Applied Energy 88 (2011) 3197–3206

Contents lists available at ScienceDirect

Applied Energy

journal homepage: www.elsevier.com/locate/apenergy

Wind energy evaluation for electricity generation using WECS in seven selected locations in Nigeria

O.S. Ohunakin [a,*], M.S. Adaramola [b], O.M. Oyewola [c]

[a] Mechanical Engineering Department, Covenant University, P.M.B 1023, Ota, Ogun State, Nigeria
[b] Department of Energy and Process Engineering, Norwegian University of Science and Technology, Trondheim, Norway
[c] Department of Mechanical Engineering, University of Ibadan, Oyo State, Nigeria

ARTICLE INFO

Article history:
Received 12 November 2010
Received in revised form 14 February 2011
Accepted 18 March 2011
Available online 11 April 2011

Keywords:
Mean wind speed
Weibull distributions
Power density
Wind turbine
North-West geo-political region
Nigeria

ABSTRACT

This paper statistically examine wind characteristics from seven meteorological stations within the North-West (NW) geo-political region of Nigeria using 36-year (1971–2007) wind speed data measured at 10 m height subjected to 2-parameter Weibull analysis. It is observed that the monthly mean wind speed in this region ranges from 2.64 m/s to 9.83 m/s. The minimum monthly mean wind speed was recorded in Yelwa in the month of November while the maximum value is observed in Katsina in the month of June. The annual wind speeds range from 3.61 m/s in Yelwa to 7.77 m/s in Kano. It is further shown that Sokoto, Katsina and Kano are suitable locations for wind turbine installations with annual mean wind speeds of 7.61, 7.45 and 7.77 m/s, respectively. The results also suggest that Gusau and Zaria should be applicable for wind energy development using taller wind turbine towers due to their respective annual mean speeds and mean power density while Kaduna is considered as marginal. In addition, higher wind speeds were recorded in the morning hours than afternoon periods for this region. A technical electricity generation assessment using four commercial wind turbines were carried out. The results indicate that, while the highest annual power is obtained with Nordex N80–2.5 MW as 14233.53 kW/year in Kano, the lowest is in Yelwa having 618.06 kW/year for Suzlon S52. It is further shown that the highest capacity factor is 64.95% for Suzlon S52–600 kW in Kano while the lowest is 3.82% for Vestas V80–2 MW in Yelwa.

1. Introduction

Energy is considered a prime agent in the generation of wealth, a significant factor in economic development and the driving force of industrialization [1,2]. Nigeria has a high population growth rate and is heavily dependent on oil and gas as her main source of revenue, which coupled with policy instability to expose the economy to global energy dynamics thereby, rendering the industry as one of the most inefficient in satisfying the needs of the populace globally [2]. The demand for energy and particularly for electricity has witnessed an escalating growth due to the rising population together with the social and economic development of the country, which took an upswing since 1999 with the commencement of the democratic mode of governance in the country [2].

According to Ohunakin [2], energy outlook of Nigeria reflected that energy demand is very high and increasing geometrically while the supply remains inadequate, insecure, and irregular, it is decreasing with years. The mix hitherto is dominated by fossil sources which are fast being depleted apart from being environmentally unfriendly [2,3]. 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 resources which includes hydropower (large and small), solar, biomass and wind [2,3]. Some parts of Nigeria are 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 [2].

Wind is an inexhaustible resource whose energy utilization has been increasing around the world at an accelerating pace while the development of new wind projects continues to be hampered by the lack of reliable and accurate wind resource data in many parts of the world, especially in the developing countries. Such data are needed to enable governments, private developers and other investors determine the priority that should be given to wind energy utilization and to identify potential areas that might be suitable for its development [4]. They also noted that the most important parameter for evaluation of wind energy resources is the wind speed and any choice of wind turbine design must be based on

* Corresponding author. Tel.: +234 8050961739; fax: +234 1 7900724.
E-mail address: olayinka.ohunakin@covenantuniversity.edu.ng (O.S. Ohunakin).

0306-2619/$ - see front matter © 2011 Elsevier Ltd. All rights reserved.
doi:10.1016/j.apenergy.2011.03.022

the mean wind velocity at the selected wind turbine construction site. However, wind energy potential is not easily estimated since it depends to a large extent on the site characteristics and topography [5]. But, an accurate wind resource assessment is an important and critical factor to be well understood for harnessing the power of the wind.

In order to determine the suitability of a site for wind energy development, the US Department of Energy's Federal Wind Energy Program, Battelle-Pacific Northwest Laboratory (PNL), numerically classified wind resources into different classes ranging from class 1 (lowest) to class 7 (highest) [6,7]. Each class represents a range of wind power density or a range of equivalent mean wind speed at specified height above ground level. In general, Class 4 and above are considered suitable for most wind turbine applications, Class 3 areas are suitable for wind energy development using taller wind turbine towers, Class 2 regions are considered marginal for wind power development and Class 1 regions are unsuitable.

1.1. Previous work

The characteristics and pattern of wind speed across Nigeria have been investigated by some researchers in the past. Due to accessibility to wind speed data information, some researchers reported wind speed data in one or two locations [e.g. 8–11] while others reported wind speed data across the country [e.g. 12–16]. Ojosu and Salawu [12] reported wind speed data from 1951–1975 from 22 stations across the country and they concluded that Sokoto area (in northern part) have highest wind speed of about 5.12 m/s in the month of June with annual mean of 3.92 m/s. Furthermore, they reported wind speed of about 2 m/s or less in the middle and southern areas. Adekoya and Adewale [13] based on wind data from 30 stations, reported that the mean wind speed in Nigeria is in the range of 1.5–4.1 m/s. In addition, they noted that the annual mean wind speed is equal to or greater than 2.5 m/s in the northern parts of the country while the mean wind of less than 2.5 m/s were observed in the southern locations. Similarly, based on wind data from 1979–1988 for 18 stations, Fagbenle and Karayiannis [14] reported that mean wind speeds in Nigeria ranged from about 2 m/s to about 4 m/s with highest mean speeds of about 3.5 m/s and 7.5 m/s in the southern and northern areas, respectively. Furthermore, Chineke [15] reported the monthly mean wind speed measured at 10 m height from 1961to 1990 in the 36 states capitals of Nigeria. Similar to previous studies, he reported that the monthly mean wind speed range from 1.3 m/s in Oshogbo in the south west to about 3.9 m/s in Jos (north central) and Katsina (north west) areas.

However, while the above cited studies reported that the wind speed in Nigeria varied from 2 m/s to 4 m/s, recent measured wind data presented by Fadare [16] shows that the annual mean wind speeds range from about 2 m/s to 9.5 m/s. The different in the range of wind speeds reported by these authors may be related to the period in which the wind data were recorded. While Adekoya and Adewale [13] and other researchers used wind speed data that ranged from 1951–1992 for their analysis, Fadare [16] on the other hand used recent data from 1983–2003 for his analysis. Furthermore, the higher measured wind data reported by Fadare [16] may be due to increment in wind speed as a result of deforestation activities across the country. Also, most recent wind data (1987–2007) reported by Fagbenle et al. [11] for two locations (Maiduguri and Potiskum) in the north-east part of the country is in agreement with Fadare [16] findings. For instance, while Ojosu and Salawu [12] reported that the monthly mean wind speed for Maiduguri and Potiskum varied from 2.22 m/s to 3.52 m/s and 2.16 m/s to 4.84 m/s respectively, Fagbenle et al. [11] reported that

