via 2-parameter-Weibull and other statistical analyses) in five (5) chosenlocalities in the South-western zone of Nigeria. The results interpreted that the measured speeds of the wind at 10 *m*etresscaled from 1.3 to 13.2 *m/s*, average monthly speeds of the wind scaled from 2.72 to 7.72 *m/s*, and average seasonal wind speeds ranged from 3.47 to 6.55 *m/s* for dry (October to March) and 3.83 to 6.94 *m/s* for wet (April to September) seasons. Furthermore, the Weibull shape and scale parameters were discovered to be between $2.99 \leq k \leq 5.32$ and $3.02 \leq c \leq 8.57$ respectively. The yearly average power densities for Abeokuta, Akure, Ibadan, Ikeja, and Oshogbo are 65.09, 145.07, 176.96, 387.07, and 87.34 W/m^2, respectively, and the average yearly values of the most probable wind speed are 3.82, 4.97, 5.23, 7.03, and 4.01 *m/s*, respectively, while the yearly values of the wind speed carrying maximum energy are 4.12, 5.48, 5.87, 7.50 and 4.55 *m/s*. The results reveal that wind speed in all of the stations has a realistic possibility for wind-to-electricity at a height of 10 *metres* for the majority of the locations evaluated, and that it is more viable at a height above 10 *metres*.

In Nigeria's South-South (coastal) region, Uquetan [13] reported a wind power density of 3.11 W/m^2 and an yearly wind speed of 1.3 *m/s* for Calabar, determining that the city's wind speed regime is low; Udo [14] reported a wind power density of 3.11 W/m^2 and an annual wind speed is 1.3 *m/s* for Calabar, concluding that the city's wind speed regime is low. Wind speed statistics from NiMET archive were empirically investigated over four (4) *years* at four (4)different meteorologically based stations in Nigeria's coastal zones (Calabar, Uyo, Warri, and Ikeja) using descriptive analysis (2008 – 2011). The Weibull shape factor (k) and scale parameter (c) were computed in order to find out Weibull wind speeds and wind power density using power law at hub heights (10 and 70 *metres*). The maximum average monthly wind speeds were 3.88 *m/s* in December over Calabar, 4.73 *m/s* in January over Uyo, *3.98 m/s* in April over Warri, and 8.37 *m/s* in August over Ikeja, respectively. According to the study's findings, the Weibull model outperforms the Rayleigh model for characterizing wind speed distributions over coastal areas, including the Ikeja area is especially well-suited for wind turbine applications; Eboibi [15] investigated the wind energy potential of six (6) chosenpositions in Nigeria's South-south geopolitical zone using ten (10) *years* wind data obtained at 10 *metres* height, revealing that the yearly average wind speeds for Asaba, Benin, Calabar, Port Harcourt, Uyo, and Warri were 3.3, 4.4, 3.4, 3.5, and 3.7 *m/s*, with correspondingaverage power density of 21.8, 21.4, 35.8, 23, 25.2 and 30.8 W/m^2 and the mean energy output of 183.4, 205.4, 311.7, 200.9, 220.9 and 274.3 KWh/m^2 were discovered for the respective states, with Calabar station proving to be the best location for the setting up of wind turbines for generation of power.

The overall average wind power densities and yearly average power densities fell under class 1 of the wind classification scheme, indicating that the average wind speed fell short of the required standard of 6 *m/s* for large-scale wind energy generation set up, but positioning suitable wind turbines at reasonable higher altitudes, the amount of generated power could be increased.

Ngala [16] investigated the viability of wind energy as a source of power in Maiduguri, Borno State, North-Eastern Nigeria, using ten (10) *years* of wind data (1995-2004) and the Weibull distribution. The outcomes hinted that the wind energy utilisation has a good chance due to the high wind speed, with energy densities ranging from 4.712 to 27.449 *MWh/month* at 25 *m* height; Fagbenle [17] examined the wind energy potentialat height (10 *m*) via 2-parameter Weibull and other statistical analyses for 21 *years* (1987-2007) of two (2) sites namely are Maiduguri and Potiskum in Nigeria's North-eastern zone. The average monthly mean wind speed variation in Potiskum ranged from 3.90 to 5.85 *m/s*, while in Maiduguri it aligned from 4.35 to 6.33 *m/s*. Wind speeds in Maiduguri aligned from 5.10 *m/s* (dry) to 5.59 *m/s* (wet), while in Potiskum they aligned from 4.46 *m/s* (dry) to 5.16 *m/s* (wet). The wind power density varied from 102.54 to 300.15 W/m^2 for Potiskum and from 114.77 to 360.04 W/m^2 for Maiduguri, proving that Maiduguri was determined to be the most suitable of the two (2) sites in terms of monthly and seasonal variation of mean wind speed, but both are well suited for stand-alone and medium scale generation of wind power.

Ajayi [2] examined data (monthly mean wind speed) at a height (10 *metres*) in Kano, Nigeria, using a 21-*year* (1987-2007) dataset, subjecting it to various statistical tests and comparing it to the 2-parameter Weibull probability density function. Wind-to-electricity was found to be economically viable at average monthly wind speeds ranging from 6.6 to 9.5 *m/s*, or at and above a height of 10 *m*. Wind speeds averaged 6.6 to 8.5 *m/s* during the dry (October to March) and wet (April to September) seasons respectively. Furthermore, the estimated two Weibull statistics were discovered to lie between $2.1 \leq k \leq 4.9$ and $7.3 \leq c \leq 10.7$, respectively and finally, the monthly wind power aligned between 3.6 and 12.5 MWh/m^2.

Ajayi [18] determined whether Jos, Plateau state has aviable wind resource potential for the electricity generation using monthly mean wind speeds for years(1987 to 2007). The findings indicated that Jos in North-central zone of Nigeria was a suitable location for various-sized wind farm projects, and that electricity (ranging from *MWh* to *GWh*) would most likely be produced over the course of months, seasons, and years. Furthermore, it was determined that the site's typical wind speed ranged from 6.7 to 11.8 *m/s* throughout the various months, years, and seasons; Ahmed [19] used (2000-2006) wind data for Plateau State acquired from an Abuja meteorological station at 10 *metres* height.Within the period of years considered, the topmost wind speed is 15.4 *m/s* in January and the least wind speed for this site was discovered to be 8.7 *m/s* in August, the Weibull parameters i.e. scale, c has an average value of 10.76 *m/s* and shape, k factors has an average value of 7.47 respectively, and the power density varies between 368 and 1056 W/m^2 indicating that over a longer period, the wind would be very important for power generation. Moses [5] using 1961 to 2014 wind speed data, investigated the energy potential via wind speed characteristics in Makurdi, at height (10 *m*) measured and derived from the Nigerian Meteorological Agency, Lagos to assess the availability and prospect of using energy (wind) for region's generation of electricity. The Weibull distribution function was well-used to analyse the potential of wind energy in Makurdi, and the outcome shows that the peak of the dry season (April) had the peak output for wind harvest, while the onset of the dry season had the lowest yield (i.e., November). Furthermore, the reported study's topmost values (Weibull shape and scale parameters) suggested the presence of wind speed and the windy character, while the wind power density of 86.85 W/m^2 indicates that Makurdi wind can be converted into generate electricity.

According to Ajayi [20], Nigeria's northern, middle belt, and south-eastern zones have significant wind energy potential. The average wind speed in the southern zone was reported to be 3.00 to 3.50 *m/s* and 4.00 to 7.50 *m/s* in the northern zone due to the hill-like terrain.It was reported on the numerous obstacles to wind energy development in Nigeria and potential solutions that could be proposed to promote wind energy technology in the country. Ogbonnaya [21] investigated on the potentials of wind energy in seven (7) cities spanning the different Nigeria geopolitical zones of the federation (Enugu, Jos, Ikeja, Abuja, Warri, Sokoto, and Calabar), using four (4) years' data on wind. The yearly wind speed at height (10 *metres*) for cities was also presented to scale between 3.0 to 3.9 *m/s* for highland, 3.4 *m/s* for sites along the coast and 2.3 *m/s* for semi-arid regions. Furthermore, the monthly average wind power was estimated to be around 50.1 W/m^2 and that the Sokoto site could generate 97 *MWh/year* of wind energy.

