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Wind resource evaluation in six selected high altitude locations in Nigeria

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ABSTRACT

This paper presents an assessment of wind energy potentials of six selected high altitude locations within the North-West and North-East geopolitical regions, Nigeria, by using 36-year (1971–2007) wind speed data subjected to 2-parameter Weibull distribution functions. The results showed that the maximum mean wind speed is obtained in Katsina as 9.839 m/s while the minimum value of 3.397 m/s is got in Kaduna for all the locations considered. The annual wind power density and energy variation based on the Weibull analysis ranged from 368.92 W/m^2 and 3224.45 kWh/m^2/year to 103.14 W/m^2 and 901.75 kWh/m^2/year in Kano and Potiskum for the maximum and minimum values respectively. Furthermore, Katsina and Kano will be suitable for wind turbine installations while Gusau will only be appropriate for wind energy utilization using taller wind turbine towers whereas Kaduna, Bauchi and Potiskum will be considered marginal for wind power development based of their respective annual mean wind speeds and power densities.

1. Introduction

Renewable energy sources among which are wind, solar, hydro, biomass etc. have been gaining prominence in developed countries with increasing efficiencies of renewable energy technologies as recorded over years and the decreasing generating costs associated with deployment of the technology [1]. In addition [1], these energy sources are inexhaustible, clean, free and offer many environmental and economical benefits in contrast to conventional energy sources. In [2], wind power is becoming the world's fastest growing renewable energy source whose strong growth is attributable to the promotion of models of renewable energy sources, energy supply security, fuel diversity concerns, ecological awareness and economic reasons. Its worldwide acceptance as a clean source of energy showed a reflection in the total installed capacity and annual output that reached 121,188 MW and 260 TWh respectively at the end of 2008, recording approximately 27% increase above year 2006 and contributing more than 1.5% to global electricity consumption [2,3]. It is a fuel-free energy source that does not cause pollution in electricity production, with an advantage of generating power near load centers thereby eliminating loss in lines through transmission.

Energy has been a major challenge in Nigeria in spite of government's efforts at meeting the energy need of the populace. The existing generation in 2007 was put at a total installed capacity of 7876 MW (75.9% thermal and 24.1% hydro), available capacity of 4914 MW (67.8% thermal and 32.2% hydro) and an operational capacity of 3149 MW (68.2% thermal and 31.8% hydro) [4]. It is evident that electricity generation is largely dominated by fossil fuel sources while the present production of 3149 MW is grossly insufficient for a country with an approximate population of 150 million people. According to Sambo [5], only about 40% of the nation's population have access to grid electricity while at the rural level where about 70% of the population live, the availability of electricity drops to 15% and in Ohunakin [4], the projected electricity demand from year 2005–2030 shows an increasing trend on the four adopted growth scenarios (Fig. 1) indicating a high economic growth rate whereas the energy consumed over the years shows a decreasing trend with increasing population (Table 1).

Hence, there is need for the full exploitation of the renewable energy resources proven to be in vast deposit, to supplement conventional energy means, avert looming energy crises and increase electricity access for sustainable national development [4,5].

In view of these, the inception of the democratic dispensation in 1999, commenced with the federal government embarking on power sector reforms by putting several policy frameworks in place to improve infrastructure of energy supply; starting the reforms

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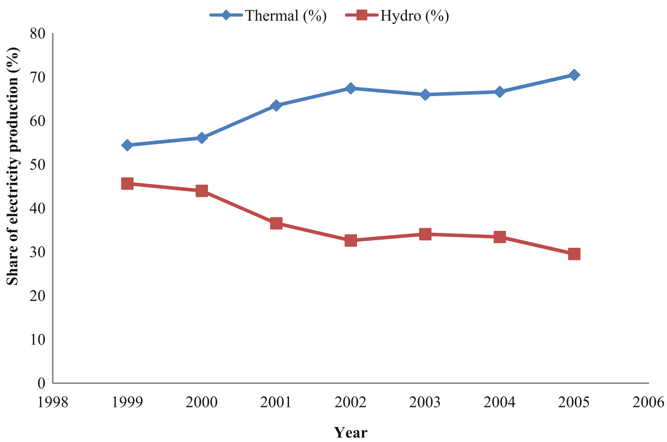

Fig. 1. Thermal and hydropower contribution to total electricity production in Nigeria between 1999 and 2005. Data source: Ref. [6].