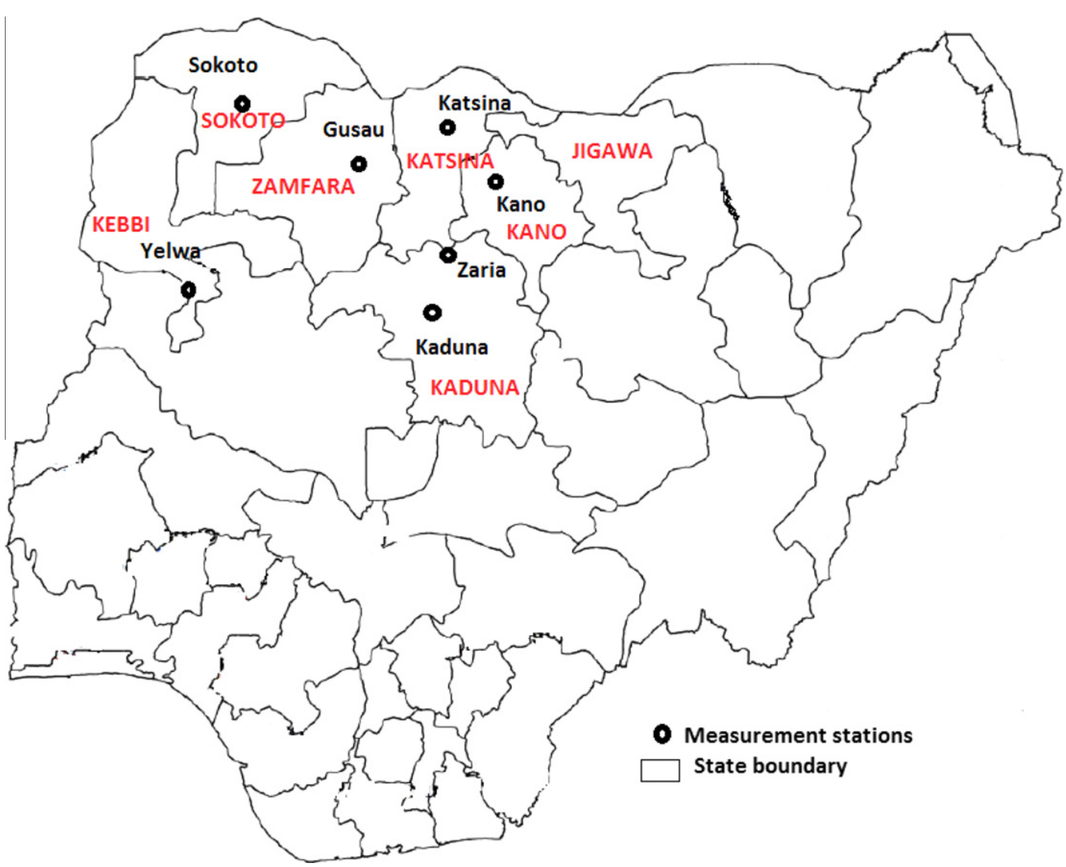

Fig. 1. Map of Nigeria showing the measurement stations in North-West geo-political region.

the monthly mean wind speed for these two locations respectively varied from 3.90 m/s to 5.85 m/s and from 4.35 m/s to 6.33 m/s. The observed difference is in agreement with finding of Fagbenle and Karayiannis [14]. These authors reported that the Weibull function scale parameter and shape parameter and hence, wind speed, depends on the period and duration when the wind data are collected.

1.2. Present work

As mentioned previously, the recent studies have shown that there is significant difference in recent wind speed data (1971–2007) and those based on wind data from around 1951 to 1992. Therefore, there is need to analysis the wind speed data across the country based on current or recent information, since update information about wind speed are essential if right decision have be made regarding the wind energy development. Most previous studies have identified the northern (especially the North-West) part of Nigeria as the more suitable region for wind energy resource development. This paper therefore aims at further investigating and quantifying the wind characteristics as well as the possibility of adopting wind energy as an electricity generation source in selected locations in North-West geo-political region of Nigeria, based on recent long range wind data from seven meteorological stations spreading across the region (see Fig. 1). Furthermore, most previous studies focus on the wind speed and wind power density distribution while less attention was given to evaluation of the performance commercial wind turbines. The information about the performance wind turbine will be helpful to government and any organization to make an informed decision regarding investment in wind energy resource in this part of the country. In addition, business investors will also find this information useful.

2. Wind data and analysis

2.1. Wind speed data

The wind data used in this study were obtained from the Nigerian Meteorological Agency (NIMET), Oshodi, Lagos. The geographical coordinates of the meteorological stations, where wind speed data were captured at 10 m height by a cup-generator anemometer, are given in Table 1. 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 Yelwa, Zaria, Sokoto, Gusau, Kaduna, Katsina and Kano. The recorded wind speeds were computed as the mean of the speed for each month.

2.2. Data analysis

Even though ANN technique is proved to be efficient and accurate [16] when compared with other statistical techniques commonly used in wind data modeling, the two-parameter Weibull probability distribution function is the most appropriate distribution function for wind speed data analysis [17]. In addition, it gives a better fit for measured monthly probability density distributions than other statistical functions [6,17,18]. Therefore, the two-parameter Weibull probability density function was used in this study. The Weibull probability density function is given as [18]:

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

where $f(v)$ = the probability of observing wind speed (V), k = dimensionless Weibull parameter and c = the Weibull scale parameter (m/s). The scale factor could be related to the mean wind speed through the shape factor and this factor determines the uniformity of the wind speed in a given site; the uniformity of the wind at any given site increases with increasing value of k for a given scale parameter. The cumulative distribution $F(V)$ is the integral of the probability density function and it is expressed as [18]:

$$F(V) = 1 - e^{-(V/c)^k} \tag{2}$$

The monthly and annual values of Weibull parameters were calculated using standard deviation method among other methods listed in [19]. This method is useful due to the following [20–22]: (i) appropriate in situations, where only the mean wind speed and standard deviation are available, (ii) it gives better results than graphical method and (iii) its relatively simple expression when compared with other methods. In addition, most other methods may require more detailed wind data (which in some cases are not readily available) for the determination of the Weibull distribution shape and scale parameters. The shape and scale factors are thus computed from Eqs. (3) and (4) given by [23]:

$$k = \left(\frac{\sigma}{V_m}\right)^{-1.086} \quad (1 \leqslant k \leqslant 10) \tag{3}$$

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

where σ is the standard deviation, V_m is the mean wind speed (m/s) and $\Gamma(x)$ is the gamma function which is defined as [20]:

$$\Gamma(x) = \int_0^\infty t^{x-1} e^{-t} dt \tag{5}$$

The shape factor and scale factor are related by [23]:

$$V_m = c\Gamma\left(1 + \frac{1}{k}\right) \tag{6}$$

The two significant wind speeds for wind energy estimation are the most probable wind speed (V_{mp}), and the wind speed carrying maximum energy (V_{maxE}). They can be expressed respectively as [5]:

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

$$V_{maxE} = c\left(\frac{k+2}{k}\right)^{1/k} \tag{8}$$

Wind turbine system operates at its maximum efficiency at its design or rated wind speed and hence, it is essential that the rated wind speed and the wind speed carrying maximum energy should be as close as possible [24].

2.3. Extrapolation of wind speed at different hub height

In most cases, the available wind data are measured at height different from the hub height and since the wind speed at the hub height is of interest for wind power application, the available

Table 1
Geographical coordinates of North-West region.

