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Assessment of wind energy resources for electricity generation using WECS in North-Central region, Nigeria

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ABSTRACT

This paper presents a statistical analysis of wind characteristics of five locations covering the North-Central (NC) geo-political zone, Nigeria, namely Bida, Minna, Makurdi, Ilorin and Lokoja using Weibull distribution functions on a 36-year (1971–2007) wind speed data at 10 m height collected by the meteorological stations of NIMET in the region. The monthly, seasonal and annual variations were examined while wind speeds at different hub heights were got by extrapolating the 10 m data using the power law. The results from this investigation showed that all the five sites will only be adequate for non-connected electrical and mechanical applications with consideration to their respective annual mean wind speeds of 2.747, 4.289, 4.570, 4.386 and 3.158 m/s and annual average power densities of 16.569, 94.113, 76.399, 71.823 and 26.089 W/m^2 for Bida, Minna, Makurdi, Ilorin and Lokoja in that order. Weibull parameters k and c together with the energies for the respective locations were computed while further observation revealed that Bida, Minna, Makurdi and Ilorin are windier in the morning than afternoon periods for many months in a year whereas Lokoja had a windy afternoon. Additionally, four wind turbines De wind 48—600 kW, De wind D6—1250 kW, De wind D7—1500 kW and De wind D8—2000 kW were technically assessed for electricity generation by calculating their respective yearly energy output and capacity factor in all the locations.

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1. Introduction

The growth experienced in world energy consumption has increased significantly in the last decades through increased social development and economic growth with fossil fuels dominating major portion of the energy supply [1,2]. However, the use of fossil fuels have been creating serious environmental problems, such as acid emissions, air pollution and climate changes thereby making current energy trends to be unsustainable thus necessitating a better balance between energy security, economic development, and protection of the environment [2]. Renewable energy sources (wind, solar, hydro, biomass etc.) are inexhaustible, clean, free and offer many environmental and economical benefits in contrast to conventional energy sources; the role of renewable resources has been growing by leaps and bounds among other resources as their generating costs continue to decrease. [3].

According to Ohunakin [1], the energy outlook of Nigeria showed that energy demand is very high and increasing geometrically while the supply remains inadequate, insecure, irregular and is decreasing with years; the mix hitherto being dominated by fossil sources which are fast being depleted apart from being environmentally non-friendly. Approximately 40% of the population in Nigeria have access to grid connected power leaving the rest to the mercy of the local sources of energy such as firewood and direct solar radiation [1]. The situation calls for the diversification of the energy supply mix by creating full awareness to promote and develop the vast renewable energy resources present in the country. Nigeria has a large potential for renewable energies ranging from: hydropower (large and small), solar, biomass and wind. Ohu-

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Fig. 1. Map of Nigeria showing the six geo-political zones.

nakin [1], lately discussed some parts of Nigeria as endowed with strong wind conditions like the coastal areas and the offshore States namely Lagos, Ondo, Delta, Rivers, Bayelsa, Akwa-Ibom, the inland hilly regions of the North, the mountain terrains in the middle belt and the northern part of the country.

Wind utilization for effective electricity production has dated to the last two decades by means of modern wind turbines and has proved to be a mature, reliable and efficient technology for electricity production. Worldwide installed capacity of wind energy approximates 59,322 MW in 2005 with Europe producing almost 69% of the total, with 40,504 MW and expected to have reached 70,000 MW by 2010 [2,3].

Accurate wind resource assessment is very important and must be well understood for harnessing the power of the wind since wind speeds and directions present extreme transitions at most sites, thus requiring detailed study of spatial and temporal variations of wind speed values. In [5], output power generation of any wind energy conversion systems (WECS) is closely related not only to the system's performance but also to operating conditions, which are the wind characteristics of the selected site. Hence, best sites are in general where the wind blows most regularly.

The possibility of adopting wind energy as an electricity generation source using WECS in some locations covering North-Central (NC) region, Nigeria is explored by considering long range wind data from five meteorological stations spread across the region (Fig. 1). The wind data used in this study was obtained from the Nigerian Meteorological Agency (NIMET), Oshodi, Lagos. A 36-year (1971–2007) monthly wind data together with a synoptical data captured at two respective hours of 9:00 and 15:00 daily were obtained for Bida (latitude—09.06′N; longitude—06.01′E; elevation—144.3), Minna (latitude—09.37′N; longitude—06.32′E; elevation—256.4), Makurdi (latitude—07.44′N; longitude—08.32′E; elevation—112.9), Ilorin (latitude—08.29′N; longitude—04.35′E; elevation—307.4) and Lokoja (latitude—07.47′N; longitude—06.44′E; elevation—62.5). The wind speed data were recorded at a height of 10 m by a cup-generator anemometer at the respective stations of NIMET situated at each of the locations considered. The recorded wind speeds were computed as the average of the speed for each month.

