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Wind profile characteristics and turbine performance analysis in Kano, north-western Nigeria

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Abstract

This study analyzed the electricity generation potential from wind at Kano, Nigeria (12.05°N; 08.2°E; altitude 472.5 m; air density 1.1705 kg/m³). Twenty one years (1987 to 2007) monthly mean wind speed data at a height of 10 m were assessed from the Nigeria Meteorological Department, Oshodi. The data were subjected to different statistical tests and also compared with the two-parameter Weibull probability density function. The outcome shows that the average monthly wind speed ranged from 6.6 to 9.5 m/s. Seasonally, average wind speeds ranged between 6.6 to 8.5 m/s and 7.4 to 9.5 m/s for dry (October to March) and wet (April to September) seasons, respectively. Also, estimated monthly wind power ranged between 3.6 and 12.5 MWh/m². The most probable and maximum energy carrying wind speeds were also determined and the two parameters of the Weibull statistics were found to lie between $2.1 \leq k \leq 4.9$ and $7.3 \leq c \leq 10.7$, respectively. These results indicate that wind speeds at Kano may be economically viable for wind-to-electricity at and above the height of 10 m. In addition, five practical turbine models were assessed for the site's wind profile, with results suggesting strong economic viability.

Keywords: Wind power; Renewable energy; Weibull; Kano; Nigeria

Background

Globally different sources of energy production which include fossil fuel burning, small and large scale hydro, nuclear power, biomass burning, etc., have made major headlines in national and regional discussions of energy development. Some of these sources indeed have produced adequate amount of energy for community and national electricity production. However, the need to secure the environment while also developing the national economy has driven the trend toward diversification of energy production modules across the globe [1,2]. More so, the finite nature of conventional energy sources renders them unsustainable for long-term energy planning. Based on this, the focus of energy development and planning has shifted to include the non-conventional yet environmentally friendly sources of wind, solar, biomass, geothermal, and other renewable energy sources.

Moreover, before reasonable financing for renewable energy is provided by local or international investors, adequate resource and viability assessments must be made, among many other policy initiatives and derivatives. For Nigeria, the national energy policy and the renewable energy master plan [3,4] stipulate the country's desire to increase electricity production through the development of its alternative energy sources, of which wind, solar and biogas are major. Thus, efforts at measuring and assessing these sources for electricity generation are vital to its energy development. Since wind resources are site specific, wind energy measurements of as many sites as possible are required to have a proper wind classification of a nation. Based on this, several studies have attempted to classify the wind profile characteristics of Nigeria either, by site, region, or nation [5-26]. Ajayi [5,6] and Ohunakin et al. [9] profiled the results of some wind energy assessment studies in Nigeria to include those of pre-2000 and few post-2000 wind databases. On regional basis, different studies exist that characterized the wind profiles of sites in the North West [8,9], North East [7,8,11], North Central [8,10], South West [14] and South East [26] regions, respectively. Some

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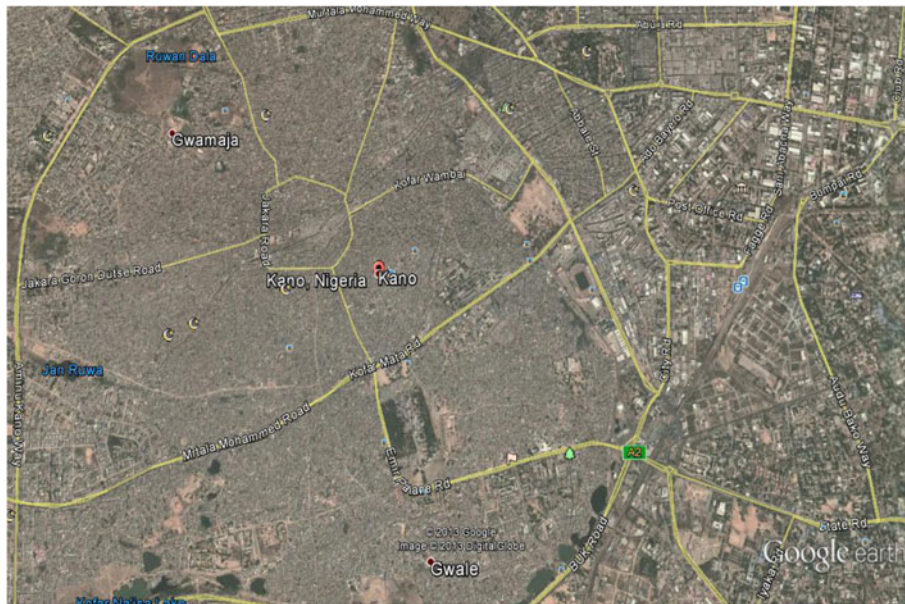


Figure 1 A view of the studied site at Kano, Kano State.

recent studies also exist that profiled the wind characteristics of single sites in Nigeria [12,13,15,17,21,23].