Station	Latitude °N	Longitude °E	Elevation (m)
Yelwa	10.53	04.45	244.0
Zaria	11.06	07.41	110.9
Sokoto	12.28	04.13	220.0
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

wind speeds are adjusted to the wind turbine hub height using the following Power law expression [18]:

$$\frac{V}{V_o} = \left(\frac{h}{h_o}\right)^{\alpha} \tag{9}$$

where V is the wind speed at the required height h, V_o is wind speed at the original height h_0, and α is the surface roughness coefficient and is assumed to be 0.143 (or 1/7) in most cases. However, the surface roughness coefficient can also be determined from the following expression [4]:

$$\alpha = [0.37 - 0.088\ln(U_o)] \Big/ \left[1 - 0.088\ln\left(\frac{h_o}{10}\right)\right] \tag{10}$$

Alternatively, the Weibull probability density function can be used to obtain the extrapolated values of wind speed at different heights. This approach is used in this study. The Weibull parameters at measurement height are related to the parameters at the wind turbine height by the following expressions [18,25]:

$$c(h) = c_o\left(\frac{h}{h_o}\right)^{n} \tag{11}$$

$$k(h) = k_o\left[1 - 0.088\ln\left(\frac{h_o}{10}\right)\right] \Big/ \left[1 - 0.088\ln\left(\frac{h}{10}\right)\right] \tag{12}$$

where c_o and k_o are the scale factor and shape parameter respectively at the measurement height h_o and h is the hub height. The exponent n is defined as:

$$n = [0.37 - 0.088\ln(c_o)] \Big/ \left[1 - 0.088\ln\left(\frac{h}{10}\right)\right] \tag{13}$$

2.4. Wind power density

The power of wind can be estimated by using the following equation [4]:

$$P(V) = \frac{1}{2}\rho A v_m^3 \tag{14}$$

However, the wind power density (wind power per unit area) based on the Weibull probability density function can be calculated using the following equation [18]:

$$p(V) = \frac{P(V)}{A} = \frac{1}{2}\rho c^3 \Gamma\left(1 + \frac{3}{k}\right) \tag{15}$$

where $P(V)$ = the wind power (W), $p(V)$ = the wind power density (W/m^2), ρ = the air density at the site (assumed to be 1.21 kg/m^3 in this study), A = the swept area of the rotor blades (m^2).

2.5. Estimation of wind energy

The extractible mean daily and monthly energy, together with the annual energy are defined by the following relationships in Eqs. (16)–(18) [26]:

$$\overline{E}_j = 24 \times 10^{-3} \quad \overline{P}_T \ (\text{kW h/m}^2) \tag{16}$$

$$\overline{E}_{jm} = 24 \times 10^{-3} \quad d\overline{P}_T \ (\text{kW h/m}^2) \tag{17}$$

$$\overline{E}_a = \sum_{n=1}^{12} \overline{E}_{jm} \ (\text{kW h/m}^2/\text{year}) \tag{18}$$

where $\overline{P}_T = p(V)$ in (W/m^2) and d is the number of days in the month considered.

2.6. Power output of wind turbine and capacity factor

By matching the actual wind frequency distribution of a site with a suitable model of the WECS, the energy output can be maximized [18]. Hence, a wind energy conversion system can operate at maximum efficiency only if it is designed for the particular site, since the rated power, cut-in and cut-off wind speeds must be defined based on the site wind characteristics. These parameters can be chosen so as to maximize the delivered energy for a given amount of available wind energy. The mean power output $P_{e,ave}$ and capacity factor C_f are important performance parameters of WECS. While $P_{e,ave}$ determines the total energy production, C_f represents the fraction of the mean power output over a period of time to the rated electrical power (P_{eR}) [4,18]. The mean power output $P_{e,ave}$ and capacity factor C_f of a wind turbine can be calculated using the following expressions [18]:

$$P_{e,ave} = P_{eR}\left(\frac{e^{-\left(\frac{v_c}{c}\right)^k} - e^{-\left(\frac{v_r}{c}\right)^k}}{\left(\frac{v_r}{c}\right)^k - \left(\frac{v_c}{c}\right)^k} - e^{-\left(\frac{v_f}{c}\right)^k}\right) \tag{19}$$

$$C_f = \frac{P_{e,ave}}{P_{eR}} \tag{20}$$

where v_c, v_r, v_f are the cut-in wind speed, rated wind speed and cut-off wind speed respectively. For an investment in wind power

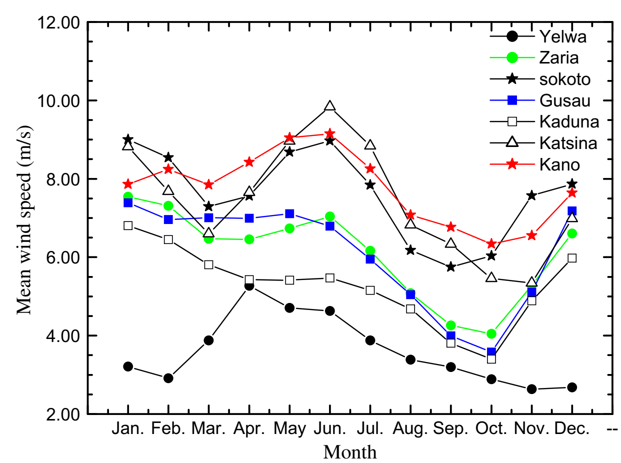

Fig. 2. Monthly mean wind speeds variations at 10 m height.

Table 2
Seasonal variations of wind characteristics for the seven sites at 10 m height for the period 1971–2007.

Season	Mean wind speed (m/s) @ 10 m	V_{mp}	V_{maxE}	Average power density (W/m^2) @ 10 m
Yelwa				
Rainy season	3.99	4.00	5.07	58.74
Dry season	3.06	3.14	3.71	22.81
Sokoto				
Rainy season	7.18	7.49	7.96	264.92
Dry season	7.82	8.08	9.17	347.67
Gusau				
Rainy season	5.45	5.67	6.25	120.83
Dry season	6.42	6.63	7.55	207.31
Kaduna				
Rainy season	4.78	4.99	5.27	74.61
Dry season	5.52	5.75	6.36	126.70
Katsina				
Rainy season	7.96	8.27	9.37	391.31
Dry season	7.19	7.22	9.03	314.13
Zaria				
Rainy season	5.64	5.89	6.34	130.80
Dry season	6.31	6.57	7.31	188.51
Kano				
Rainy season	7.81	8.03	9.51	371.03
Dry season	7.74	7.85	9.60	367.86

to be cost effective, the capacity factor should generally lie between 0.25 and 0.40; $C_f \geqslant 0.40$ indicate strong interaction between the wind turbine system and the environment [27].

3. Results and discussion

3.1. Mean wind speed and seasonal variation

The monthly variations of mean wind speed for selected sites at height of 10 m are shown in Fig. 2. The minimum mean wind speed in this region is observed to be about 2.64 m/s and was observed in November at Yelwa while the maximum mean wind speed of about 9.83 m/s was observed in the month of June at Katsina. Furthermore, four of the sites (Zaria, Sokoto, Gusau and Kaduna) have their highest mean wind speeds of 7.54, 9.00, 7.39 and 6.90 m/ respectively, in the month of January. However, Zaria, Gusau and Kaduna have their lowest mean wind speed values in October while Sokoto has its lowest value of mean wind speed in September. Katsina and Kano have the maximum mean wind speeds occurring in June while the minimum value was recorded in November for Katsina and in October for Kano. Yelwa on the other hand, has its maximum mean wind speed in April and minimum in November.