2. Theoretical analysis

According to [2], there are several probability density functions that are often used to describe the wind speed frequency curve; commonly used for fitting the measured wind speed probability distributions are Weibull, Rayleigh and lognormal functions. However, the Weibull distribution provided a good match with experimental data and as such it is the most commonly used statistical distribution for describing wind speed data. The Weibull distribution function is expressed as [3]:

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

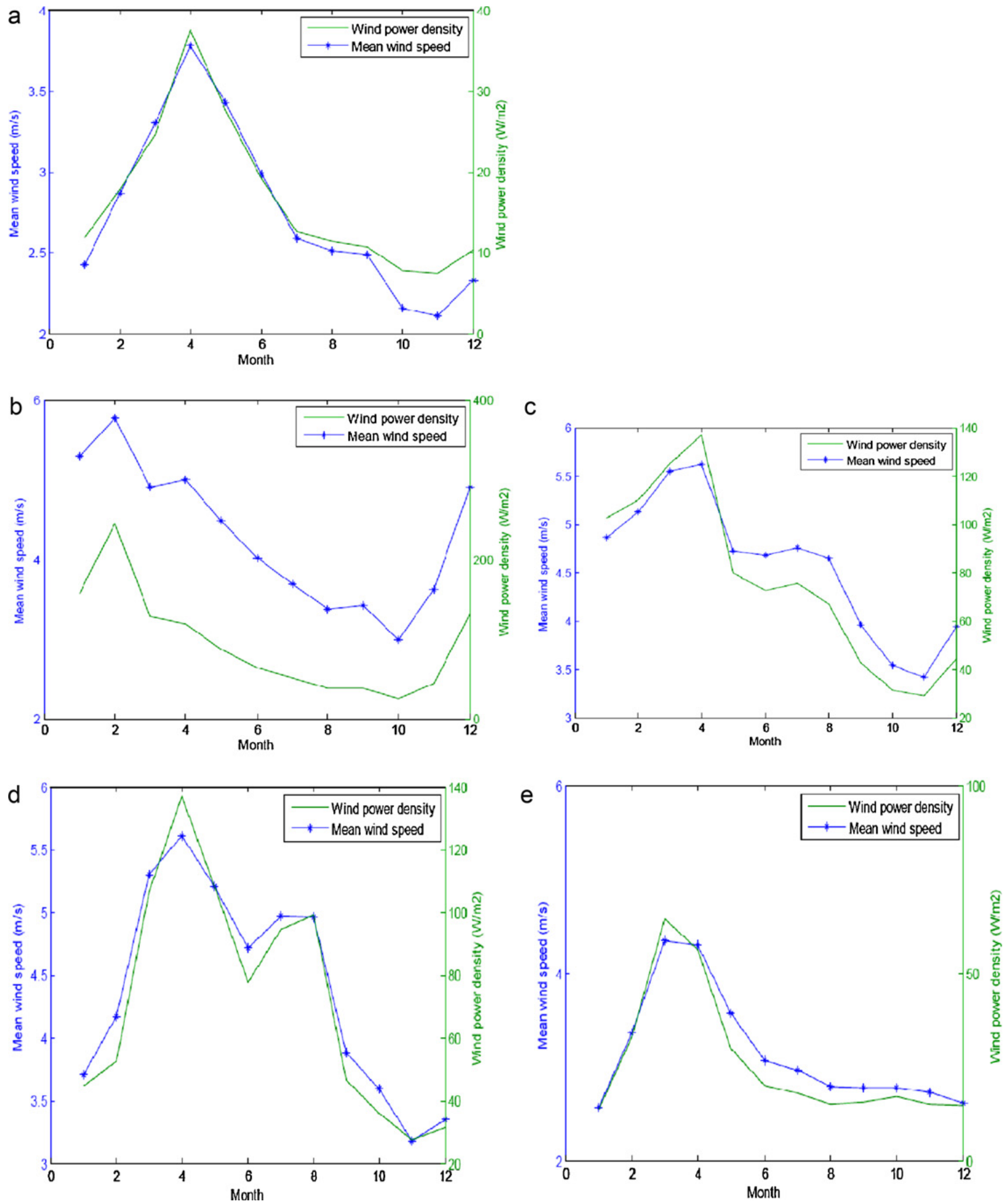

Fig. 2. Monthly variation of mean wind speeds and average power density for (a) Bida, (b) Minna, (c) Makurdi, (d) Ilorin and (e) Lokoja.

while the corresponding cumulative probability function is given by

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

Weibull parameters k and c can be computed using any of the following approach [2]: (i) Weibull probability plotting paper, (ii) standard deviation, (iii) moment, (iv) maximum likelihood and (v) energy pattern factor methods. The standard deviation method given by (3) and (4) is adopted in this article.

$$k = \left(\frac{\delta}{v_m}\right)^{-1.086} \qquad (1 \le k \le 10) \tag{3}$$

$$c = \frac{v_m}{\Gamma(1 + (1/k))} \tag{4}$$

where δ is the standard deviation, v_m is the average wind speed (m/s) and $\Gamma(x)$ is the gamma function of (x).