Outside of Nigeria, several researchers, including Youm [22], Al-Buhairi [23], Khouloud [24], Erik [25], and Samira [26], have used Weibull parameters to statistically analyse wind characteristics.

Fewer reviews on the potential for wind energy in Nigeria's North-Central region, but none in Lafia, Nasarawa State. As a result, the research's purpose is to evaluate and comprehend the wind regimes and prospects in Lafia at various heights, i.e. a crucial consideration for any given site in estimating wind energy power and can provide backup electricity to the state's epileptic power supply. It also seeks to help evaluate existing wind resources to enhance wind energy technology (WET) in Nigeria.

Materials and Methods

The research location of this work is Lafia (Longitude 8.5115°*E*, Latitude 8.5242°*N* and Altitude 186 *m*), the capital city of Nasarawa State in Nigeria (Fig. 1) with a population of about 330,712. It is classified as *Aw* on a Köppen climate classification and located within a tropical savannah climate. The average climatic data for Lafia is as follows: temperature (26.7^{o}C), total annual rainfall (1,645 *mm*), average rainy days (251.1 *days*), and average relative humidity (74 %). The data used in this study were recorded in a period of 6 years, and provided by the NASA POWER data access portal, using MERRA-2 data (on $0.5^{0} \times 0.625^{0}$ resolution), through https://power.larc.nasa.gov/data-access-viewer/).

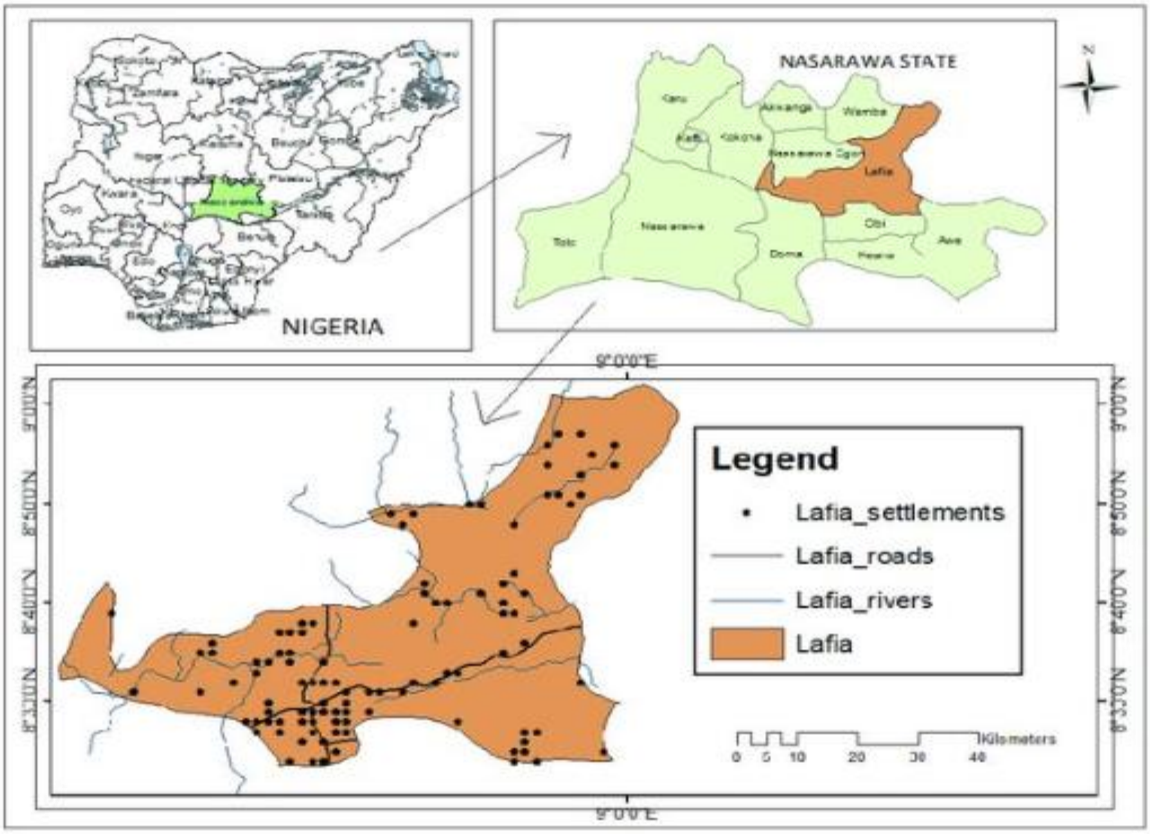

Figure 1: Geographical location of Lafia, the study area in Nigeria, West Africa [31]

The wind statistics used in this investigation was examined using the Weibull distribution model. The fluctuations in speed of wind from the Weibull distribution are best described by the probability density function and its associated cumulative distribution functions. At any specified velocity, *V* the probability of the wind is provided by the Weibull probability density function, which is represented as [2, 4]:

$$f(V) = \left(\frac{k}{c}\right)\left(\frac{V}{c}\right)^{k-1} exp[-\left(\frac{V}{c}\right)^{k}], \qquad (1)$$

where, *V* is the wind speed (*m/s*), *c* is the Weibull scale parameter (*m/s*), *k* is a Weibull shape parameter (dimensionless).

The likelihood that the wind velocity is less than or greater than V, or enclosed in the stated range of wind speed provided by the cumulative distribution function, *F(V)* of the velocity, V. It is the integral of the probability density function and expressed as [2, 4]:

$$F(V) = 1 - exp[-\left(\frac{V}{c}\right)^{k}] \qquad (2)$$

Table 2: Properties of the 5-MW NREL Wind Turbine [30]

S/N	Property	Description
1	Rated power	5-MW
2	Type	Horizontal Upwind
3	Control	Variable speed, Collective pitch
4	Hub Height	90 *m*
5	Rated wind speed	11.4 *m/s*
6	Rotor diameter	126 *m*
7	Tower height	87.6 *m*
8	Mass of Rotor	111,000 *kg*
9	Mass of Nacelle	240,000 *kg*
10	Mass of Tower	347,460 *kg*
11	Rotor speed range	6.9 to 12.1 RPM

The wind speed features namely are Weibull shape parameter, Weibull scale parameter, most probable wind speed, wind speed carrying maximum energy, wind power and mean energy densities at 3 distinct heights (*2 metres, 10 metres and 50 metres*) were computed. The wind speed data from 2000 - 2005 were evaluated by averaging 12 *months* for each year over 6 *years* to yield the mean wind speed, V_m separately via Microsoft Excel and then, input into the following parameters of the Weibull distribution were computed using formulae taken from several authors stated below:

1. The Weibull shape parameter, k was derived using the expression [13]:

$$k = \left(\frac{\sigma}{V_m}\right)^{-1.086} \quad (3)$$

Where, V_m is the mean wind speed and σ is standard deviation.