The observed trend in the monthly mean wind speed is related to the elevation of each site above sea level and their weather condition during the year. The North-West region of Nigeria is generally characterized by two seasons (rainy and dry) and the selected locations having different elevations ranging from 110.9 m in Zaria to 645.4 m in Kaduna (Table 1). In addition, Zaria, Sokoto, Gusau, Kaduna, Katsina and Kano have similar seasonal duration range from June to September (rainy season) and October to May for the dry season, whereas Yelwa is having rainy season between April to October and dry season from November to March. Topography in the region is generally characterized by undulating land, with sand dunes of various sizes spanning across the region with savannah vegetation and a semi-arid climate. Harmattan is experienced across the zone during dry season as a result of the

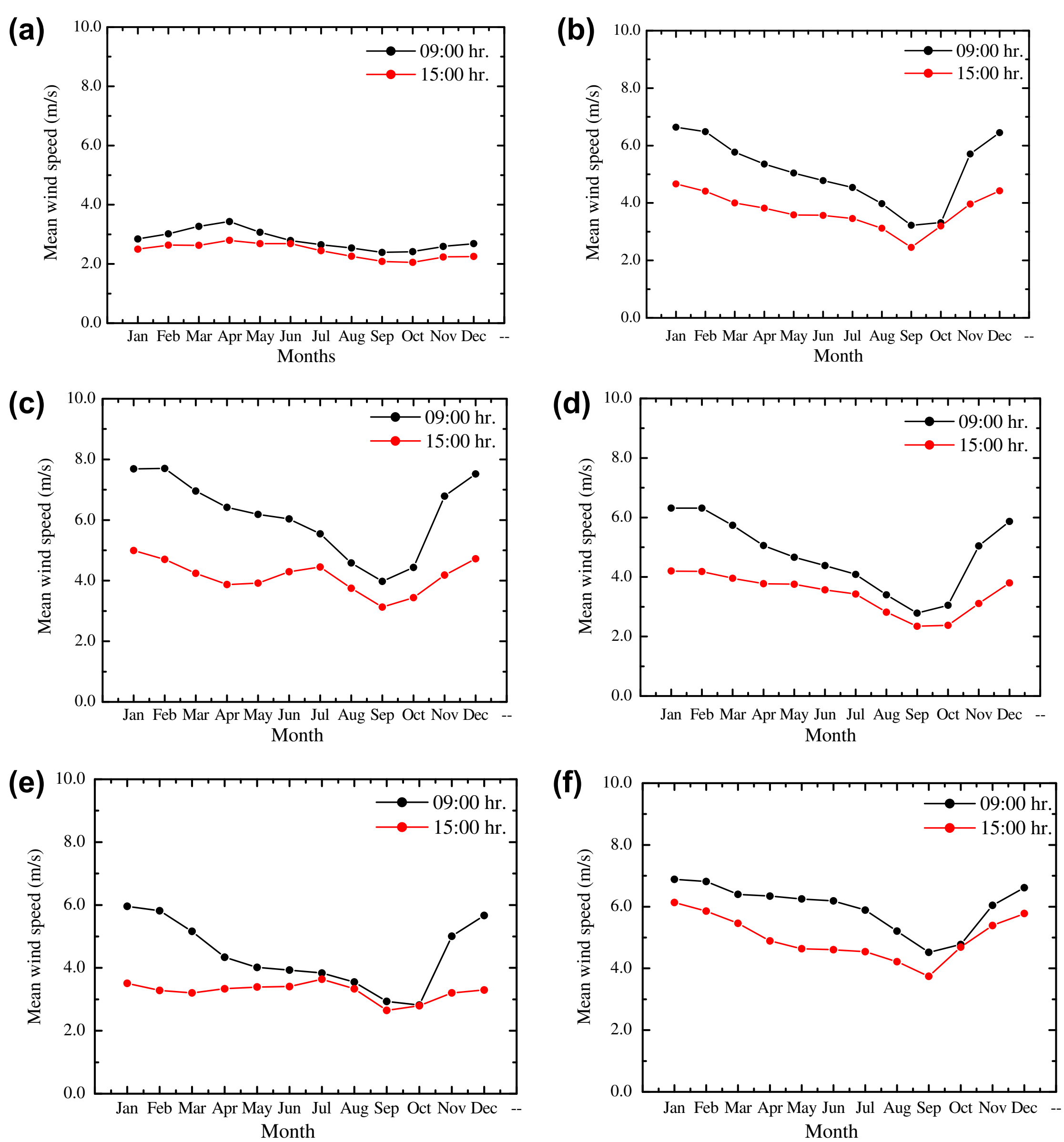

Fig. 3. Monthly variations of wind speeds at two synoptical hours of 9:00 and 15:00 at 10 m height for (a) Yelwa, (b) Zaria, (c) Sokoto, (d) Gusau, (e) Kaduna and (f) Kano.

North-East trade wind blowing across the whole area from Sahara and resulting in significantly low temperature during this period, with variation of a hot afternoon and a cold morning. However, the rainy season is characterized by slow moving westerly winds, whereas in Yelwa, strong squalls are observed to accompany the westerly winds at start of the rainy season (April), bringing about a high wind speed and later followed by a continual decrease in wind speed to a least at the commencement of dry period (November).

The effect of seasonal variation on the annual mean wind speed distribution is presented in Table 2. This table shows that seasonal effect on the mean 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%. However, the seasonal effect is significant in Yelwa, where β is about 26%. In addition, it is observed that the mean speed ranges from 3.06 m/s in Yelwa (dry season) to 7.96 m/s in Katsina (rainy season) while the mean power density is between 22.81 and 371.03 W/m^2 for Yelwa (dry season) and Kano (rainy season) respectively. Furthermore, the mean wind speed is generally stronger during the dry season in Sokoto, Gusau, Kaduna, and Zaria; this is in agreement with results of Fagbenle and Karayiannis [14] for Sokoto. On the other hand, Yelwa, Katsina and Kano have stronger mean wind speed in the Rainy season. This could be attributed to: (i) changing temperature stratification and (ii) vertical exchange in momentum more prominent during the rainy seasons in the respective sites, thus causing an increase of wind speed as a result of thermal convection.

Fig. 3 shows 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. At the time of this research work, synoptical data were only available for six locations wind data while that of Katsina is yet to be reported. Similar to the results of Fagbenle and Karayiannis [14] for Sokoto, it can be observed from the trend of plotted curves that irrespective of the location higher mean wind speeds occur in the morning hour periods. This could still be connected to thermal convection causing an increase of wind speeds as previously discussed. Furthermore, the difference in mean wind speeds between these two reported hours of the day is more pronounced during the dry season months. In addition, Zaria, Sokoto, Gusau, Kaduna, and Kano (Fig. 3b–f) showed similar pattern for the two study hours with a continual steady decrease in wind speeds during the rainy seasons as a result of the slow moving Westerly winds, followed by a gradual increase in wind speeds from the beginning of the dry season due to the arrival of the North-West trade winds. Higher wind speed noticeable at the start of the rainy season in Yelwa (April) as shown in Fig. 3a could be said to be the strong squalls trailing the Westerly winds as earlier discussed.

3.2. Monthly mean power and energy density

The monthly variations of mean power density and mean energy density for selected sites at height of 10 m are shown in Fig. 4. As expected, the monthly mean power density (Fig. 4a) follows the same trend as the mean wind speed (see Fig. 2). The monthly mean power density in this region ranges from about 12.74 W/m^2 (December) in Yelwa to 654.77 W/m^2 (month) in Katsina. In addition, based on the monthly mean power density, the wind resources in Kano fall into Class 4 or higher for all the months of the year except in October when it falls into Class 3. The wind resource can be classified into Class 3 or higher for Katsina and Sokoto for all the months except in September and November respectively, when they fall into Class 2. Therefore, these three locations can be considered as excellent sites for wind energy development. In addition, it can be observed that wind resources in both Gusau and Zaria fall into Class 3 in most of the