In [2,4,6,7], wind power density is expressed as:

$$P(v) = \frac{1}{2}\rho A v_m^3 \tag{5}$$

while the power of the wind per unit area is given as

$$p(v) = \frac{1}{2}\rho v_m^3 \tag{6}$$

Based on the Weibull probability density function, wind power density (wind power per unit area) can be calculated as:

$$p(v) = \frac{p(v)}{A} = \frac{1}{2}\rho c^3 \Gamma\left(1 + \frac{3}{k}\right) \tag{7}$$

where $P(v)$ = the wind power (W), $p(v)$ = the wind power density (W/m^2), ρ = the air density at the site (1.21 kg/m^3), A = the sweep area of the rotor blades (m^2). According to Ucar and Balo [2], wind speed data were extrapolated using the Power-law formula given as:

$$\frac{v}{v_0} = \left(\frac{h}{h_0}\right)^n \tag{8}$$

where 'v' is the wind speed at the required height 'h', 'v_0' is wind speed at the original height 'h_0', and 'n' is the surface roughness coefficient which lies in the range 0.05–0.5. A value of 0.3 is used in this paper for extrapolation at various heights. This value was chosen because the location of each site where the anemometer is cited to measure the wind speed falls into surface topology that comprises of suburbs and small towns.

Capacity factor (Cf) represents the fraction of the average power output over a period, to the rated electrical power (P_{eR}) [2,8]. The average power output $P_{e,ave,}$ and capacity factor Cf of a wind turbine can be calculated thus [7]:

$$P_{e,ave} = P_{eR}\left(\frac{e^{-(v_c/c)^k} - e^{-(v_r/c)^k}}{(v_r/c)^k - (v_c/c)^k} - e^{-(v_f/c)^k}\right) \tag{9}$$

$$\mathrm{Cf} = \frac{P_{e,ave}}{P_{eR}} \tag{10}$$

where v_c, v_r and v_f are the cut-in wind speed, rated wind speed and cut-off wind speed respectively. The average power output $P_{e,ave}$ and capacity factor Cf are important performance parame-