2. The Weibull scale parameter, c was derived using the expression [4]:

$$c = \frac{V_m k^{2.6674}}{0.184 + 0.816 k^{2.73855}} \quad (4)$$

3. The most probable wind speed, V_F was derived as [5, 12].

$$V_F = c\left(\frac{k-1}{k}\right)^{1/k} \quad (5)$$

4. The wind speed carrying maximum energy, V_E was derived using [12]:

$$V_E = c\left(\frac{k+2}{k}\right)^{1/k} \quad (6)$$

5. Wind power density, P_D (wind power per unit area) is affected by the cube of the wind speed, the air density, and the frequency distribution of the wind speed. Therefore, this parameter is often regarded as a more accurate predictor of the resource of wind than wind speed. It was computed as [2, 19]:

$$P_D = \frac{P(V)}{A} = \frac{1}{2}\rho V^3 = \frac{1}{2}\rho c^3 \Gamma\left(1 + \frac{3}{k}\right) \quad (7)$$

where, A is area, ρ is the site's density of air typically is 1.225 kg/m^3, $P(V)$ is the wind power (W), Γ is the gamma function is [27]:

$$\Gamma = \frac{V_m}{c\left(1+\frac{1}{k}\right)} \quad (8)$$

6. Over a specified time span, T, the mean energy density (E_D) was obtained as [4]:

$$E_D = \frac{1}{2}\rho c^3 \Gamma\left(1 + \frac{3}{k}\right) T \quad (9)$$

The graphs were also plotted to show the comparison between the variations of mean wind speed, Weibull shape parameter, Weibull scale parameter, the most probable wind speed, wind speed carrying maximum energy, wind power and mean energy densities at distinct heights (2, 10 and 50 *metres*, respectively) for 6 years span.

Results and Discussion

Figure 2 depicts the monthly variation of mean wind speed for various sets of years (2000 to 2005) at (2, 10 and 50 *m*) altitudes. The wind speed increases from November/December to January/February i.e. 1.34 – 3.45 *m/s* at 2 *m* altitude, 2.38 – 4.91 *m/s* at 10 *m* altitude and 3.71 – 7.26 *m/s* at 50 *m* altitude as shown by year 2000 curve. Then, because of the possibility of heavy rain in Lafia during these months (March-April-September-October), wind speed decreases until it increases again in November-December i.e. 3.01 – 1.22 *m/s* at 2 *m* altitude, 4.24 – 2.00 *m/s* at 10 *m* altitude and 6.12 – 3.18 *m/s* at 50 *m* altitude. Wind speeds in Lafia increase during December, January, and February, respectively.

The plots also show that the mean wind speed differs with altitude, with 50 *metres* being much higher than 10 *metres* and much higher than 2 *metres*. In other words, as height increases, so does wind speed. As shown by the variation trends of wind speed [11], the increasing trends of wind speed observed in this study could be caused by changes in time, season, climate, and anthropogenic activities such as pollution [5, 32].

Figure 3 indicates the monthly variation of mean (average) wind speed over a six-years span, with the maximum mean (average) wind speed of 3.51 *m/s* observed in January 2002 and the minimum mean (average) wind speed of 1.16 *m/s* observed in October 2003, respectively, at altitude (2 *m*). It shows the maximum mean (average) wind speed of 5.15 *m/s* in January 2002 and the minimum mean (average) wind speed of 1.88 *m/s* in October 2003 at altitude (10 *m*), and it also shows the maximum and minimum mean (average) wind speed at altitude (50 *m*) in January 2002 of 7.80 *m/s* and October 2003 of 2.86 *m/s*. This is due to the peak dry season (Harmattan), which is characterised by the dusty and dry North-easterly trade wind, which begins in January and causes high temperatures as a result to high wind speeds [16, 17].

In general, the monthly wind profile for Lafia shown in Fig. 3 indicates that at 2 *m* altitude, it is located in Nigeria's low wind prospect zone, with wind speeds less than (3.00 - 4.00 *m/s*) the cut-in wind speed required for operation of most wind turbine generators; at 10 *m* altitude, it lies into a moderate (i.e. average) wind prospect zone of Nigeria, which is approximately close to (3.00 - 4.00 *m/s*) the cut-in wind speed required for most wind; at 50 *m* altitude, it is located in Nigeria's high wind prospect zone, with mean (average) wind speed greater than (3.00 - 4.00 *m/s*) the cut-in wind speed required for operation of most wind turbine generators.

Figure 2: Seasonal variations of the monthly mean wind speed V_m in Lafia at altitudes (2, 10 & 50 *m*) for the period from 2000 to 2005

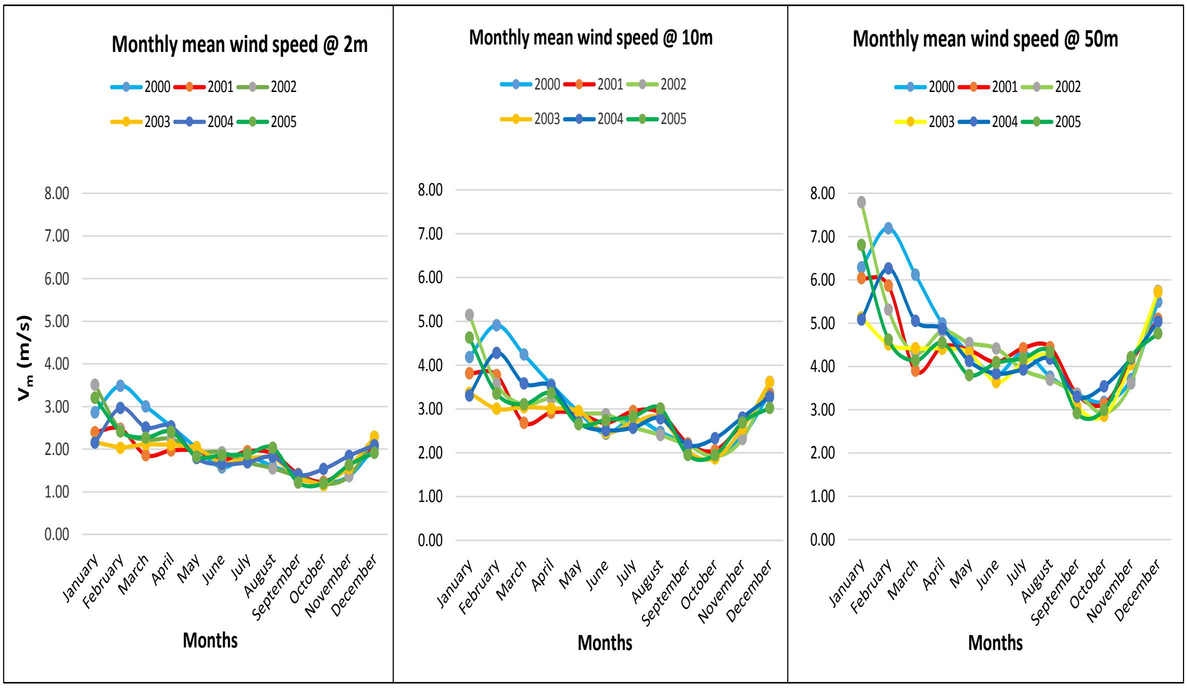

Figure 3: Time series of the annual Average wind speed in Lafia at altitudes (2, 10 & 50 *m*) for the period from 2000 to 2005