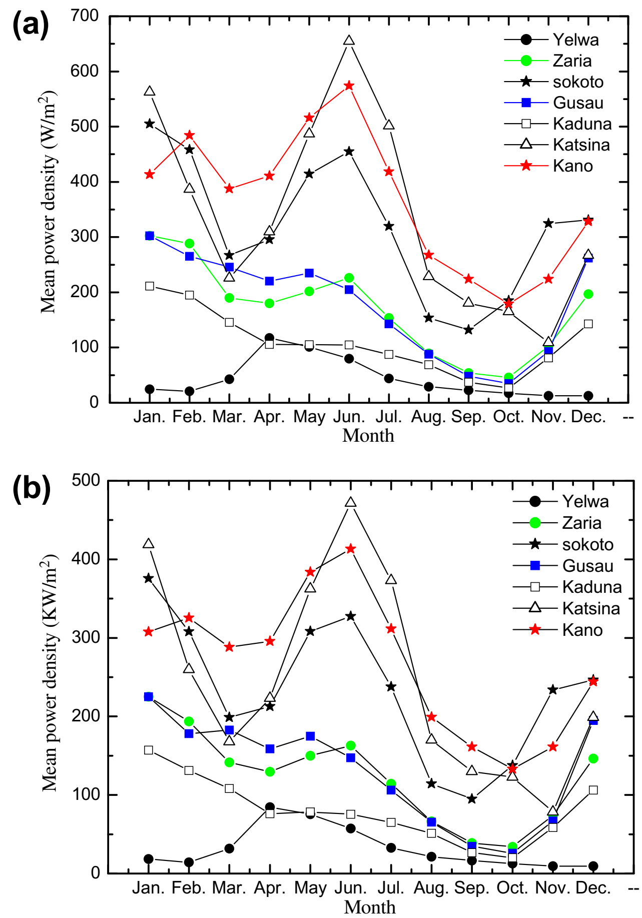

Fig. 4. Monthly variations for (a) mean power density and (b) mean energy density at 10 m height.

months except between August and November. Thus, these locations are suitable for wind energy development but taller wind turbine towers will be required to enhance the WECS performance. The figure also shows that Kaduna and Yelwa in general, falls into Class 2 and Class 1 respectively. Hence, Kaduna can therefore, be marginally considered for wind energy development while Yelwa can be considered unsuitable.

The mean monthly energy density follows the same characteristics similar to the monthly power density pattern (Fig. 4b). The monthly mean power density in this region ranges from about 9.28 kW h/m^2 (December) in Yelwa to 471.44 kW h/m^2 (June) in Katsina.

The summary of the annual wind characteristics for the seven sites for the period 1971–2007 and the wind resource classes of these sites are shown in Table 3. The annual mean wind speed

Table 3
Annual wind characteristics for the seven sites at 10 m height for the period 1971–2007.

Locations	Annual mean wind speed (m/s)	Annual mean power density (W/m^2)	Annual energy (kW h/m^2/year)	Class
Yelwa	3.61	43.77	383.65	1
Sokoto	7.61	320.09	2795.76	6
Gusau	6.09	178.48	1560.83	3
Kaduna	5.27	109.30	953.92	2
Katsina	7.45	339.85	2976.29	6
Zaria	6.08	169.27	1476.99	3
Kano	7.77	368.92	3224.44	6

ranges from 43.77 W/m^2 in Yelwa to 368.92 W/m^2 in Kano, and annual mean wind lies between 3.61 m/s in Yelwa and 7.77 m/s in Kano. Similarly, Kano has the highest annual mean energy of 3224.44 kW h/m^2 while Yelwa has the least value of 383.65 kW h/m^2.

3.3. Correlation between monthly mean wind speed and power density

The relationship between the monthly mean power density and the monthly mean wind speeds for the locations are presented in Fig. 5. Also presented in Fig. 5 is the correlation curve for all the

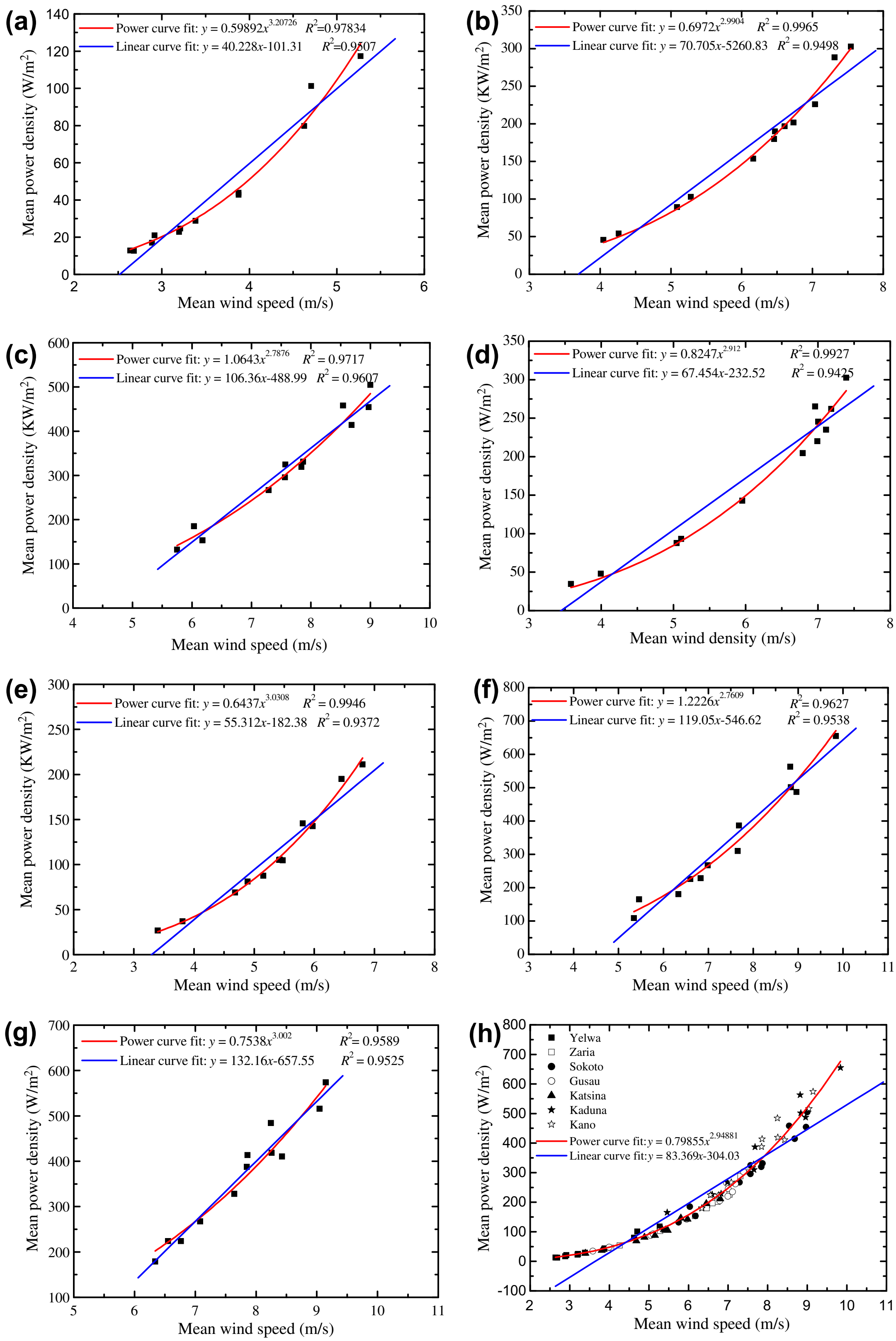

Fig. 5. Selected plot of monthly mean power density against monthly mean wind speed (a) Yelwa, (b) Zaria, (c) Sokoto, (d) Gusau, (e) Kaduna, (f) Katsina, (g) Kano and (h) All locations.