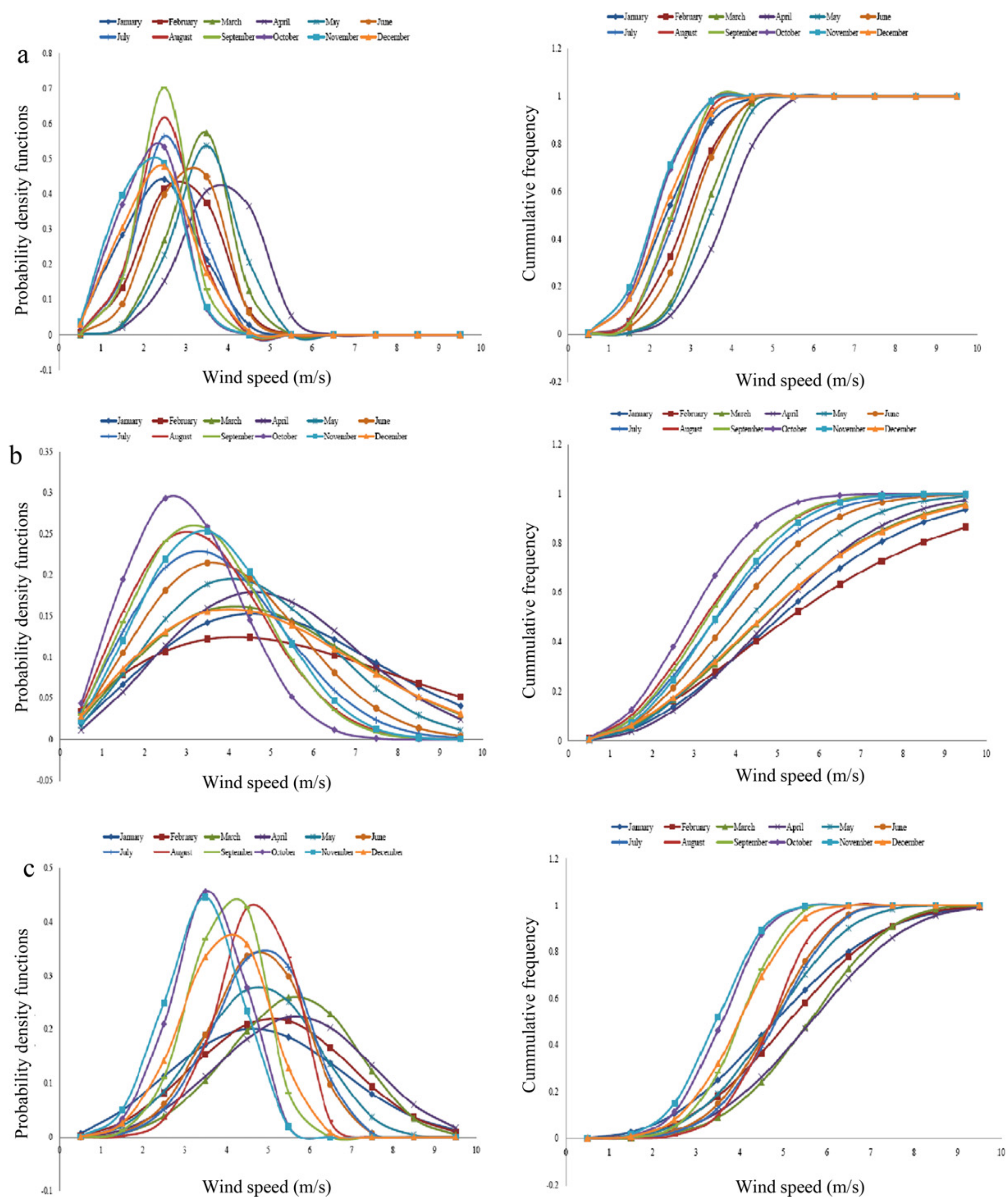

Fig. 3. Monthly wind speed probability density and cumulative frequency distributions for (a) Bida, (b) Minna, (c) Makurdi, (d) Ilorin and (e) Lokoja.

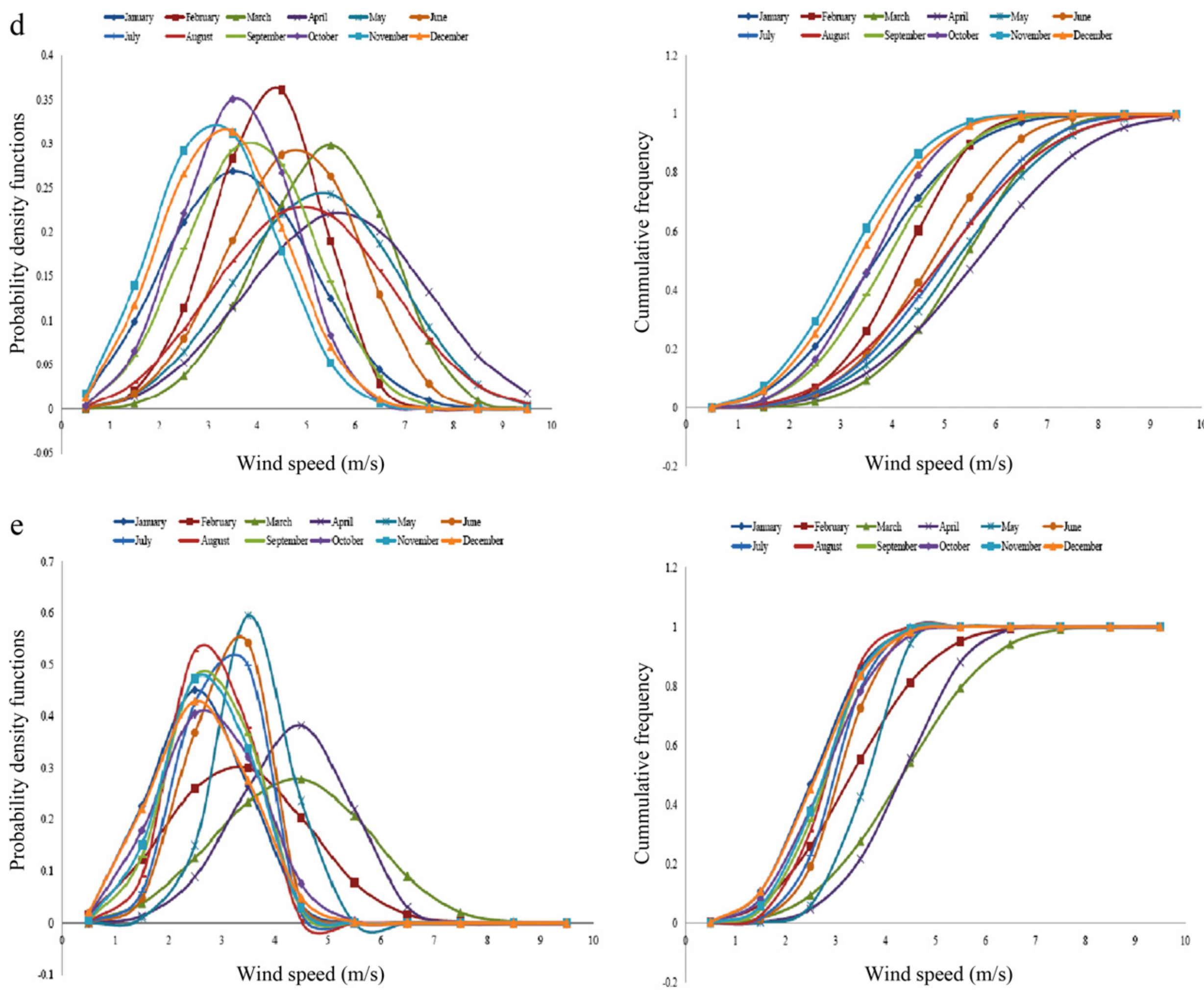

Fig. 3. (*Continued*).