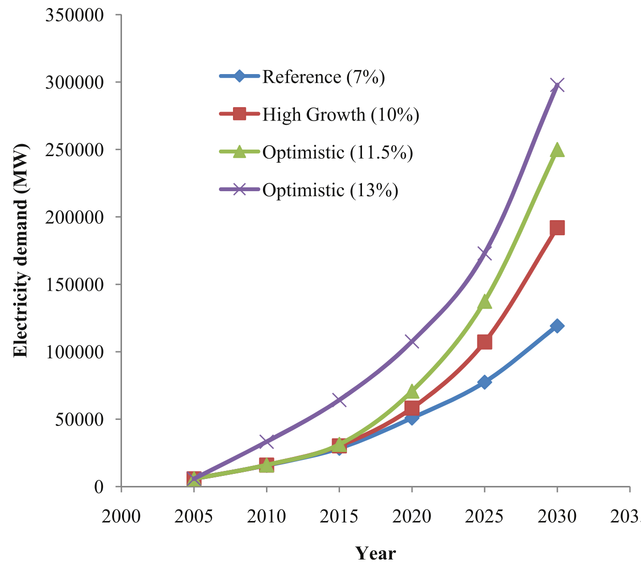

Fig. 2. Graph showing the projected electricity demand between 2005 and 2030. Data source: Ref. [4].

was the preparation of a National Electric Power policy in 2001. Among the policies approved are the overall National Energy Policy in 2003, liberalization of the power sector in 2005 through the passage of the Electric Power Sector Reform Act (EPSR) and establishment of the Nigerian Electricity Regulatory Commission (NERC) [4,6]. The reform broke the monopolistic framework in the power sector thereby allowing:(i) private operators to apply for and obtain a license through the Nigerian Electricity Regulatory Commission (NERC) to build and operate a power plant with aggregate capacity above 1 MW and (ii) the establishment of the Rural Electrification Agency (REA) together with an independent Rural Electrification Fund (REF) whose major objective is to fully incorporate renewable energy in the energy options. Furthermore, the EPSR Act allows a person to construct, own or operate an off-grid power plant not exceeding1MW in aggregate at a site without a license [6].

Hydro (large and small) has been contributing substantially to the total electricity generation among the renewable sources deposited in Nigeria; however, its contribution to the total energy mix is experiencing a decreasing trend (Fig. 2), which is expected to continue since water inflow into the Kainji lake that feeds Kainji and Jebba power plants has dropped as a result of climate change and the power dam initiated by Niger Republic on the Niger river [6].

In addition, according to Sambo [7], the projected electricity supply by fuel-mix by the Energy Commission of Nigeria, clearly reflected a good contribution from wind energy among the rests of the renewable energy sources, other than hydro (Table 2). In spite of the potential of wind as a source of energy in the country, its contribution to the total energy consumption has been very insignificant [4]. Till date, there is no record of wind power plants connected to the national grid [8]; the few ones in existence are still operational and are two pilot wind electricity schemes-5kWp Sayya Gidan Dada and a 0.75kWp wind electricity projects at Sokoto and Danjawa village respectively while other small scale stand-alone wind power plants were installed since early 1960s in some northern states to power water pumps and grind mills in places such as Goronyo in Katsina and Kedada in Bauchi [9].

The vast potentials of different renewable energies in Nigeria have been widely discussed as Ohunakin [4], lately exposed some parts of the country 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. However, several papers were published in time past in Nigeria, to determine wind characteristics, and electricity generation cost [10–14]. This study therefore evaluates wind resource characteristics among the selected high altitude locations

Table 1
Per capita primary energy consumption in Nigeria.

Year	Energy Consumed (Mtoe)	Population (million)	Per Capita Energy Consumption (toe/capita)
2002	18.783	122.365	0.153
2003	19.106	126.153	0.151
2004	16.267	129.927	0.125
2005	17.707	133.702	0.132
2006	12.421	140.003	0.089
2007	11.387	144.203	0.097

Source: Ref. [4].

Table 2
Projected electricity supply by fuel-mix for 7 and 13% growth rate.

	Hydro	Small hydro	Solar	Wind	Hydro	Small hydro	Solar	Wind
	7%				13%			
2010	3702	40	5	0	3702	208	30	500
2015	4962	90	10	126	4962	360	80	1200
2020	6479	140	34	1471	6479	1000	750	3971
2025	9479	227	75	3019	9479	1956	2670	6920
2030	11,479	701	302	5369	11,479	2353	4610	15,567

Source: Ref. [7].

Table 3
Geographical coordinates of the selected locations.

Station	Latitude °N	Longitude °E	Elevation (m)
Gusau	12.10	06.42	463.9
Kaduna	10.36	07.27	645.4
Katsina	13.01	07.41	517.6
Kano	12.03	08.12	472.5
Bauchi	10.17	09.49	609.7
Potiskum	11.42	11.02	414.8

Table 4
Variation of monthly mean and annual wind speeds of selected locations at 10 m height.