locations put together. Both power curve fit and linear curve fit methods were used to find the correlation between the mean power density and mean wind speed. It can be observed that both methods indicated a strong correlation ($R^2 > 0.91$) between the two variables. However, irrespective of the locations, power curve fit method provides higher R^2 value than the linear curve fit method and hence, it may be considered to be a better correlation method for wind data analysis. In addition, the exponent of the power curve fit varied from 2.76 (Kano, Fig. 5f) to 3.21 (Yelwa, Fig. 5a), which is in agreement with the cubic wind speed relationship with the power density. Furthermore, the observed strong linear correlation between these variables is due to the Weibull probability density function $f(V)$ which is involved in the expression of (V^3) [5]. Fig. 5h shows that there is an excellent power fit correlation between the mean power density and wind speed for the sites reported in this study. The exponent of the power curve fit equation is approximately 3. Therefore, the mean power density (W/m^2) for the North-West region of Nigeria as a function of the mean wind speed (U m/s) can be expressed in form of power law and it is given as:

$$\frac{P}{A} = 0.79855U^{2.94881} \tag{21}$$

3.4. The weibull parameters and site useful wind speed

The monthly and annual variation of Weibull parameters (k and c) at the seven sites at the measurement height (10 m) are shown in Tables 4. The lowest monthly value of Weibull shape parameter k is obtained as 2.31 in the month of October in Katsina and the highest value of 10.13 in the month of June in Sokoto. Therefore, in this region, the wind speed is most uniform in Sokoto in June while it is least uniform in Katsina in October. The monthly scale parameter c has the lowest value of 2.88 m/s in the month of December in Yelwa and highest value of 10.68 m/s in the month of June in Katsina. The annual shape parameter varied between 4.04 in Kano and 6.11 in Kaduna while the annual scale parameter varied between 3.98 m/s in Yelwa and 8.57 m/s in Kano.

Table 5 shows the monthly and annual values for the most probable wind speed (V_{mp}), and the wind speed carrying maximum energy (V_{maxE}) at height of 10 m. It can be observed that Kano has the highest annual values of 7.91 m/s and 9.57 m/s among the selected sites, while Yelwa has the least annual values of 3.64 m/s and 4.50 m/s for V_{mp} and V_{maxE} respectively. According to Bagiorgas et al. [5], the most probable wind speed (V_{mp}) is a statistical characteristic which is not directly connected to wind energy. Therefore, it does not necessarily mean that Kano has much higher wind potentials than other locations considered. However, as was mentioned before, the efficiency of a WECS is closely related to these parameters especially V_{maxE} which should be as close as possible to design or rated wind speed of the system. Therefore, wind turbine installed in Kano, Katsina and Sokoto would likely produce more power than other locations.

However, monthly consideration shows that Katsina has the highest values of 10.27 m/s in June and 11.45 m/s in January for V_{mp} and V_{maxE} respectively while Yelwa is having the least monthly values in November and December with 2.75 m/s and 2.99 m/s in V_{mp} and V_{maxE} respectively. As expected, the sites wind speed

Table 4
Monthly and annual variation of Weibull parameters (k and c) for the seven sites at 10 m height.

Month	Yelwa		Zaria		Sokoto		Gusau		Kaduna		Katsina		Kano	
	k	c (m/s)	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	4.0131	3.5401	4.8162	8.2330	5.1713	9.7831	3.9549	8.1584	6.0435	7.3304	3.2127	9.8476	2.9831	8.8023
February	3.0152	3.2643	4.1369	8.0501	4.1800	9.4000	3.5059	7.7348	4.3374	7.0848	2.9814	8.6057	2.9114	9.2444
March	4.2111	4.2660	4.9220	7.0546	5.2699	7.9145	4.5839	7.6660	4.0625	6.4004	3.5233	7.3328	3.3603	8.7401
April	3.3679	5.8711	6.1633	6.9499	5.5094	8.1923	8.0037	7.4258	6.6754	5.8182	5.2476	8.3157	5.3942	9.1389
May	2.4415	5.3071	6.5752	7.2206	9.5395	9.1459	7.1541	7.5957	6.5069	5.8123	5.7532	9.6817	5.0327	9.8468
June	3.3306	5.1571	7.4738	7.4961	10.127	9.4231	7.0778	7.2545	8.6197	5.7923	5.3468	10.6748	3.9530	10.099
July	3.9063	4.2843	6.9021	6.5946	6.4462	8.4166	5.7711	6.4311	8.3397	5.4594	4.3454	9.7056	4.0421	9.1026
August	4.0365	3.7319	5.6591	5.4999	7.2632	6.5916	5.4437	5.4661	6.0243	5.0477	4.4975	7.4803	3.8999	7.8229
September	4.9352	3.4844	4.9778	4.6416	5.1192	6.2539	3.9097	4.4151	6.0693	4.1039	4.7188	6.9225	4.3854	7.4229
October	4.7477	3.1543	5.2265	4.3958	3.0423	6.7522	3.8868	3.9598	5.3878	3.6837	2.3110	6.1638	4.8710	6.9143
November	4.8948	2.8761	4.9889	5.7536	3.9709	8.3545	4.9844	5.5628	5.1122	5.3193	4.5991	5.8480	3.4194	7.2918
December	6.5946	2.8753	5.5512	7.1530	5.6461	8.5114	4.7636	7.8455	6.1295	6.4321	3.5413	7.8606	4.1854	8.4089
Annual	4.1245	3.9843	5.6161	6.5869	5.9404	8.2283	5.2533	6.6263	6.1090	5.6904	4.1732	8.2032	4.0364	8.5696

Table 5
Average monthly and annual values of the most probable wind speed (V_{mp}) and maximum wind speed (V_{maxE}) at 10 m height for the period 1971–2007.

Month	Yelwa		Zaria		Sokoto		Gusau		Kaduna		Katsina		Kano	
	V_{mp}	V_{maxE}	V_{mp}	V_{maxE}	V_{mp}	V_{maxE}	V_{mp}	V_{maxE}	V_{mp}	V_{maxE}	V_{mp}	V_{maxE}	V_{mp}	V_{maxE}
January	3.296	3.915	7.845	8.849	9.385	10.422	7.579	9.048	7.114	7.685	8.768	11.449	7.676	10.454
February	2.856	3.864	7.529	8.855	8.805	10.322	7.028	8.798	6.669	7.732	7.504	10.225	8.000	11.063
March	4.000	4.678	6.736	7.561	7.605	8.413	7.265	8.296	5.970	7.063	6.669	8.331	7.868	10.043
April	5.288	6.743	6.753	7.274	7.899	8.666	7.303	7.636	5.678	6.051	7.987	8.843	8.798	9.689
May	4.277	6.781	7.042	7.518	9.040	9.330	7.438	7.862	5.665	6.057	9.366	10.196	9.423	10.524
June	4.632	5.939	7.353	7.738	9.327	9.592	7.100	7.514	5.709	5.934	10.269	11.328	9.380	11.201
July	3.972	4.763	6.447	6.842	8.199	8.777	6.223	6.771	5.376	5.602	9.139	10.589	8.485	10.054
August	3.478	4.123	5.314	5.802	6.459	6.816	5.266	5.789	4.898	5.234	7.074	8.118	7.251	8.699
September	3.328	3.733	4.437	4.968	5.994	6.670	4.094	4.907	3.984	4.301	6.582	7.461	6.997	8.087
October	3.001	3.397	4.221	4.677	5.923	7.972	3.668	4.406	3.546	3.906	4.823	8.073	6.596	7.420
November	2.745	3.085	5.501	6.156	7.766	9.258	5.318	5.952	5.098	5.674	5.544	6.326	6.590	8.343
December	2.805	2.993	6.902	7.561	8.223	8.981	7.467	8.445	6.248	6.735	7.066	8.807	7.878	9.231
Annual	3.640	4.501	6.34	6.983	7.885	8.768	6.312	7.119	5.495	5.998	7.566	9.146	7.912	9.567