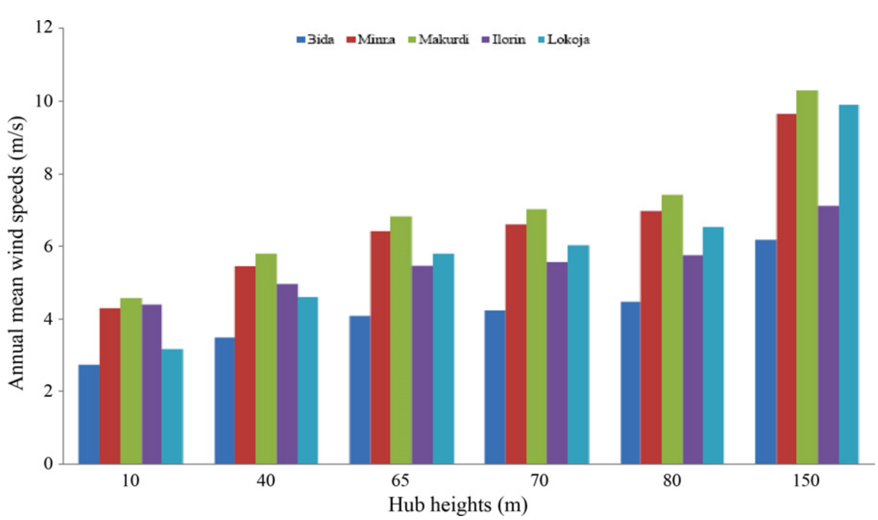

Fig. 4. Variation of annual mean wind speeds with different hub heights for the five sites.

ters of WECS. $P_{e,ave}$ determines the total energy production and total income.

The annual energy is defined by the relationship given by [9]:

$$\overline{E_a} = \sum_{n=1}^{12} \overline{E_{jm}} \, (\mathrm{kWh/m^2/year}) \tag{11}$$

where E_{jm} is the extractible is mean monthly energy given by $24 \times 10^{-3} d\bar{P}$, $\bar{P}$ is mean wind power density in (W/m^2) and d is the number of days in the month considered.

3. Results and discussion

Table 1 shows the mean monthly wind speeds and power densities for the five selected locations at 10 m heights. The maximum mean monthly wind speed value is obtained in Minna as 5.768 m/s in February while the minimum value is 2.108 m/s in November for Bida.

The maximum average power density occurred as 245.54 W/m^2 in February at Minna whereas the minimum average value is obtained in Bida as 7.48 W/m^2 in November. In Table 2, a maximum value of annual mean wind speed is obtained in Makurdi as 4.570 m/s and the minimum value of 2.747 m/s is got in Bida; Minna gave an annual average power density and energy of 94.11 W/m^2 and 816.19 kWh/m^2/year respectively while the minimum is also obtained in Bida as 16.57W/m^2 and 144.85 kWh/m^2/year for the annual average power density and energy in that order. The respective values of monthly and annual mean wind speed, power density and energy for the remaining locations considered are listed in Tables 1 and 2.

Table 3 depicts the monthly and annual variation of Weibull shape and scale parameters (k and c) respectively for the five sites. It can be observed that Weibull parameter k varies between 1.818 in Minna (February) to 6.542 in Lokoja (May). Therefore, in this region, the wind speed is most uniform in Lokoja in May while it is least uniform in Minna in February. The scale parameter c ranges from 2.347 to 6.489 m/s in Bida (November) and Minna (February) respectively.

Fig. 2 shows the variation of the monthly mean wind speeds together with average power densities for the selected five sites at 10 m height. It can be seen that similar changing trends is given by the two plots but with different rate of change. Minna has the highest mean wind speed and average power density of 5.768 m/s and 245.54 W/m^2 respectively while the minimum values are obtained in Bida with 2.108 m/s and 7.477 W/m^2. Furthermore, it can be observed from Table 3 that the seasonal mean wind speed ranged from 2.531 m/s in Bida (dry season) to 4.889 m/s in Ilorin (rainy season) while the average power density is between 13.295 and 122.020 W/m^2 in Bida and Minna respectively during the dry season.

Fig. 3 depicts the monthly Weibull probability density and cumulative frequency distributions derived from the time series data of the five locations for the whole year. It is shown that all the curves have a similar tendency of the wind speeds for the two distributions.