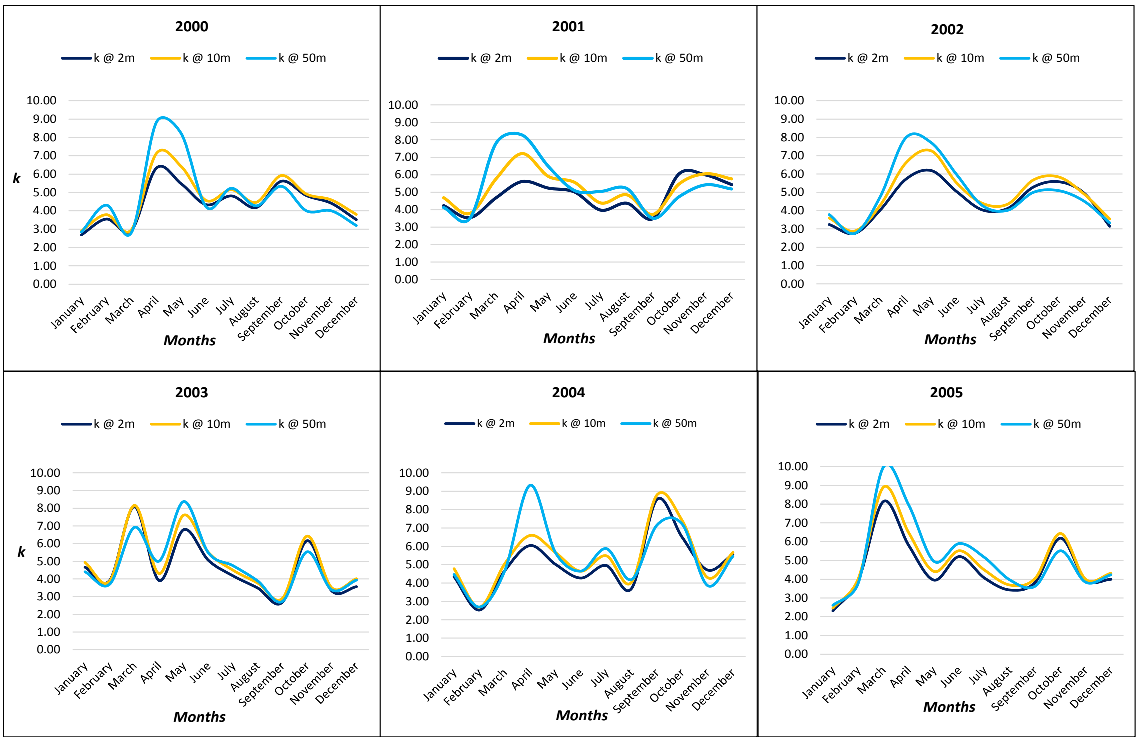

Figure 4: Weibull shape parameter, *k* plot at different height for 6 years (2000 – 2005)

In the year 2000, the Weibull shape parameter *k* has a monthly mean (average) arraying from 2.69 to 6.33 with yearly mean (average) value of 4.47 at an altitude of 2 *m*, 2.91 to 7.12 with yearly mean (average) value of 4.80 at an altitude of 10 *m*, 2.84 to 8.83 with yearly mean (average) value of 4.91 at an altitude of 50 *m*, and 2.84 to 8.83 with yearly mean (average) value of 4.91 at an altitude of 50 *m*. The high *k* value suggests that the data spread is typical and that there is good homogeneity with relatively minor scatter. The consistency of the speeds in the wind computed by the shape parameter, *k* at a specific site [4], can simply be used to relate the scale parameter, *c* to the mean (average) wind speed.

The wind speed approximated by the Weibull shape parameter, *k* is known as the scale parameter, *c*. In Fig. 5, it is worth noting that in the year 2000, the maximum values of c at different altitudes (2, 10 and 50 *m*) are 3.88, 5.44, and 7.92 ms^{-1}, respectively were observed in February, which corresponds to the maximum mean wind speeds at different altitudes (2, 10 and 50 *m*) are 3.49, 4.91 and 7.20 ms^{-1}, respectively, while the minimum values of c at different altitudes (2, 10, and 50 *m*) were 1.33, 2.18 and 3.51 ms^{-1}, respectively, the minimum mean wind speeds at different altitudes (2, 10 and 50 *m*) were 1.22, 2.00 and 3.18 ms^{-1}. Fig. 5 also shows that the maximum values of c at different altitudes (2 and 10 *m*) were 2.76 and 4.18 ms^{-1}, respectively in February, 2001, and the maximum value of c at 50 *m* was 6.67 ms^{-1} in January, 2001, while the minimum values of c at different altitudes (2, 10 and 50 *m*) were 1.34, 2.23 and 3.43 ms^{-1}, respectively.

In the year 2002, Fig. 5 shows the maximum values of *c* at different altitudes (2, 10 and 50 *m*) are 3.92, 5.72 and 8.64 ms^{-1}, respectively were observed in January while the minimum values of *c* at different altitudes (2, 10 and 50 *m*) are 1.28, 2.06 and 3.18 ms^{-1}, respectively were observed in October. Fig. 5 dictates the maximum values of *c* at (2, 10 and 50 *m*) altitudes are 2.55 , 3.99 and 6.33 ms^{-1}, respectively were observed in December, 2003 while the minimum values of *c* at different altitudes (2, 10 and 50 *m*) are 1.24, 2.01 and 3.10 ms^{-1}, respectively were observed in October, 2003.

In the year 2004, Fig. 5 deduces the maximum values of *c* at different altitudes (2, 10 and 50 *m*) are 3.34, 4.82 and 7.05 ms^{-1} respectively were observed in February while the minimum values of *c* at different altitudes (2, 10 and 50 *m*) are 1.47, 2.28 and 3.51 ms^{-1}, respectively were observed in September. Fig. 5 indicates the maximum values of *c* at different altitudes (2, 10 and 50 *m*) are 3.62, 5.23 and 7.67 ms^{-1}, respectively were observed in January, 2005 while the minimum values of *c* at different altitudes (2 and 10 *m*) are 1.29 and 2.09 ms^{-1}, respectively were detected in October and at altitude 50 *m*, the minimum value of *c* is 3.24 ms^{-1} was observed in September, 2005.

Finally, it is noted that at high altitude (e.g., 50 *m*) for 4 years (2000 – 2005) in Figure 5, the area with high value of *c* indicates that the location's nature is windy compared to other lower altitudes (e.g., 2 and 10 *m*) which has similarity to the work of Uquetan *et al.* [13].

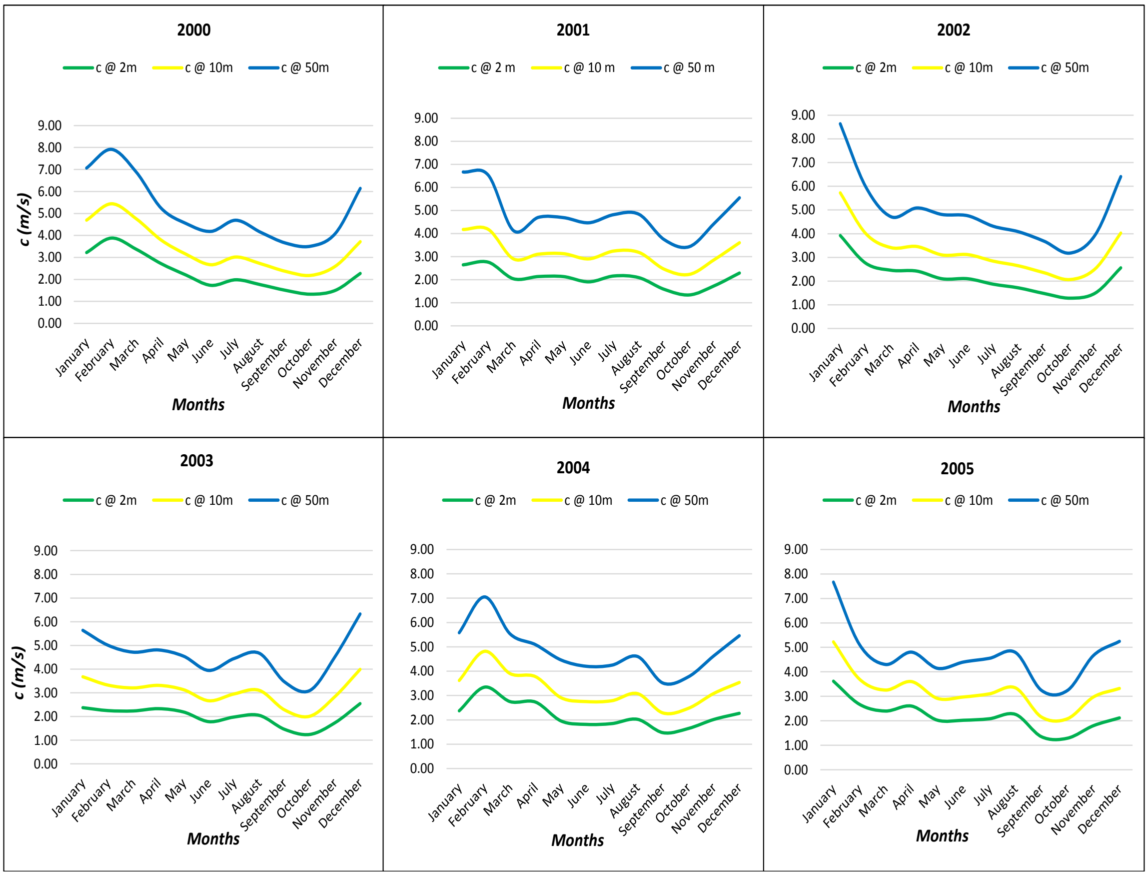

Figure 5: Weibull scale parameter, *c* (*m/s*) at different heights for the period from 2000 – 2005