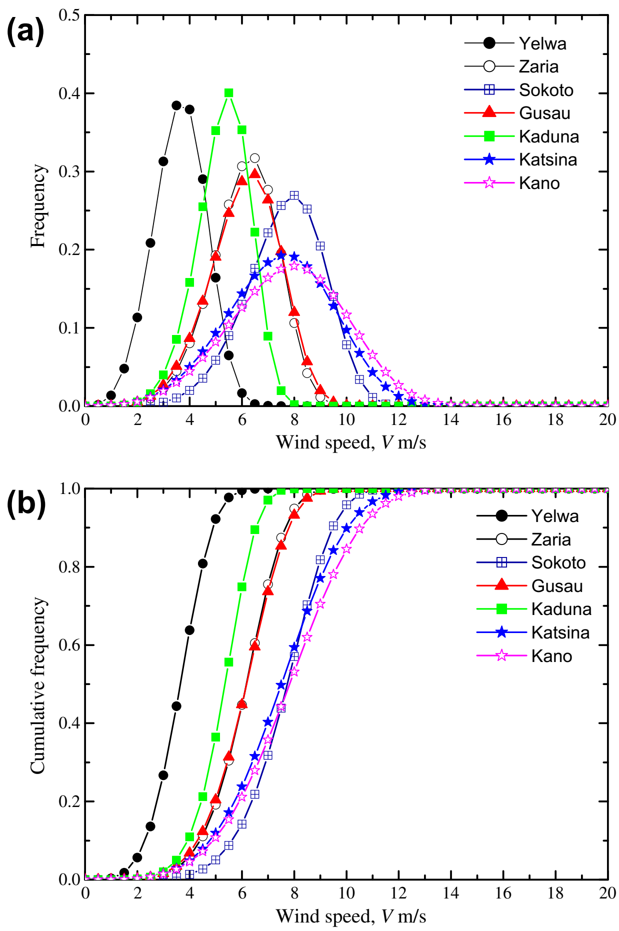

Fig. 6. Weibull annual wind speed distribution (a) frequency distribution and (b) cumulative distribution.

Table 6
Characteristics of the selected wind turbines.

Characteristics	Suzlon S52-600 kW	Suzlon S82-1.5 MW	Vestas V80-2 MW	Nordex N80-2.5 MW
Hub height (m)	75	78.5	67	70
Rated power Pr (kW)	600	1500	2000	2500
Sweep area (m^2)	2124	5281	5027	5026
Cut-in wind speed V_c (m/s)	4	4	4	3
Rated wind speed V_r (m/s)	13	14	16	15
Cut-off wind speed V_f (m/s)	25	20	25	25

parameters varies with the season and the maximum values of 8.27 m/s and 9.60 m/s respectively are observed for V_{mp} and V_{maxE} in Katsina (rainy period) and Kano (dry season).

3.5. Wind speed frequency distribution

The annual probability density frequency and cumulative distributions of wind speed for the seven locations obtained from the Weibull distribution functions are shown in Fig. 6. The probability density function indicates the fraction of time for which a given wind speeds possibly prevails in a location. As expected the peak of the density function frequencies of all the sites skewed towards the higher values of mean wind speed (Fig. 6a). The peak of the probability density function curve indicates the most frequent velocity. It can be observed from Fig. 6a that the most frequent wind speed expected in Yelwa, Zaria, Sokoto, Gusau, Kaduna, Katsina and Kano are about 3.5, 6.5, 8, 6.5, 5.5, 7.5 and 8 m/s respectively. These values agree with the annual values of V_{mp} presented in Table 5. In addition, the chances of wind speed exceeding 8, 11, 13, 11, 9, 15 and 16 m/s in Yelwa, Zaria, Sokoto, Gusau, Kaduna, Katsina and Kano were very limited. It can be observed that Katsina and Kano have the highest spread of the wind speed toward high wind speed among the seven locations.

The cumulative probability distributions of the wind speed in the seven locations (Fig. 6b) show a similar trend. The cumulative distribution function can be used for estimating the time for which wind speed is within a certain speed interval. For wind speeds greater or equal to 3 m/s cut-in wind speed, Yelwa, Zaria, Sokoto, Gusau, Kaduna, Katsina and Kano have frequencies of about 73.3%, 98.8%, 99.8%, 98.5%, 98.0%, 98.5% and 98.6% respectively, while the same locations respectively have frequencies of about 36.2%, 94.1%, 98.6%, 93.2%, 89.0%, 95.1% and 95.5%for wind speed of 4 m/s cut-in wind speed. This indicates that wind turbine system with cut-in wind speed of 3 m/s is suitable for all the locations. If a wind turbine system with design cut-in wind speed of 2.2 m/s is use in these sites as suggested by Ojosu and Salawu [12] for wind energy resource for electricity generation in Nigeria, all the sites will have frequencies of more than 90%.

3.6. Performance of selected wind turbines

Four wind turbines (Suzlon S52, Suzlon S82, Vestas V80 and Nordex N80) each with rated power (*Pr*) 600, 1500, 2000 and 2500 kW respectively are selected to simulate their performance in these seven locations. The characteristic properties of these wind turbines are given in Table 6 while their power curves can be found in Ucar and Balo [4]. The annual power output and capacity factors of the selected wind turbines for these locations are shown in Table 7. The annual power output and capacity are computed with Eqs. (13) and (14) respectively, where the annual values *k* and *c* at the respective turbine hub height are used. It can be observed that accumulated power output using Suzlon S52–600 kW (75 m hub height) wind turbine ranges from 618.06 kW/year (Yelwa) to 4677.06 kW/year (Kano). Similar trend is observed for the other wind turbines in all the locations. However, the highest annual power is recorded using Nordex N80–2.5 MW with 14233.53 kW/year in Kano while the lowest is estimated for Yelwa with 618.06 kW/year for Suzlon S52. The highest annual power is

Table 7
Annual power output and capacity factor of the selected wind turbine for the locations.

Location	Suzlon S52-600 kW		Suzlon S82-1.5 MW		Vestas V80-2 MW		Nordex N80-2.5 MW	
	$P_{e,\ ave}$ (kW/year)	C_f (%)	$P_{e,\ ave}$ (kW/year)	C_f (%)	$P_{e,\ ave}$ (kW/year)	C_f (%)	$P_{e,\ ave}$ (kW/year)	C_f (%)
Yelwa	618.06	8.585	1317.33	7.32	916.09	3.82	1614.82	5.38
Zaria	2274.85	31.60	4555.48	25.31	2400.89	10.01	4479.75	14.94
Sokoto	4437.87	61.64	9728.49	54.04	6378.31	26.58	11416.86	38.06
Gusau	2495.47	34.66	5103.10	28.35	2973.74	12.39	5333.65	17.78
Kaduna	1136.80	15.79	2212.63	12.29	1089.88	4.54	2084.65	6.95
Katsina	4295.75	59.66	9276.95	51.54	8307.27	34.62	12912.78	43.05
Kano	4677.06	64.96	10170.26	56.50	9223.35	38.43	14233.53	47.45

recorded in Kano because the value of V_{maxE} is nearest to the V_{rated} of the wind turbines there.