Furthermore, a critical study of Fig. 3 shows that there is the tendency of obtaining wind speeds above 10 m/s in some months in Minna while Makurdi and Ilorin can have months with the likelihood of wind speeds not exceeding 10 m/s. There is no month in Bida and Lokoja where wind speeds can go beyond 6 and 7 m/s respectively. Meanwhile, Bida, Ilorin and Lokoja has monthly peak frequencies of 70, 37 and 60% in September, February and May respectively while Minna and Makurdi has 30 and 46% monthly peak frequencies respectively in October.

Table 1
Mean monthly wind speed and power density for the respective locations at height 10 m.

Locations	Bida		Minna		Makurdi		Ilorin		Lokoja	
	Mean wind speed (m/s)	Average power density (W/m^2)	Mean wind speed (m/s)	Average power density (W/m^2)	Mean wind speed (m/s)	Average power density (W/m^2)	Mean wind speed (m/s)	Average power density (W/m^2)	Mean wind speed (m/s)	Average power density (W/m^2)
January	2.422	11.887	5.297	157.529	4.868	102.612	3.705	44.617	2.573	13.662
February	2.868	17.799	5.768	245.538	5.131	110.091	4.173	52.593	3.365	32.839
March	3.3	24.566	4.911	127.752	5.544	125.011	5.303	106.546	4.346	64.575
April	3.778	37.632	5.003	119.107	5.615	137.176	5.608	137.166	4.303	56.277
May	3.429	27.716	4.484	87.612	4.725	79.917	5.203	108.420	3.570	30.110
June	2.984	19.091	4.014	63.699	4.678	72.289	4.714	77.835	3.076	19.993
July	2.589	12.589	3.686	50.392	4.763	75.603	4.973	94.487	2.968	17.997
August	2.514	11.365	3.376	38.237	4.647	66.988	4.959	99.063	2.786	15.013
September	2.486	10.669	3.422	38.190	3.959	42.567	3.878	46.410	2.778	15.645
October	2.157	7.736	2.986	25.597	3.541	31.341	3.595	35.798	2.778	17.138
November	2.108	7.477	3.619	44.201	3.419	28.871	3.181	27.481	2.732	15.190
December	2.332	10.304	4.905	131.500	3.947	44.321	3.343	31.463	2.619	14.626