Figure 6: Most probable wind speed, V_F plot at different heights for 6 years

Figure 6 displays the monthly mean most likely wind speed, V_F at three (3) distinct heights (2, 10, and 50 *metres*) for the year 2000. These values range from 1.27 to 3.54 ms^{-1}, 2.09 to 5.02 ms^{-1}, and 3.27 to 7.45 ms^{-1}, respectively with an annual mean value at different heights are 2.11 ms^{-1} (Table 2), 3.19 ms^{-1} (Table 3) and 4.79 ms^{-1} (Table 4), respectively. The highest most probable wind speed at all heights occurs in February, 2000 and the lowest most probable wind speed occurs in October, 2000.

The monthly mean most probable wind speed, V_F at distinct heights (2, 10, and 50 *metres*) for year 2001 is at its peak values from 2.51 ms^{-1} in February, 3.97 and 6.23 ms^{-1} in January respectively and the least values of the most probable wind speed occurs in October are 1.34, 2.15 and 3.26 ms^{-1}, respectively. At (2, 10, and 50 *metres*) distinct heights, the monthly mean most probable wind speed, V_F for year 2002 is at its maximum values from 3.50, 5.23 and 7.96 ms^{-1} in January respectively and the minimum values of the most probable wind speed occurs in October are 1.28, 2.00 and 3.05 ms^{-1}, respectively.

The monthly mean most probable wind speed, V_F for year 2003 at distinct heights (2, 10, and 50 *metres*) is at its peak (maximum) values from 2.25 and 3.51 ms^{-1} in January and 5.87 ms^{-1} in December respectively and the least (minimum) values of the most probable wind speed are 1.21 and 1.96 ms^{-1} occurs in October and 2.93 ms^{-1} occurs in September, respectively. At distinct heights (2, 10, and 50 *metres*), the monthly most probable wind speed, V_F for year 2004 is at its peak values in February are 2.74, 4.05 and 5.94 ms^{-1}, respectively and the least (minimum) values of the most probable wind speed occurs in September are 1.45, 2.25 and 3.44 ms^{-1}, respectively. The monthly mean most probable wind speed, V_F at distinct heights (2, 10, and 50 *metres*) for year 2005 is at its peak (maximum) values in January are 3.62, 4.22 and 6.37 ms^{-1}, respectively and the least (minimum) values of the most probable wind speed occurs in September are 1.25, 2.01 and 2.97 ms^{-1}, respectively.

In Fig. 7, the annual mean wind speed carrying maximum energy, V_E for the year 2000 at distinct heights (2, 10, and 50 *metres*) were 2.56, 3.79 and 5.76 *m/s*, respectively. It is typically more than the observed yearly mean wind speeds at distinct heights (2, 10, and 50 *metres*) were 2.08, 3.12 and 4.71 *m/s*, respectively.

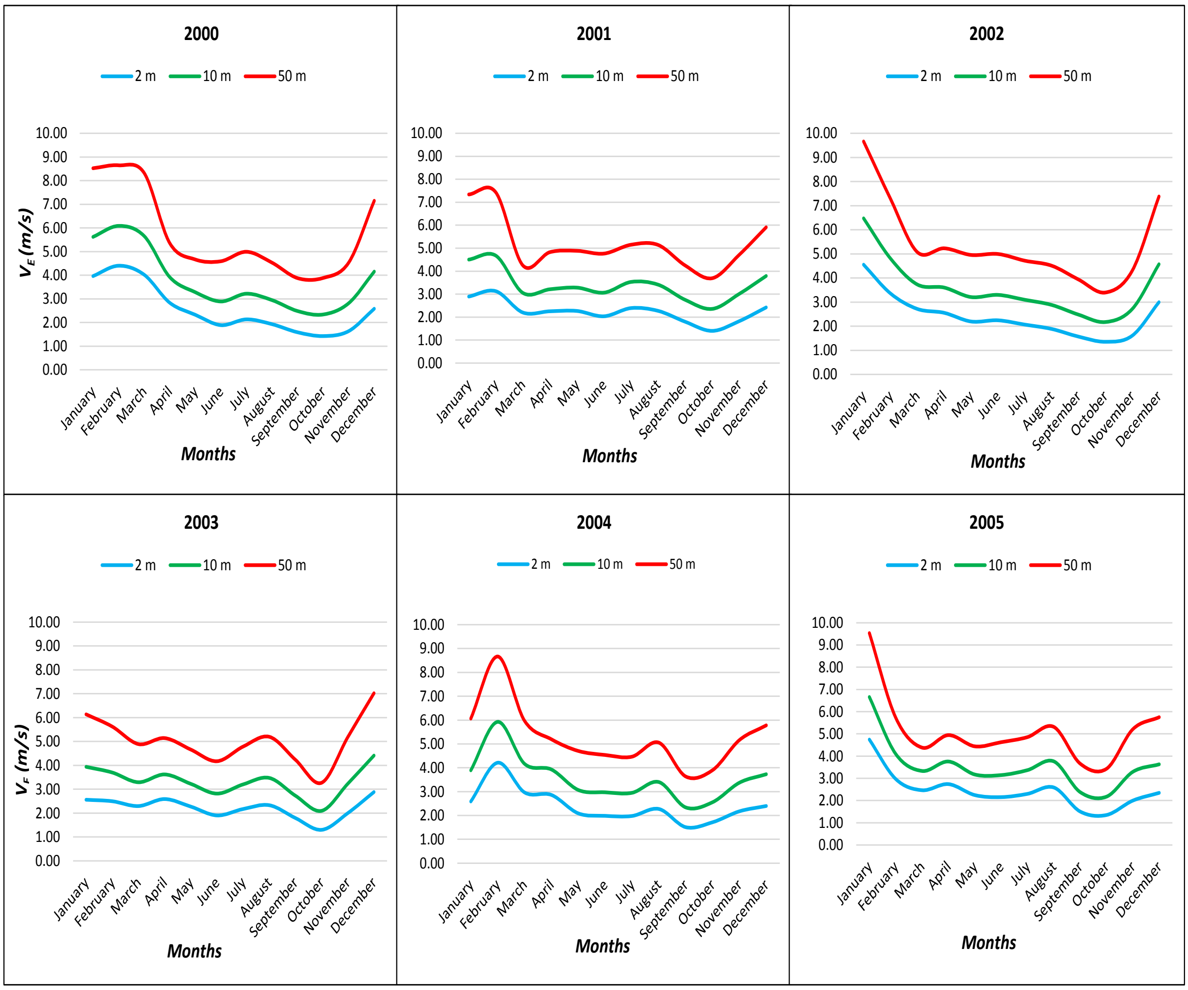

Figure 7: Wind speed carrying maximum energy, V_E plot at different heights for 6 *years*

In year 2001 plot indicates that February has the highest monthly wind speed carrying maximum energy, V_E at distinct heights (2, 10, and 50 *metres*) as follows; 3.13, 4.68 and 7.43 *m/s*, respectively thereby also deducing that at 50 *m* altitude has the highest monthly wind speed carrying maximum energy amidst other stated heights (2 and 10 *m*). Furthermore, the yearly mean wind speed carrying maximum energy, V_E at distinct heights (2, 10, and 50 *metres*) were 2.24, 3.39 and 5.20 *m/s*, respectively which is greater than the observed annual mean wind speed at distinct heights (2, 10, and 50 *metres*) were 1.89, 2.91 and 4.44 *m/s*, respectively.