The capacity factor shows similar trend to the annual power output for all the sites and wind turbine models. The highest capacity factor is calculated as 64.96% for Suzlon S52–600 kW in Kano while the lowest is computed as 3.82% for Vestas V80–2 MW in the case of Yelwa at 67 m hub height. In general, this table shows that for given wind turbine model, a wind turbine sited in Kano, Katsina and Sokoto would generate more power than other locations. This may be related to the ratio of the rated wind speed to the mean wind speed (V_r/V_m) for these three sites which are closer to the suggested value of 1.3 for site with trade winds [27]. With increasing value of V_r/V_m, the capacity factor decreases for the all the sites. Other factors that could influence the performance of a wind turbine in a given site include both the designed rated and cut-in wind speeds of the turbine. Furthermore, Table 7 shows that the capacity factor is greater than the recommended minimum value of 0.25 for all the sites expected Yelwa and Kaduna for the wind turbine models Suzlon S52–600 kW and Suzlon S82–1.5 MW. For Vestas V80–2 MW and Nordex N80–2.5 MW models only Sokoto, Katsina and Kano have capacity factors greater than 0.25. This also follows previous observation that Kano, Katsina and Sokoto locations are excellent sites for wind energy development to be used for electricity generation while Zaria and Gusau are partially suitable. It can be suggested that medium size wind turbine with rated power of less than 1 MW, cut-in wind speed of around 3 m/s and rated wind speed between 10 and 13 m/s will be suitable for this region.

4. Conclusions

The wind energy potential of seven locations in North-West geo-political zone of Nigeria was analyzed based on the wind data from 1971 to 2007 using two-parameter Weibull distributions. The results can be concluded as follows:

- The minimum monthly mean wind speed is recorded in Yelwa as 2.64 m/s in November while the maximum is found to be 9.84 m/s in June in Katsina. The annual wind speeds range from 3.61 m/s in Yelwa to 7.77 m/s in Kano.
- Weibull shape parameter k varies from 2.31 to 10.13 while the scale parameter c is between 2.88 and 10.67 m/s.
- A relationship between the monthly mean power density and mean wind speed is expressed in the form of linear and power law. Both methods indicated a strong correlation ($R^2 > 0.91$) between the two variables. However, the power curve fit gave a better fit with higher R^2 values than linear curve fit.
- The lowest annual average power density and energy are obtained in Yelwa as 43.77 W/m^2 and 383.65 kW h/m^2/year respectively while the highest values are obtained in Kano as 368.92 W/m^2 and 3224.44 kW h/m^2/year in that order.
- Katsina has the highest values for V_{mp} and V_{maxE} with 10.269 and 11.449 m/s respectively, whereas the lowest values are available as 2.745 and 2.993 m/s in Yelwa for the V_{mp} and V_{maxE} respectively.
- The monthly variations of mean wind speeds taken at two synoptical hours of 9:00 and 15:00 shows that higher wind speeds are only available in the morning hours than afternoon periods for all the locations.
- The highest annual power is obtained with Nordex N80–2.5 MW as 14233.53 kW/year in Kano while the lowest is got in Yelwa having 618.06 kW/year for Suzlon S52. Furthermore, 64.95% is computed as the highest capacity factor for Suzlon S52–600 kW in Kano while the lowest is calculated as 3.82% for Vestas V80–2 MW in Yelwa.
- Sokoto, Katsina and Kano with annual average power densities 320.09, 339.85 and 368.95 W/m^2 respectively fall under Class 6 of the international system of wind classification and are considered very suitable for wind turbine applications; Gusau and Zaria with annual average power densities 178.48 and 169.27 W/m^2 respectively exist in Class 3 and will be suitable for wind energy development using taller wind turbine towers while Kaduna will be considered marginal for wind power development having fallen under Class 2 with mean annual power density of 109.30 W/m^2. Yelwa being in Class 1 with annual mean power density of 43.77 W/m^2 may only be adequate for non-connected electrical and mechanical applications like battery charging and water pumping.

References

[1] Yuksel I. Hydropower for sustainable water and energy development. Renew Sust Energy Rev 2010;14:462–9.
[2] Ohunakin OS. Energy utilization and renewable energy sources in Nigeria. J Eng Appl Sci 2010;5:171–7.
[3] Ibitoye FI, Adenikinju A. Future demand for electricity in Nigeria. Appl Energy 2007;84:492–504.
[4] Ucar A, Balo F. Evaluation of wind energy potential and electricity generation at six locations in Turkey. Appl Energy 2009;86:1864–72.
[5] Bagiorgas HS, Assimakopoulos MN, Theoharopoulos D, Matthopoulos D, Mihalakakou GK. Electricity generation using wind energy conversion systems in the area of Western Greece. Energy Convers Manage 2007;48:1640–55.
[6] Elliott DL, Holladay CG, Barchet WR, Foote HP, Sandusky WF. Wind energy resource atlas of the United States, 1987. DOE/CH10094-4.
[7] Ilinca A, McCarthy E, Chaumel J-L, Retiveau J-L. Wind potential assessment of Quebec Province. Renew Energy 2003;28:1881–97.
[8] Anyanwa EE, Iwuagwu CJ. Wind characteristics and energy potentials for Owerri, Nigeria. Renew Energy 1995;6:125–8.
[9] Ngala GM, Alkali B, Aji MA. Viability of wind energy as a power generation source in Maiduguri, Borno state, Nigeria. Renew Energy 2007;32:2242–6.
[10] Fadare DA. A statistical analysis of wind energy potential in Ibadan, Nigeria, based on Weibull distribution function. Pac J Sci Technol 2008;9:110–9.
[11] Fagbenle RO, Katende J, Ajayi OO, Okeniyi JO. Assessment of wind energy potential of two sites in North-East, Nigeria. Renew Energy 2011;36:1277–93.
[12] Ojosu JO, Salawu RI. A survey of wind energy potential in Nigeria. Solar Wind Technol 1990;7:155–67.
[13] Adekoya LO, Adewale AA. Wind energy potential of Nigeria. Renew Energy 1992;2:35–9.
[14] Fagbenle RL, Karayiannis TG. On the wind energy resource of Nigeria. Int J Energy Res 1994;18:493–508.
[15] Chineke TC. Boosting electricity supply in Nigeria: wind energy to the rescue? Pac J Sci Technol 2009;10:553–60.
[16] Fadare DA. The application of artificial neural networks to mapping of wind speed profile for energy application in Nigeria. Appl Energy 2010;87:934–42.
[17] Akdag SA, Bagiorgas HS, Mihalakakou G. Use of two-component Weibull mixtures in the analysis of wind speed in the Eastern Mediterranean. Appl Energy 2010;87:2566–73.
[18] Akpinar EK, Akpinar S. An assessment on seasonal analysis of wind energy characteristics and wind turbine characteristics. Energy Convers Manage 2005;46:1848–67.
[19] Fyrippis I, Axaopoulos PJ, Panayiotou G. Wind energy potential assessment in Naxos Island, Greece. Appl Energy 2010;87:577–86.
[20] Justus CG, Hargraves WR, Mikhail A, Graber D. Methods for estimating wind speed frequency distributions. J Appl Meteorol 1978;17:350–3.
[21] Jowder FAL. Wind power analysis and site matching of wind turbine generators in Kingdom of Bahrain. Appl Energy 2009;86:538–45.
[22] Kwon SD. Uncertainty analysis of wind energy potential assessment. Appl Energy 2010;87:856–65.
[23] Ouammi A, Dagdougui H, Sacile R, Mimet A. Monthly and seasonal assessment of wind energy characteristics at four monitored locations in Liguria region (Italy). Renew Sust Energy Rev 2010;14:1959–68.
[24] Mathew S, Pandey KP, Kumar AV. Analysis of wind regimes for energy estimation. Renew Energy 2002;25:381–99.
[25] Safari B, Gasore J. A statistical investigation of wind characteristics and wind energy potential based on the Weibull and Rayleigh models in Rwanda. Renew Energy 2010;35:2874–80.
[26] Tchinda R, Kendjio J, Kaptouom E, Njomo D. Estimation of mean wind energy available in far north Cameroon. Energy Convers Manage 2000;41:1917–29.
[27] Mathew S. Wind energy: fundamentals, resource analysis and economics. Heidelberg: Springer; 2006.