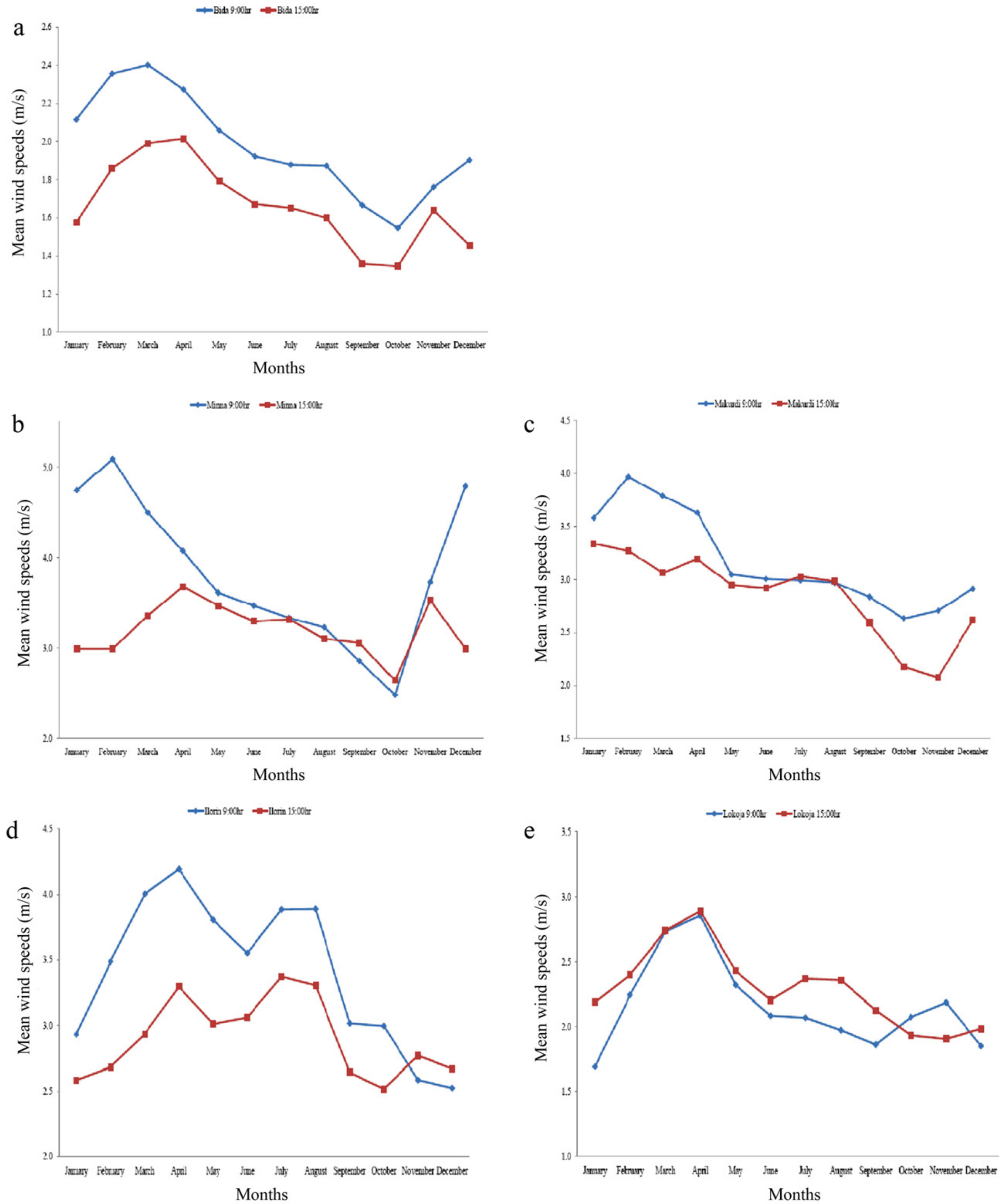

Fig. 5. Monthly mean wind speed captured at two synoptical hours of 9:00 and 15:00 for (a) Bida, (b) Minna, (c) Makurdi, (d) Ilorin and (e) Lokoja for the period 1971–2007.

Table 2
Annual wind characteristics for the five sites for the period 1971–2007.

Locations	Mean wind speed (m/s)	Average power density (W/m^2)	Average energy (kWh/m^2/year)
Bida	2.747	16.569	144.854
Minna	4.289	94.113	816.197
Makurdi	4.570	76.399	667.422
Ilorin	4.386	71.823	630.451
Lokoja	3.158	26.089	227.971

Table 4 showed that seasonal mean wind speed ranged from 2.531 m/s in the dry season in Bida to 4.889 m/s in Ilorin (rainy season) while the seasonal average power density varies between 13.295 and 122.02 W/m^2 in Bida and Minna respectively in the dry season.

The range of months making the seasons (dry and rainy) for the respective locations is shown in Table 4. Fig. 4 showed that mean wind speeds varies with increase in hub heights; as an example, the annual mean wind speeds for Bida, Minna, Makurdi, Ilorin

Table 3
Monthly variation of Weibull parameters (k and c) at the five sites.

Locations	Bida		Minna		Makurdi		Ilorin		Lokoja	
	k	*c* (m/s)	*k*	*c* (m/s)	*k*	*c* (m/s)	*k*	*c* (m/s)	*k*	*c* (m/s)
January	3.083	2.709	2.193	5.981	2.777	5.469	2.840	4.159	3.359	2.866
February	3.883	3.169	1.818	6.489	3.250	5.724	4.423	4.577	2.925	3.772
March	5.485	3.575	2.150	5.545	4.210	6.098	4.588	5.804	3.505	4.830
April	5.021	4.114	2.511	5.638	3.636	6.229	3.601	6.223	4.781	4.698
May	5.362	3.720	2.439	5.056	3.845	5.225	3.690	5.766	6.542	3.830
June	4.499	3.720	2.396	4.528	4.791	5.108	4.053	5.196	5.355	3.337
July	4.365	2.842	2.334	4.160	4.957	5.189	3.709	5.509	5.303	3.221
August	4.564	2.752	2.369	3.809	6.198	4.999	3.272	5.531	5.134	3.030
September	5.129	2.704	2.504	3.856	5.404	4.293	3.419	4.316	4.304	3.052
October	3.676	2.391	2.476	3.367	4.791	3.866	3.680	3.984	3.386	3.093
November	3.395	2.347	2.582	4.075	4.420	3.751	2.974	3.564	4.032	3.013
December	3.273	2.601	2.076	5.538	4.454	4.328	3.053	3.741	3.255	2.922

Table 4
Seasonal variations of wind characteristics for the seven sites for the period 1971–2007.

Season	Mean wind speed (10 m)	Average power density (W/m^2)	Seasonal duration range
Bida			
Rainy season	2.963	19.844	April–September
Dry season	2.531	13.295	October–March
Minna			
Rainy season	3.998	66.206	April–September
Dry season	4.581	122.02	October–March
Makurdi			
Rainy season	4.561	72.269	April – October
Dry season	4.582	82.181	November – March
Ilorin			
Rainy season	4.889	93.897	April – September
Dry season	3.883	49.750	October – March
Lokoja			
Rainy season	3.180	24.596	April–October
Dry season	3.127	28.178	November–March

and Lokoja at 65 m hub heights are 4.100, 6.401, 6.819, 5.458 and 5.800 m/s respectively.