Each of the articles cited above demonstrated that Nigeria can employ wind resources for power generation across studied sites and geopolitical zones. Of interest to this study, however, are articles that focus on sites located in and around Kano [8,9,20,27]. ECN-UNDP [20] reported wind speed results based on the outcome of work carried out by Lahmeyer (International) [22]. The work of Lahmeyer (International), according to Ajayi et al. [12], used 12 months wind speed data to determine the average wind speed for ten selected sites across the country. One of the sites is Funtua (11.52°N; 7.31°E; Altitude 616 m), a place in Kano State. It reported average wind speed of 4.07 at 10 m height. Wind power generation at the site using three different turbines was evaluated to be 116.3, 281.2, and 963.7 MWh/yr at heights 34.5, 42.0, and 44.0 m,

respectively. The models are FL 100, and 250, and V52 made by Fuhrlander and Vestas, respectively [12]. The application of this result is however limited by the number of data points (12 months). Also, because of the limited data spread, the monthly and seasonal variations associated with wind speed profiles were not captured. It is worthy of note that wind speed variation are location specific and associated with high variability in time and space; therefore, good results are based on historical data of many years.

Based on the aforementioned, studies by Ohunakin et al. [9] and Ohunakin [8] employed several years' wind speed data to characterize the wind profile of a meteorological site in Kano. The site is of the Nigeria meteorological agency. Moreover, while the studies suggested that the wind profile at the site is suitable for generating electricity, they failed to properly characterize the site wind for turbine sitting and applications. For the sitting and/or application of wind turbines at a site, adequate and robust

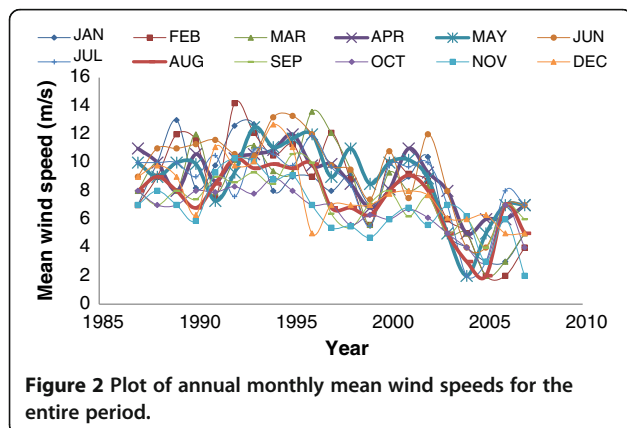


Figure 2 Plot of annual monthly mean wind speeds for the entire period.

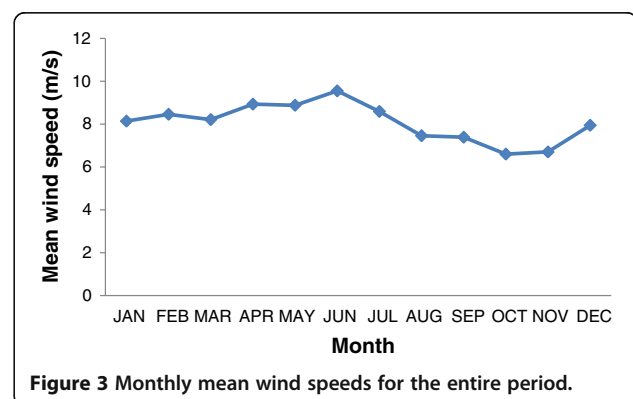
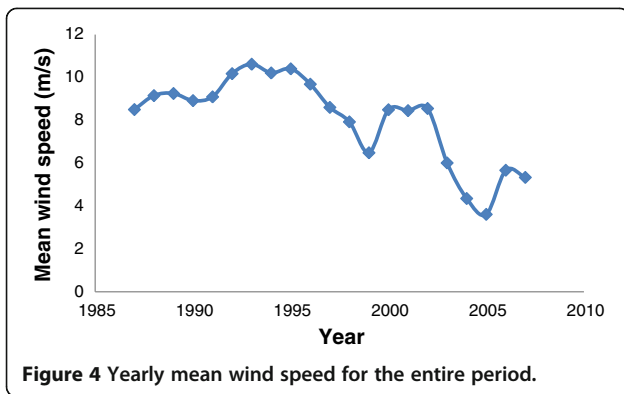