In year 2002 plot showing the highest monthly wind speed carrying maximum energy, V_E occurred in January which are 4.55, 6.47 and 9.66 *m/s*, respectively at distinct heights (2, 10, and 50 *metres*) thereby also deducing that at 50 *m* height is the highest monthly wind speed carrying maximum energy amidst other stated heights (2 and 10 *m*). However, the annual mean wind speed carrying maximum energy, V_E at distinct heights (2, 10, and 50 *metres*) were 2.42, 3.59 and 5.45 *m/s*, respectively which is greater than the observed annual mean wind speed at distinct heights (2, 10, and 50 *metres*) were 1.98, 2.99 and 4.54 *m/s*, respectively.

The highest monthly wind speed carrying maximum energy, $V_E$at distinct heights (2, 10, and 50 *metres*) occurred in December, 2003 which are 2.88, 4.41 and 7.02 *m/s*, respectively thereby also deducing that at 50 *m* height is the highest monthly wind speed carrying maximum energy amidst other stated heights (2 and 10 *m*) as seen in Fig. 7. Furthermore, the yearly mean wind speed carrying maximum energy, V_E at distinct heights (2, 10, and 50 *metres*) were 2.22, 3.31 and 5.03 *m/s*, respectively which is greater than the observed annual mean wind speed at distinct heights (2, 10, and 50 *metres*) were 1.84, 2.78 and 4.20 *m/s*, respectively in year 2003. In Fig. 7, shows the highest monthly wind speed carrying maximum energy, V_E occurred in February, 2004 which are 4.21, 5.93 and 8.67 *m/s*, respectively at distinct heights (2, 10, and 50 *metres*) thereby also deducing that at 50 *m* height is the highest monthly wind speed carrying maximum energy amidst other stated heights (2 *m* and 10 *m*). In year 2004, the annual mean wind speed carrying maximum energy, V_E at distinct heights (2, 10, and 50 *metres*) were 2.40, 3.53 and 5.26 *m/s*, respectively which is greater than the observed annual mean wind speed at distinct heights (2, 10, and 50 *metres*) were 2.00, 2.99 and 4.45 *m/s*, respectively.

The highest monthly wind speed carrying maximum energy, V_E at distinct heights (2, 10, and 50 *metres*) occurred in January, 2005 which are 4.75, 6.66 and 9.53 *m/s*, respectively thereby also deducing that at 50 *m* height is the highest monthly wind speed carrying maximum energy amidst other stated heights (2 and 10 *m*) as seen in Fig. 7. In year 2005, the annual mean wind speed carrying maximum energy, V_E at distinct heights (2, 10, and 50 *metres*) were 2.45, 3.56 and 5.16 *m/s*, respectively which is greater than the observed annual mean wind speed at distinct heights (2, 10, and 50 *metres*) were 1.99, 2.94 and 4.28 *m/s*, respectively. Finally, the observed speed of wind carrying maximum (highest) energy was greater than the observed annual mean wind speed from this study in Fig. 7 for the 6 *years* (2000 – 2005) which is very essential in the estimation of rated wind speed or design of wind turbine system. Since wind turbine systems have been shown to function effectively at their rated speeds of the wind. It is essential that the rated wind speed and the wind speed conveying the most energy be as near as feasible [4]. Consequently, a wind turbine with a rated wind speed (3.50 - 5.50 *m/s*) at a height of at least 10 *m* and up to 50 *m* is suggested for this location.

In year 2000 from Fig. 8, the peak monthly wind power density, P_D at distinct heights (2, 10, and 50 *metres*) occurred in February are 41.69, 113.51 and 341.87 W/m^2, respectively vary proportionally to the peak monthly average wind speed are 3.49, 4.91 and 7.20 *m/s* and the least monthly wind power density, P_D occurred in October are 1.59, 7.03 and 30.19 W/m^2, respectively fluctuate proportionally to the least monthly average speeds of the wind are 1.22, 2.00 and 3.18 *m/s* as seen in Fig. 8. In year 2001, the maximum monthly wind power density, P_D at distinct heights (2, 10, and 50 *metres*) are 14.93 and 51.46 W/m^2 occurred in February and 205.73 W/m^2 occurred in January respectively fluctuate proportionally to the maximum monthly average speeds of the wind are 2.48, 3.77 and 6.05 *m/s* and the minimum monthly wind power density, P_D are 1.56, 7.34 and 27.34 W/m^2, respectively occurred in October vary proportionally to the minimum monthly mean speeds of the wind are 1.24, 2.06 and 3.14 *m/s*, respectively.

In year 2002, the peak monthly wind power density, $P_D$at distinct heights (2, 10, and 50 *metres*) occurred in January are 43.84, 133.40 and 454.12 W/m^2, respectively vary proportionally to the peak monthly average speeds of the wind are 3.51, 5.15 and 7.79 *m/s* and the least monthly wind power density, P_D occurred in October are 1.39, 5.80 and 21.64 W/m^2, respectively vary proportionally to the least monthly average speeds of the wind are 1.18, 1.91 and 2.92 *m/s* as seen in Fig. 8. In year 2003, the high monthly wind power density, P_D at distinct heights (2, 10, and 50 *metres*) occurred in December are 11.74, 44.28 and 117.21 W/m^2 respectively vary proportionally to the high monthly mean speeds of the wind are 2.29, 3.61 and 5.72 *m/s* and the low monthly wind power density, P_D occurred in October are 1.26, 5.30 and 19.70 W/m^2 respectively vary proportionally to the low monthly average speeds of the wind are 1.16, 1.88 and 2.86 *m/s*.

In Fig. 8, the maximum monthly wind power density, P_D at distinct heights (2, 10, and 50 *metres*) in the year 2004 are 28.64, 84.33 and 264.40 W/m^2 occurred in February respectively vary proportionally to the maximum monthly average speeds of the wind are 2.97, 4.28 and 6.27 *m/s* and the minimum monthly wind power density, P_D are 2.02, 7.53 and 20.09 W/m^2 respectively occurred in September vary in proportion to the minimum monthly average speeds of the wind are 1.40, 2.18 and 3.30 *m/s* respectively. In Fig. 8, the maximum monthly wind power density, P_D at distinct heights (2, 10, and 50 *metres*) in the year 2005 are 37.13, 109.98 and 342.35 W/m^2 respectively occurred in January vary proportionally to the maximum monthly average speeds of the wind are 2.97, 4.63 and 6.81 *m/s* and the minimum monthly wind power density, P_D are 1.41, 5.91 and 22.64 W/m^2 respectively occurred in October vary proportionally to the minimum monthly average speeds of the wind are 1.20, 1.95 and 2.99 *m/s*. Finally, the highest monthly wind power density, P_D is at 50 *m* height compared to other stated heights (2 and 10 *m*) for 6 *years* (2000 – 2005).

Using the recommended Table 1; the wind speed in Lafia was categorized using classification scheme on wind power from Battelle-Pacific Northwest Laboratory (PNL) [7]. Based on this classification system over a 6-year period (2000–2005), the peak monthly mean power densities in Lafia at 10 *m* altitude are as follows: 113.51 W/m^2 for year 2000 (class 2: $100 < P_D \leq 150$) i.e. Marginal in February, 51.46 W/m^2 for year 2001 (class 1: $P_D < 100$) i.e. Poor in February, 133.40 W/m^2 for year 2002 (class 2: $100 < P_D \leq 150$) i.e. Marginal in January, 44.28 W/m^2 for year 2003 (class 1: $P_D < 100$) i.e. Poor in December, 84.33 W/m^2 for year 2004 (class 1: $P_D < 100$) i.e. Poor in February and 109.98 W/m^2 for year 2005 (class 2: $100 < P_D \leq 150$) i.e. Marginal in January respectively in terms of wind resource potential.