Fig. 5 depicts the monthly variations of mean wind speeds of the sites, taken at two synoptical hours of 9:00 and 15:00 for the whole year under study.

It can be seen from the plot that Bida, Minna, Makurdi and Ilorin are windier in the morning period than afternoon hours; further observation showed that between July to November, June to August and November to December, Minna, Makurdi and Ilorin are windier in the afternoon than morning periods. Lokoja has higher wind speeds in the afternoon for most part of the year until October to November when higher wind speeds is noticeable in the morning. The varying wind speeds noticeable may be connected to: (i) changing temperature stratification and (ii) vertical exchange in momentum more prominent during the rainy seasons in the respective sites (Table 4), thus causing an increase of wind speed as a result of thermal convection.

The characteristic properties of the four selected wind turbines namely, De wind 48, De wind D6, De wind D7, and De wind D8 each with rated power (Pr) 600, 1250, 1500, and 2000 kW respectively are given in Table 5. The computed annual power output and capacity factors of the selected wind turbines for the five locations are shown in Table 6.

It can be concluded from this table that accumulated power output using De wind 48—600 kW (40 m hub height) wind turbine ranges from 5.25 kW/year in Bida to 128.82 kW/year (Minna). Similar trend is followed by the other wind turbines concerning the respective locations. In addition, Minna recorded the highest annual power of 513.27 kW/year using De wind D8—2 MW while the lowest is got in Bida with 5.25 kW/year for De wind 48. Furthermore, the highest capacity factor (Cf) is calculated as 28.42% for De wind D7—1500 kW in Minna while the lowest is computed as 0.88% for De wind 48 in Yelwa at 40 m hub height. Table 6 also showed that capacity factor varies with each wind turbine type in a

Table 5
Characteristics of the selected wind turbines.

Characteristics	De wind 48	De wind D6	De wind D7	De wind D8
Hub height (m)	40	65	70	80
Rated power Pr (kW)	600	1250	1500	2000
Sweep area (m^2)	1808	3019	3846	5027
Cut-in wind speed v_c (m/s)	2.5	2.8	3	3
Rated wind speed v_r (m/s)	11.5	12.5	12	13.5
Cut-off wind speed v_f (m/s)	25	25	25	25

Table 6
Annual power output and capacity factor of the selected wind turbine for the locations.

Location	De wind 48		De wind D6		De wind D7		De wind D8	
	$P_{e,ave}$ (kW/year)	Cf (%)	$P_{e,ave}$ (kW/year)	Cf (%)	$P_{e,ave}$ (kW/year)	Cf (%)	$P_{e,ave}$ (kW/year)	Cf (%)
Bida	5.25	0.88	15.79	1.26	24.92	1.66	26.54	1.33
Minna	128.82	21.47	314.9	25.19	426.22	28.42	513.27	25.66
Makurdi	61.92	10.32	171.92	13.75	262.55	17.50	284.41	14.22
Ilorin	69.39	11.57	191.68	15.33	290.37	19.36	317.03	15.85
Lokoja	15.22	2.54	41.05	3.52	66.55	4.44	71.86	3.59

particular site; the value for De wind D6—1.25 MW used in Makurdi is 13.75% whereas Cf is 14.22% for De wind D8—2 MW at 80 m hub height for the same location.

4. Conclusion

With regards to the computed mean wind speeds and power densities of the locations (Table 2), it can be concluded that all the five sites fell under Class 1 category of the international system of wind classification [10]. Considering the respective low yearly power outputs of the four turbines in each location, it is further supported that none of the sites can be considered very suitable for wind turbine applications or other wind energy developments even with use of a tall tower. They may only be adequate for non-connected electrical and mechanical applications like battery charging and water pumping.

In addition, the following basic facts can be further drawn from the study:

- The minimum monthly mean wind speed and average power density is recorded in Bida as 2.108 m/s and 7.477 W/m^2 respectively in November while the maximum is found to be 5.768 m/s and 245.538 W/m^2 in February in Minna.
- Weibull shape parameter k varies from 1.818 to 6.542 while the scale parameter c is between 2.347 and 6.489 m/s.
- The annual mean wind speeds ranged from 2.747 m/s in Bida to 4.570 m/s in Makurdi. The lowest annual average power density and energy are obtained in Bida as 16.569 W/m^2 and 144.854 kWh/m^2/year respectively while the highest values are obtained in Minna as 94.113 W/m^2 and 816.197 kWh/m^2/year in that order.
- The highest annual power is obtained with De wind D8— 2 MW as 513.27 kW/year in Minna while the lowest is got in Bida having 5.25 kW/year for De wind 48—600 kW. Furthermore, 28.42% is computed as the highest capacity factor for De wind D7—1.5 MW in Minna while the lowest is calculated as 0.88% for De wind 48—600 kW in Bida.

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