Station	Month												Annual
	January	February	March	April	May	June	July	August	September	October	November	December	
Gusau	7.3900	6.9600	7.0033	6.9933	7.1133	6.7900	5.9533	5.0433	3.9966	3.5833	5.1066	7.1833	6.0931
Kaduna	6.8033	6.4516	5.8065	5.4290	5.4161	5.4742	5.1516	4.6838	3.8097	3.3968	4.8903	5.9742	5.2739
Katsina	8.8217	7.6826	6.6000	7.6565	8.9609	9.8391	8.8391	6.8261	6.3348	5.4609	5.3435	6.9870	7.4461
Kano	7.8583	8.2444	7.8472	8.4278	9.0444	9.1472	8.2555	7.0806	6.7639	6.3389	6.5528	7.6417	7.7669
Bauchi	5.1212	5.6061	5.4970	7.0394	5.2970	4.2455	4.2031	4.2394	3.9576	4.0818	4.4152	4.3000	4.8336
Potiskum	4.8306	5.15	5.3833	5.4167	5.6806	5.4694	5.2444	4.4278	3.9167	3.9806	4.2194	3.9306	4.8042

by considering long range wind data from six meteorological stations spreading across the North-West and North-East geopolitical zones of Nigeria. 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 from the Nigerian Meteorological Agency (NIMET) for Gusau, Kaduna, Katsina, Kano, Bauchi and Potiskum. The geographical coordinates of the selected sites are shown in Table 3. 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. Mathematical model

2.1. Weibull distribution function

In [1,15,16], the Weibull distribution function is a special case of generalized gamma distribution for wind speed among the several density functions used in describing wind speed frequency curve and estimation of wind power density. The probability density function $f(v)$ is expressed as [1]:

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

while the corresponding cumulative probability function is given by [15]:

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

where c and k are the Weibull scale and shape parameters respectively, which can be computed by any of the following approaches [17]: (i) Weibull probability plotting paper (ii) standard deviation (iii) moment (iv) maximum likelihood and (v) energy pattern factor methods. The standard deviation method expressed by equations (3) and (4) is adopted in this article. Once the mean and variance of the wind speeds are known, the Weibull parameters k and c can be calculated by the following approximations [11]:

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

$$c = \frac{v_m}{\Gamma\left(1+\frac{1}{k}\right)} \quad (4)$$

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

2.2. Wind power density and wind energy

According to Dahmouni et al. [15], wind power density of a location is the most important parameter that should be estimated in citing a WECS; it takes into consideration the wind speed, wind speed distribution and air density. The mean wind power of any selected site per unit area can be expressed as [15]:

$$p(v) = \frac{1}{2}\rho v_m^3 \quad (5)$$

Furthermore in [15], equation (5) is dependent on the frequency of each velocity, hence, based on the Weibull probability density

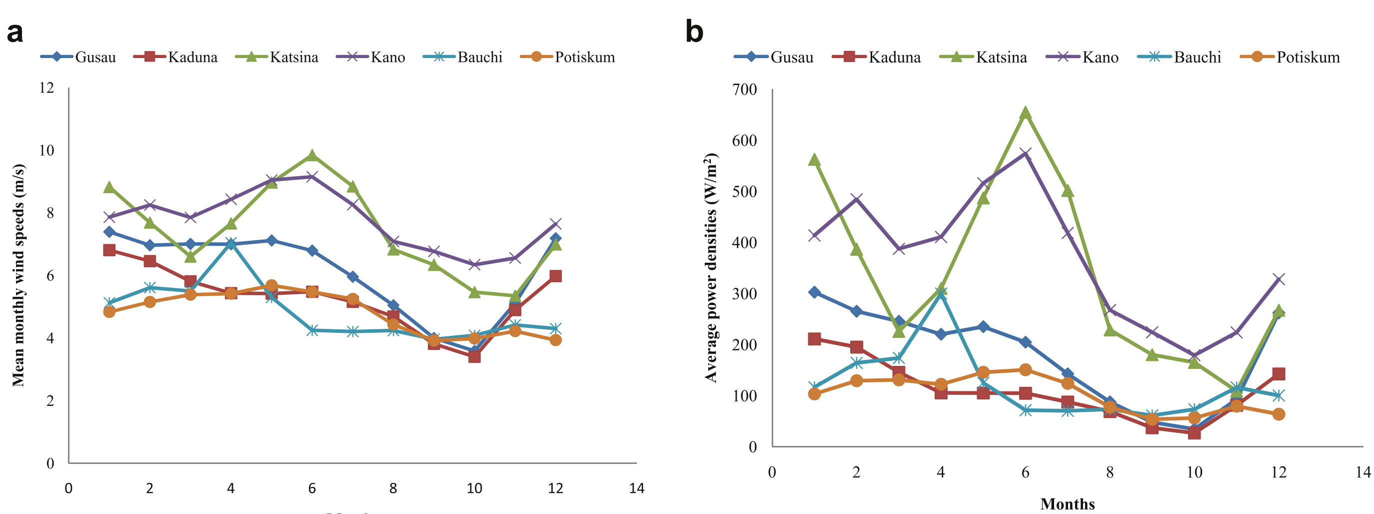

Fig. 3. Monthly variations of (a) mean wind speeds and (b) average power densities for the selected locations.

Table 5
Monthly and annual variations of average power densities and energies for the six sites for the period 1971–2007.