Furthermore, at 50 *m* altitude, the peak monthly mean power densities are 341.87 W/m^2 for year 2000 (class 3: $300 < P_D \leq 399$) i.e. Moderate in February, 199.04 W/m^2 for year 2001 (class 1: $P_D < 199$) i.e. Poor in February, 454.12 W/m^2 for year 2002 (class 4: $400 < P_D \leq 499$) i.e. Good in January, 177.21 W/m^2 for year 2003 (class 1: $P_D < 199$) i.e. Poor in December, 264.40 W/m^2 for year 2004 (class 2: $200 < P_D \leq 299$) i.e. Marginal in February and 342.35 W/m^2 for year 2005 (class 3: $300 < P_D \leq 399$) i.e. Moderate in January respectively in terms of wind resource potential. Therefore, the ability to generate electricity directly from wind energy is determined by wind power density, with higher power densities having a higher potential for producing electricity than lower densities. As a result, it appears that Lafia has promising prospects for wind energy resources at higher altitudes (50 *m* and above).

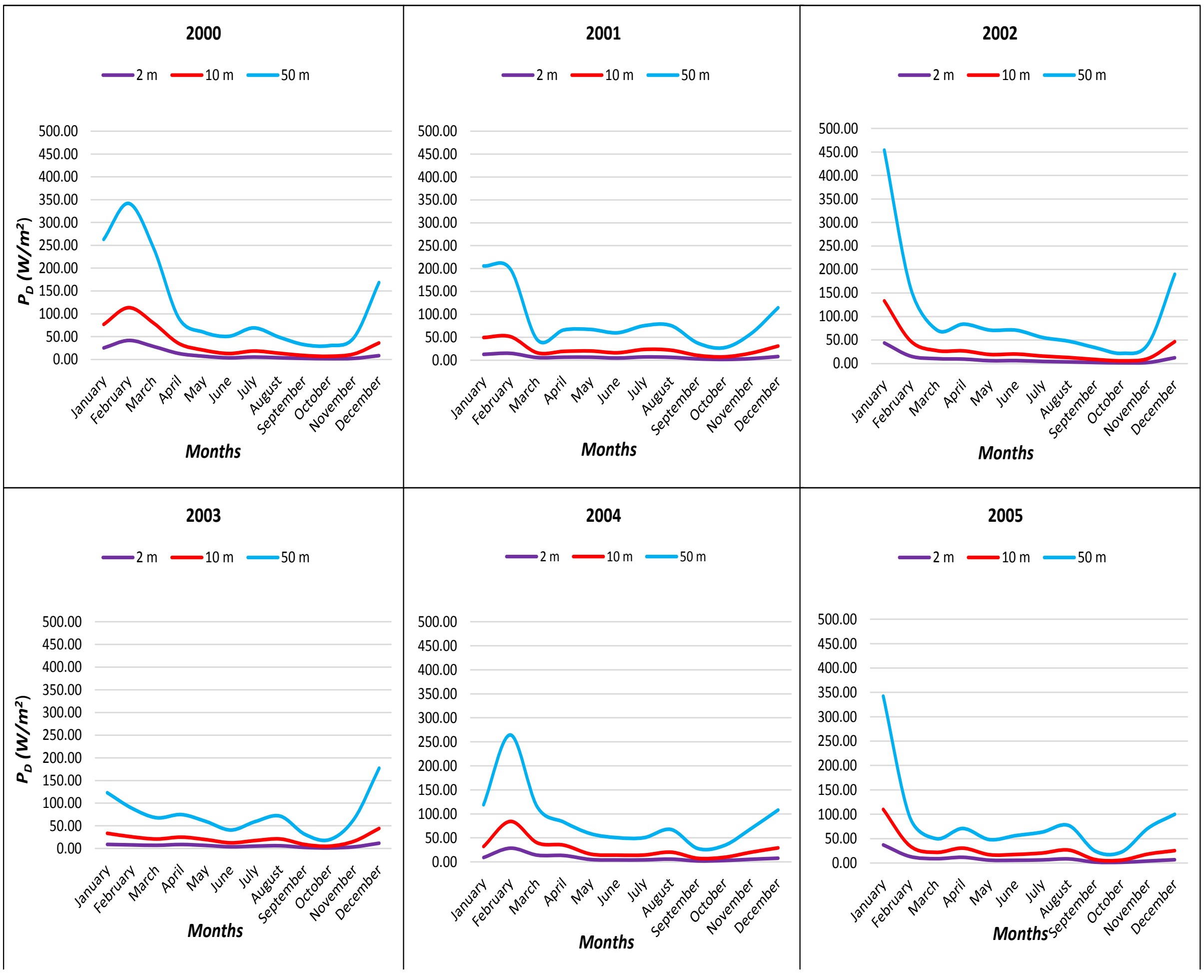

Figure 8: Wind power density, P_D plot at different heights for 6 years (2000 – 2005)

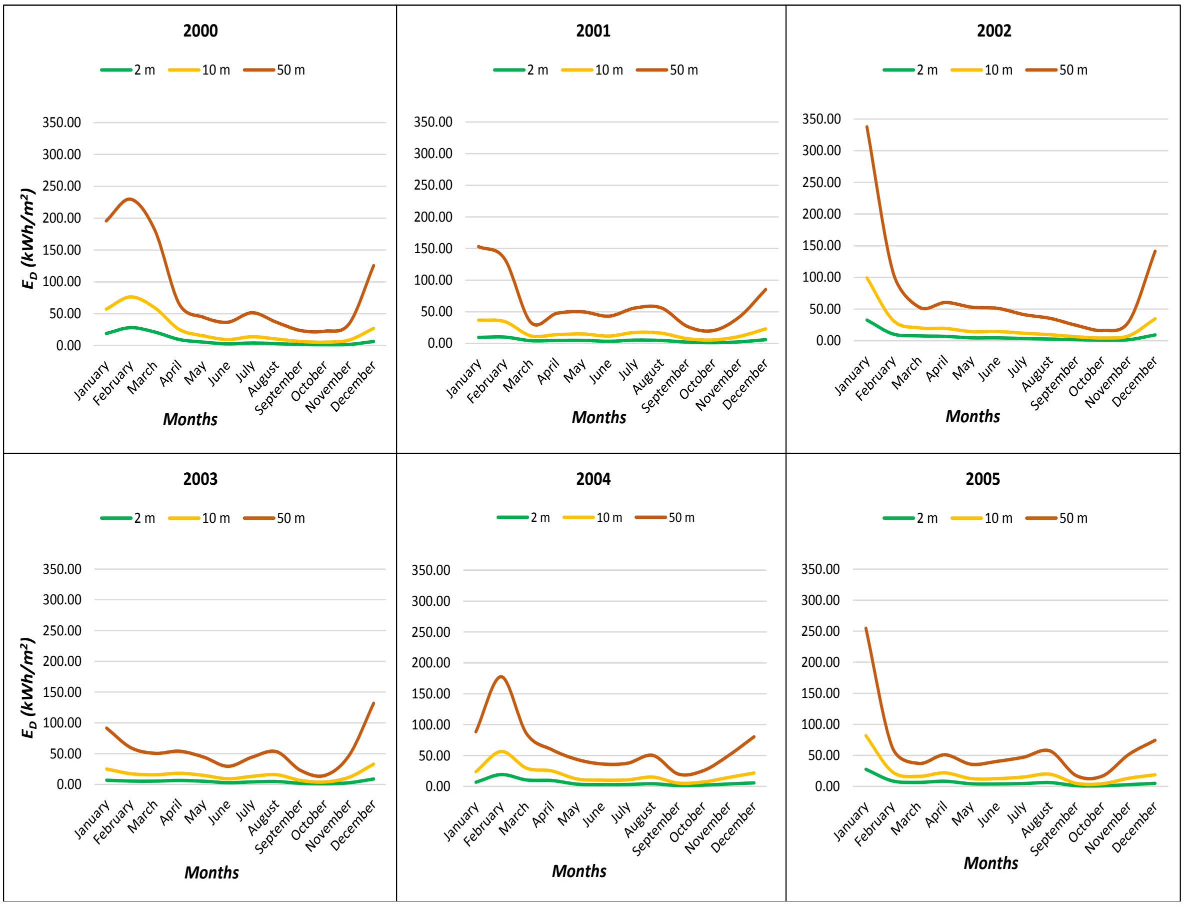

Figure 9: Mean energy density, E_D plot at different heights for 6 years (2000 – 2005)