Month	Gusau		Kaduna		Katsina		Kano		Bauchi		Potiskum	
	Average power density (W/m^2)	Average energy (kWh/m^2)	Average power density (W/m^2)	Average energy (kWh/m^2)	Average power density (W/m^2)	Average energy (kWh/m^2)	Average power density (W/m^2)	Average energy (kWh/m^2)	Average power density (W/m^2)	Average energy (kWh/m^2)	Average power density (W/m^2)	Average energy (kWh/m^2)
January	302.5789	225.1187	211.1644	157.1064	562.6185	418.5881	413.6105	307.7262	116.4126	86.6110	103.3925	76.9241
February	265.2268	178.2324	195.1570	131.1455	386.5992	259.7947	484.2904	325.4432	164.1533	110.3110	129.3448	86.9197
March	245.525	182.6706	145.738	108.1612	225.6756	167.9026	387.4978	288.2983	173.7776	129.2905	131.1401	97.5683
April	220.2157	158.5553	105.5361	75.986	309.8546	223.0953	410.6856	295.6936	299.8824	215.9153	122.3321	88.0791
May	235.0083	174.8462	105.2077	78.2745	487.0621	362.3742	515.8626	383.8018	125.2144	93.1595	145.7591	108.4447
June	204.6991	147.3833	104.7965	75.4534	654.7724	471.4361	573.9195	413.2221	71.5914	51.5458	150.8400	108.6048
July	142.7405	106.199	87.6354	65.2008	501.5989	373.1896	418.5727	311.4181	70.3124	52.3125	124.084	92.3185
August	87.8332	65.3479	68.9516	51.2999	228.614	170.0892	267.5072	199.0254	73.3965	54.6070	77.4847	57.6486
September	48.0650	34.6068	37.0514	26.6769	180.2393	129.7723	224.1211	161.3672	61.3300	44.1576	53.8195	38.7500
October	34.7171	25.8295	26.8959	20.0105	165.1114	122.8429	179.0676	133.2263	73.3602	54.5799	56.2391	41.8419
November	93.0768	67.0153	81.2352	58.4894	108.9543	78.44710	223.8252	161.1542	116.1745	83.6457	79.5254	57.2583
December	262.1317	195.026	142.6297	106.1165	267.1517	198.7608	328.0487	244.0683	100.4108	74.7057	63.6971	47.3906
Annual	**178.485**	**1560.831**	**109.333**	**953.921**	**339.854**	**2976.293**	**368.917**	**3224.445**	**120.501**	**1050.842**	**103.138**	**901.749**

function, wind power density (wind power per unit area) can be calculated as [11]:

$$p(v) = \frac{P(v)}{A} = \frac{1}{2}\rho c^3 \Gamma\left(1+\frac{3}{k}\right) \tag{6}$$

where $P(v)$ = wind power (W), $p(v)$ = wind power density (W/m^2), ρ = air density at the site (1.21 kg/m^3), A = sweep area of the rotor blades (m^2).

The annual energy is defined by the relationship given by [18]:

$$\overline{E_a} = \sum_{n=1}^{12} \overline{E_{jm}}\left(\text{kWh/m}^2/\text{year}\right) \tag{7}$$

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

2.3. Wind speed extrapolation

Wind speeds used for this article are collected at 10 m height. However, for the purpose of installation of a WECS, it is necessary for the wind speed to be estimated at the respective turbine hub heights. Power law method is most commonly used to adjust wind velocity at a reference level to another. It is expressed as [19]:

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

where 'v' is the wind speed at the required height 'h', 'v_0' is wind speed at the reference height 'h_0', and 'n' is the surface roughness coefficient which lies in the range 0.05–0.5. A value of 0.3 was chosen in this paper for extrapolation at various heights 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 towns.

3. Results and discussion

Table 4 showed the computed mean monthly and annual wind speeds of the six selected sites at 10 m height. It can be deduced from the table that all the stations have an annual mean wind

Table 6
Seasonal variations of wind characteristics for the six sites for the period 1971–2007.

Season	Mean wind speed (10 m)	Average power density (W/m^2)	Monthly seasonal duration range
Gusau			
Rainy season	5.45	120.83	June–September
Dry season	6.42	207.31	October–May
Kaduna			
Rainy season	4.78	74.61	June–September
Dry season	5.52	126.70	October–May
Katsina			
Rainy season	7.96	391.31	June–September
Dry season	7.19	314.13	October–May
Kano			
Rainy season	7.81	371.03	June–September
Dry season	7.74	367.86	October–May
Bauchi			
Rainy season	4.39	80.37	May–September
Dry season	5.16	149.17	October–April
Potiskum			
Rainy season	4.02	46.31	September–December
Dry season	5.20	89.57	January–August

Table 7
Monthly and annual variation of Weibull parameters (k and c) at the selected sites.

Month	Gusau		Kaduna		Katsina		Kano		Bauchi		Potiskum	
	k	c (m/s)	k	c (m/s)	k	c (m/s)	k	c (m/s)	k	c (m/s)	k	c (m/s)
January	3.9549	8.1584	6.0435	7.3304	3.2127	9.8476	2.9831	8.8023	2.8969	5.7435	2.6461	5.4356
February	3.5059	7.7348	4.3374	7.0848	2.9814	8.6057	2.9114	9.2444	2.5861	6.3126	2.5271	5.8028
March	4.5839	7.6660	4.0625	6.4004	3.5233	7.3328	3.3603	8.7401	2.2259	6.2066	3.0593	6.0232
April	8.0037	7.4258	6.6754	5.8182	5.2476	8.3157	5.3942	9.1389	2.9380	7.8902	3.6921	6.0029
May	7.1541	7.5957	6.5069	5.8123	5.7532	9.6817	5.0327	9.8468	3.0464	5.9277	3.4222	6.3210
June	7.0778	7.2545	8.6197	5.7923	5.3468	10.6748	3.9530	10.0985	2.5706	4.7813	2.6364	6.1559
July	5.7711	6.4311	8.3397	5.4594	4.3454	9.7056	4.0421	9.1026	2.5269	4.7358	2.9348	5.8785
August	5.4437	5.4661	6.0243	5.0477	4.4975	7.4803	3.8999	7.8229	2.4683	4.7795	2.7597	4.9752
September	3.9097	4.4151	6.0693	4.1039	4.7188	6.9225	4.3854	7.4229	2.3830	4.4649	2.7444	4.4018
October	3.8868	3.9598	5.3878	3.6837	2.3110	6.1638	4.8710	6.9143	2.1499	4.6091	2.7643	4.4724
November	4.9844	5.5628	5.1122	5.3193	4.5991	5.8480	3.4194	7.2918	1.7374	4.9553	2.1959	4.7644
December	4.7636	7.8455	6.1295	6.4321	3.5413	7.8606	4.1854	8.4089	1.8392	4.8400	2.2192	4.4381

speeds above 4.8 m/s with some locations like Katsina and Kano having annual mean wind speeds above 7.0 m/s. Fig. 3(a and b) depicts the monthly variations of mean wind speeds and average power densities of the six sites and it further corroborated the fact that Kano and Katsina regions are very windy.

The wind speed has a maximum value of 9.839 m/s in Katsina (June) while the minimum wind speed is recorded in October as 3.397 m/s in Kaduna. The annual minimum mean wind speed is obtained at Potiskum with a value of 4.804 m/s whereas the maximum value of annual mean wind speed is computed as 7.767 m/s in Kano. The average wind power density follows similar trend as the mean wind speeds (Fig. 3), with the highest value recorded in Katsina in June as 654.77 W/m^2 whereas the minimum value is got in Kaduna as 26.90 W/m^2 in October; similar trend follows for the recorded monthly energies, with Katsina and Kaduna having the highest and least values in that order (Table 5).

Moreover, the maximum annual value of power density and energy for the six sites selected is computed as 368.92 W/m^2 and 3224.45 kWh/m^2/year in Kano while minimum is obtained as 103.14 W/m^2, 901.75 kWh/m^2/year for the annual average power density and energy respectively at Potiskum. Other values of monthly and annual mean wind speed, average power density together with energy for the remaining locations considered at 10 m height are listed in Tables 4 and 5.

According to the international system of wind classification [20], it can be concluded that Kano and Katsina with annual power densities 339.85 and 368.95 W/m^2 respectively fall under Class 6 and are considered very suitable for wind turbine applications; Gusau with annual mean power densities of 178.48 exist in Class 3 and will be suitable for wind energy development using taller wind turbine towers while Kaduna, Bauchi and Potiskum will be considered marginal for wind power development having fallen under Class 2 with mean annual power density of 109.30, 120.50 and 103.14 W/m^2 respectively.

Two seasons (dry and rainy) are prominent in Nigeria; these seasons vary from one region to the other due to the changing prevailing winds as witnessed across the year by the respective zones. Table 6 shows the seasonal variations of wind characteristics for the selected locations at 10 m height with their corresponding monthly seasonal range. It can be seen that the seasonal mean wind speed ranged from 4.02 m/s at Potiskum to 7.96 m/s in Katsina both during the rainy season while the seasonal average wind power density varies from 46.31 to 391.31 W/m^2 in the rainy seasons at Potiskum and Katsina respectively.

Furthermore, Table 6 shows that seasonal effect on the wind speeds is less significant in Kano where changes in seasonal mean wind speeds relative to the annual mean speed, β, is less than 1% whereas, the seasonal effect is significant in Potiskum where β is about 25%. In addition, availability of wind speed computed for the locations shows that wind speed is above 5 m/s throughout the seasons in Katsina and Kano allowing WECS installed in the sites to produce energy 100% of the time while in Gusau, wind speed above 5 m/s will only be available at approximately 75 and 87.5% of the time during the rainy and dry season respectively. Kaduna, Bauchi and Potiskum will be having wind speed above 5 m/s at approximately 50 and 75%, 20 and 57%, 0 and 75% of the time in the rainy and dry seasons in that order.

The monthly variation of Weibull shape and scale parameters (k and c) are listed in Table 7 for the six selected locations. It can be observed that Weibull shape parameters k varies between 1.7374 in Bauchi (November) to 8.6197 in June at Kaduna. Hence, within these six sites, wind speed is most uniform in Kaduna in June while it is least uniform in November at Bauchi. However, the scale parameters c ranges from a minimum value of 3.6837 m/s in October in Kaduna to 10.6748 m/s in Katsina (June).