In year 2000, Fig. 9 indicates that there is a correlating peak mean energy densities at distinct heights (2, 10, and 50 *metres*) are 28.01, 76.28 and 229.74 kWh/m^2 respectively in February correspond to the mean wind speeds are 3.49, 4.91 and 7.20 *m/s* while the least mean energy densities are 1.18, 5.23 and 22.46 kWh/m^2 respectively in October correspond to the mean wind speeds are 1.22, 2.00 and 3.18 *m/s*, respectively. Therefore, monthly mean energy densities, E_D vary in proportion to the monthly mean wind speeds, V_m (Table 2) due to the wind energy's dependence on the wind speed. Thus, the annual mean energy densities at distinct heights (2, 10, and 50 *metres*) observed in this study are 8.56, 26.11 and 87.21 kWh/m^2, respectively (Table 2 – 4). Fig. 9 indicates that the maximum mean energy densities at distinct heights (2, 10, and 50 *metres*) in year 2001 are 10.03 kWh/m^2 in February, 36.80 and 153.06 kWh/m^2 in January correspond to the mean wind speeds are 2.48, 3.81 and 6.05 *m/s*, respectively whereas the minimum mean energy densities are 1.16, 5.46 and 20.34 kWh/m^2, respectively in October correspond to the mean wind speeds are 1.24, 2.06 and 3.14 *m/s*, respectively.

The maximum mean energy densities at distinct heights (2, 10, and 50 *metres*) in year 2002 are 32.62, 99.25 and 337.86 kWh/m^2 in January correspond to the mean wind speeds are 3.51 *m/s*, 5.15*m/s* and 7.79*m/s* respectively whereas the minimum mean energy densities are 1.04, 4.32 and 16.10 kWh/m^2 respectively in October correspond to the mean wind speeds are 1.18, 1.91 and 2.92 *m/s* respectively as seen in Fig. 8.

In Fig. 9, the maximum mean energy densities at different heights distinct heights (2, 10, and 50 *metres*) in year 2003 are 8.74, 32.95 and 131.84 kWh/m^2 in December correspond to the mean wind speeds are 2.29, 3.61 and 5.72 *m/s* respectively whereas the minimum mean energy densities are 0.94, 3.94 and 14.66 kWh/m^2 respectively in October correspond to the mean wind speeds are 1.16, 1.88 and 2.86 *m/s*, respectively. In year 2004, Fig. 9 shows correlating high values of mean energy densities at distinct heights (2, 10, and 50 *metres*) are 19.25, 56.67 and 177.68 kWh/m^2 in February correspond to the mean wind speeds are 2.97, 4.28 and 6.27 *m/s* while the low values of mean energy densities are 1.46, 5.42 and 20.09 kWh/m^2 respectively in September correspond to the mean wind speeds are 1.40, 2.18 and 3.30 *m/s*, respectively.

In year 2005, Fig. 9 indicates the high values of mean energy densities at distinct heights (2, 10, and 50 *metres*) are 27.63, 81.82 and 254.71 kWh/m^2 in January correspond to the mean wind speeds are 3.21, 4.63 and 6.81 *m/s* while the low values of mean energy densities are 1.05, 4.40 and 16.85 kWh/m^2 respectively in September correspond to the mean wind speeds are 1.20, 1.95 and 2.99 *m/s*, respectively.

Under investigation, the yearly average wind speeds (year 2000) at different altitudes are 2.08 ms^{-1} (2 *m*), 3.12 ms^{-1} (10 *m*) and 4.71 ms^{-1} (50 *m*) (Table 3). This indicates that Lafia is a region with moderate wind speeds. In middle belt region of Nigeria, It's noteworthy to observe that the wind speed is within the acceptable limit (values) of 2.2–10.1 ms^{-1} reported by Ahmed [19]. According to Agbetuyi [10], the majority of wind turbines begin producing power when the wind speed is approximately closed to 3.0–4.0 ms^{-1}. The monthly and annually mean speeds of the wind derived in this work indicates that there is substantially huge potential for production of power in the wind in Lafia and its environs at altitude 10 *m* and above.

Table 3: Speed features of the wind and energy potential on monthly basis in Lafia at distinct heights (2, 10, and 50 *metres*)

S/N	Month	*2 metres*		*10 metres*		*50 metres*	
		V_m (m/s)	P_D (W/m^2)	V_m (m/s)	P_D (W/m^2)	V_m (m/s)	P_D (W/m^2)
1	January	2.86	25.25	4.18	76.78	6.29	262.97
2	February	3.49	41.69	4.91	113.51	7.20	341.87
3	March	3.01	28.36	4.24	79.52	6.12	243.33
4	April	2.53	13.11	3.56	35.06	4.99	90.79
5	May	2.03	7.08	2.93	20.31	4.31	59.62
6	June	1.58	3.58	2.44	12.99	3.80	50.73
7	July	1.82	5.30	2.78	18.48	4.32	69.17
8	August	1.60	3.77	2.47	13.70	3.76	49.07
9	September	1.39	2.26	2.20	8.73	3.37	32.55
10	October	1.22	1.59	2.00	7.03	3.18	30.19
11	November	1.37	2.34	2.38	12.05	3.71	47.96
12	December	2.04	8.39	3.36	36.19	5.50	168.55
	Annual	2.08	8.19	3.12	27.11	4.71	92.89

Table 4: Annual wind power classification for Lafia

S/N	Year	P_D (W/m^2) @ 2*m*	P_D (W/m^2) @ 10*m*	P_D (W/m^2) @ 50*m*	Wind Power Class
1	2000	8.19	27.11	92.89	1
2	2001	5.98	23.48	85.93	1
3	2002	7.02	23.47	81.92	1
4	2003	5.53	18.86	65.43	1
5	2004	7.01	22.82	75.40	1
6	2005	7.12	22.47	68.40	1

The annual mean power density for Lafia is below 92.89 W/m^2 for 6 years (2000 – 2005) at 3 different altitudes (2, 10 and 50 *m*) i.e., Class 1. Thus, demonstrating that the vast majority of the monthly average power density belongs to the category of class 1 wind resources. ($P_D \leq 100$) i.e., March – November while few of the monthly average power density falls into Class 2 ($100 < P_D \leq 150$) or Class 3 ($300 < P_D \leq 399$) or Class 4 ($400 < P_D \leq 499$) wind resource category i.e., December - February. Furthermore, the resource of the wind energy in Lafia annually from the classification based by PNL may be place it in class 1 based on the data (wind) used at 3 different altitudes (2, 10, and 50 *metres*) in this study as shown in Table 4.

Conclusion

The obtained annual mean wind speeds for Lafia over a 6-year period at an altitude of 10 *m* were 3.12, 2.91, 2.99, 2.78, 2.99, and 2.94 *m/s*, which were all close to the minimum needed values (3.00 – 4.00 *m/s*) for most turbines (wind) to effectively operate. While at 50 *m* altitude, the values of 4.71, 4.44, 4.54, 4.20, 4.45, and 4.28 *m/s* were all above the minimum (3.00 – 4.00 *m/s*) is a recommendation for most wind turbines to commence producing electricity. As a result, at an altitude of 10 *m*, and even more so at an altitude of 50 *m*, Lafia and its surroundings have a great potential for wind energy production. Consequently, as power density increases, so does the site's ability to generate electricity. This suggests that Lafia's wind energy resources at higher altitudes have a bright future (50 *m* and above).

Conflicts of interest: The authors state that they have no conflict of interest or competing interests in the work.

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