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 (1971–2007) is shown in Fig. 4. It can be observed from the trend of plotted curves that Potiskum, Gusau, Kaduna and Kano have windier morning periods than afternoon; it could be due to the fact that solar intensity experience is always higher in the morning in these locations and drops down the day with the occurrence of low night time temperatures more prevalent during North-East trade winds crossing in the region. In addition, the difference in mean wind speeds between these two reported hours of the day is more pronounced during the dry season months. On the other hand, Bauchi has windy afternoon. At the time of this work, synoptical data were yet to be recorded for Katsina.

The whole year monthly probability density and cumulative frequency distributions of wind speeds for the six locations is depicted in Fig. 5. It can be seen in Fig. 5 that the peak of the probability density functions skewed toward the higher values of the mean wind speeds for all the sites considered. Further study of the figures show a tendency of obtaining wind speeds above 8 m/s only in all the months in Bauchi and Potiskum whereas there is only the likelihood of wind speeds above 6, 7, 10 and 11 m/s only in Kaduna, Gusau, Katsina and Kano respectively in all the months throughout the whole year of study. In addition, all the sites have monthly peak frequencies ranging from 21 to 41% with 21, 23, 26, 27, 31 and 41% for Bauchi (May), Potiskum (September/October), Katsina (September), Kano (October), Gusau (May) and Kaduna (August/September) respectively.

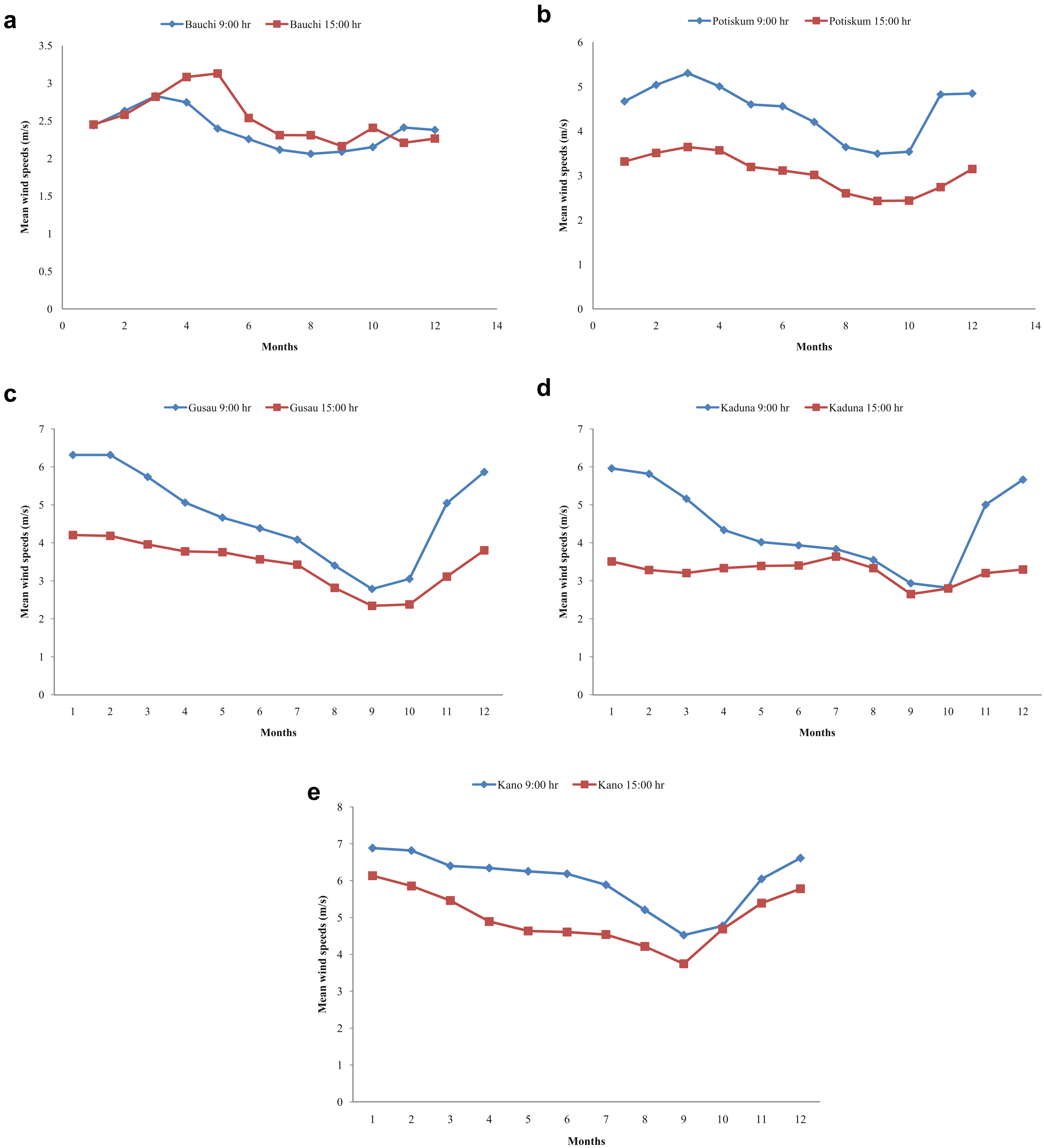

Fig. 4. Monthly variations of wind speeds at two synoptical hours of 9:00 and 15:00 for (a) Bauchi (b) Potiskum (c) Gusau (d) Kaduna and (e) Kano.

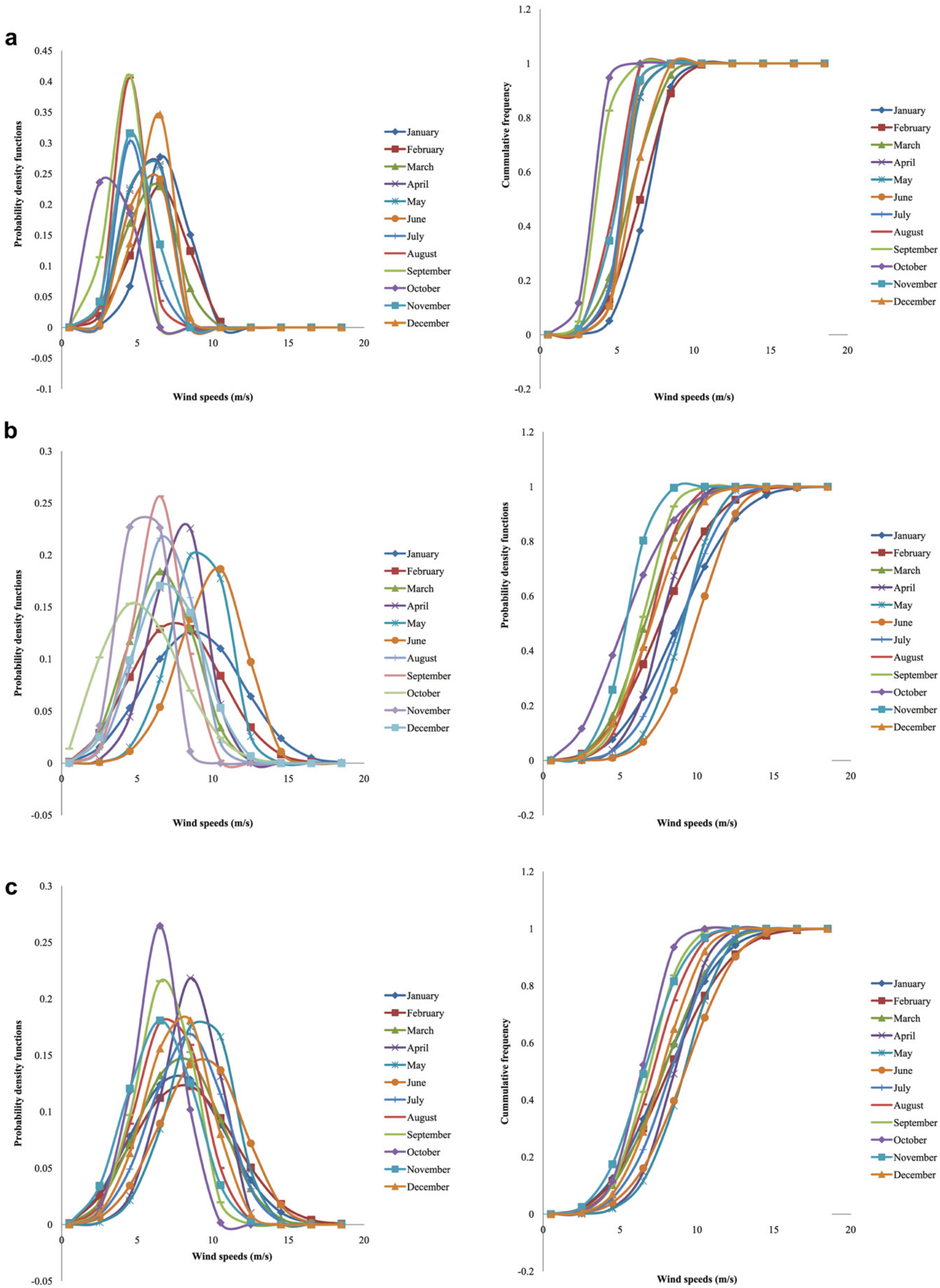

Fig. 5. Monthly wind speed probability density and cumulative distribution functions for (a) Kaduna (b) Katsina (c) Kano (d) Bauchi (e) Potiskum and (e) Gusau for whole year.

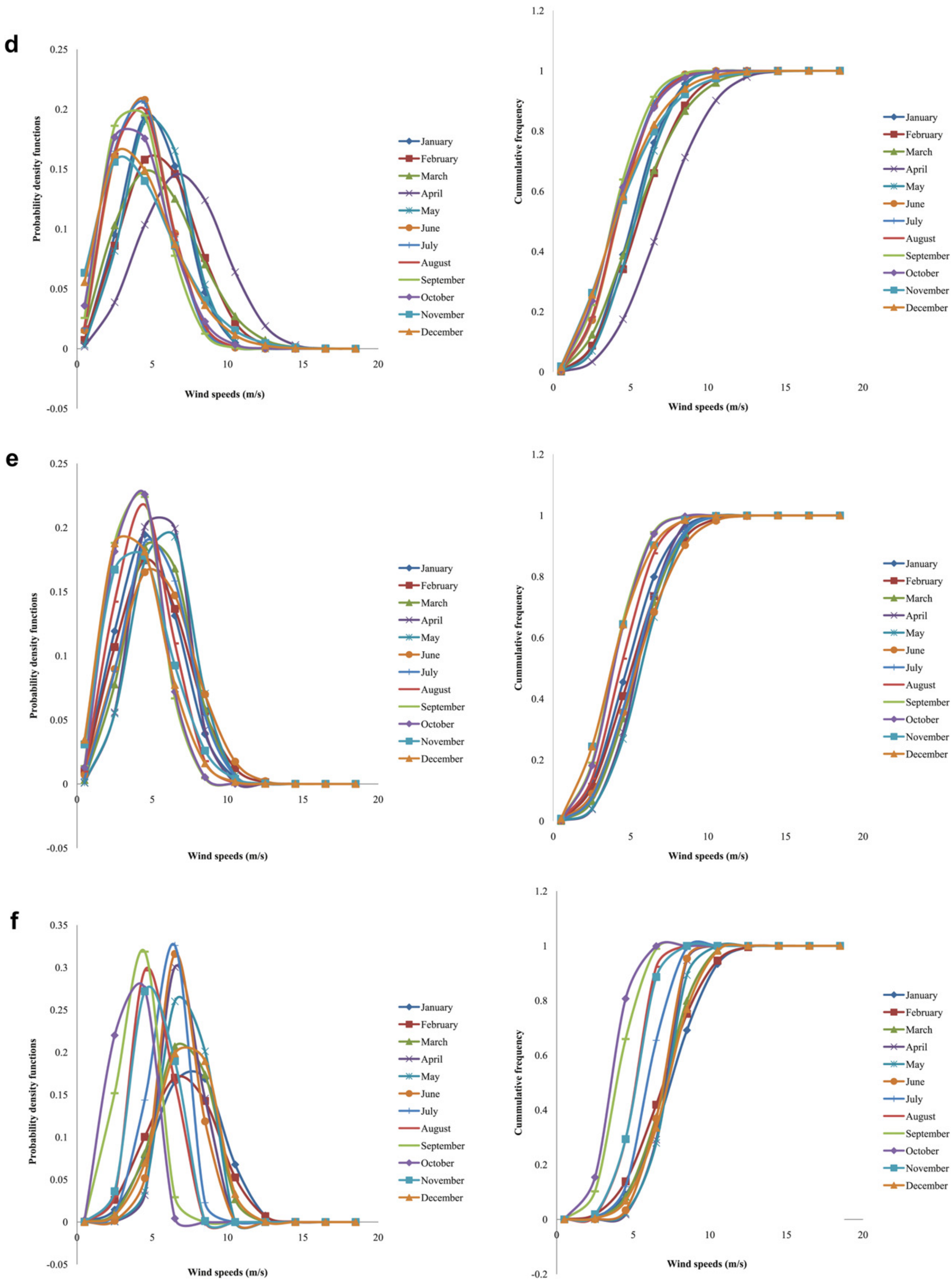

Fig. 5. (*continued*).

4. Conclusions

From the statistical data and computations, the following facts can be drawn from the study:

- All the locations considered have mean wind speeds above 4.8 m/s. Maximum mean wind speed value of 9.839 m/s is computed in June (Katsina) and a mimimum value of 3.397 m/s is got in October (Kaduna); while a minimum annual mean wind speed of 4.804 m/s is obtained in Potiskum, its maximum annual value is computed as 7.767 m/s in Kano.
- The annual values of power density and energy for the six sites selected is computed as 368.92 W/m^2, 3224.45 kWh/m^2/year in Kano and 103.14 W/m^2, 901.75 kWh/m^2/year in Potiskum for the maximum and minimum respectively.
- The Weibull shape parameters k varies between 1.7374 in Bauchi and 8.6197 in Kaduna while the scale parameter c ranges from 3.6837 to 10.6748 m/s at Kaduna and Katsina respectively.
- Based on the respective annual average wind power densities for the selected locations, Kano and Katsina are suitable for wind turbine applications and will also allow WECS to produce energy 100% of the time, Gusau will be suitable for wind energy development using tall wind turbine towers while Kaduna, Bauchi and Potiskum can only be considered marginal for wind power development.
- Potiskum, Gusau, Kaduna and Kano have higher wind speeds in the morning hours while Bauchi is windier in the afternoon periods than morning.

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