Figure 3 Monthly mean wind speeds for the entire period.



site characteristics are required. Worthy of note is the fact that sitting of a wind turbine at a potential site does not just involve collection and analysis of wind data. It should also, of necessity, involve other factors and activities. These include the knowledge and analysis of the prevailing wind directions, surface roughness, topography, upwind obstacles such as trees or buildings, wind shear profile, and/or the influence of terrain contours.

In addition to the aforementioned, Ohunakin et al. [27] worked on the economic analysis of wind energy conversion using levelized cost of energy and present value cost for some sites which include the meteorological site in Kano. However, due to the fact that the work compared potential generation from different sites, it assumed constant generation from the sites across the period spanning 37 years. This places a limitation on the econometric result. The expected value of mean, taken over a period of years, is statistically significant over the actual data. Thus, employing the mean value for the analysis would have given a better and more applicable result because of the variability associated with wind resources. Further to this, the value of the cost for operation and maintenance employed in the study is minimal and not significant with market reality. The focus of this

study was therefore to properly classify the wind profile characteristics of the meteorological site for turbine sitting and application. It also aimed at determining the economic viability of employing modern Mega wind turbines to generate wind electricity at the site. Figure 1 gives the view of the site. The study made use of monthly mean wind resource measurements averaged from daily readings to statistically analyze the wind resource potential of Kano for power generation.

Methods

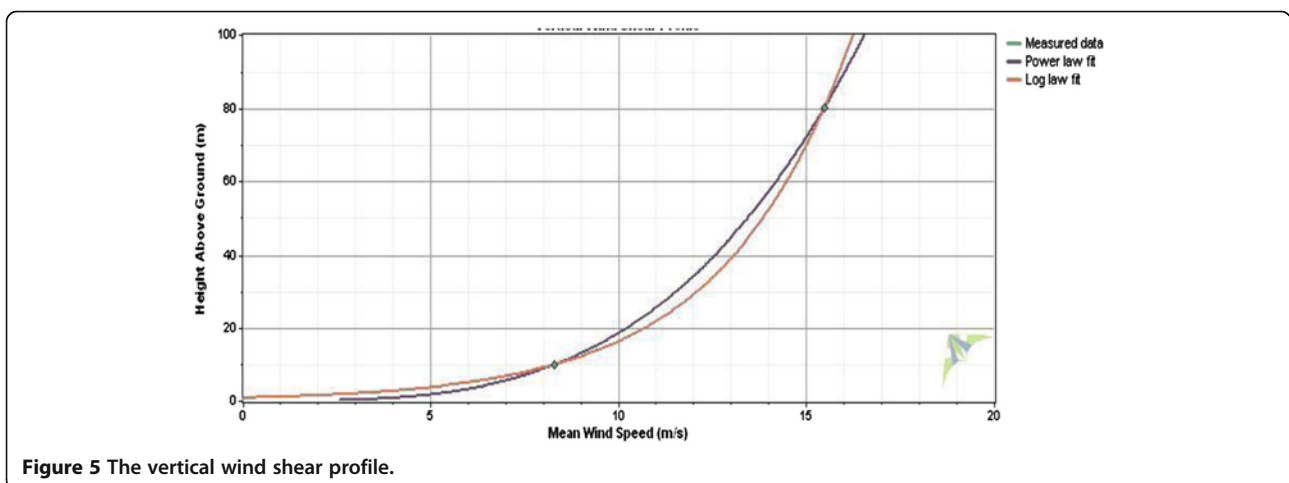
Twenty one years (1987 to 2007) monthly mean wind data for Kano (12.05°N; 08.2°E; altitude 472.5 m; and air density 1.1705 kg/m³) were sourced from records archived at the Nigeria Meteorological Department, Oshodi, Lagos State, south-west Nigeria. Three-hour daily readings over the period considered were used and subjected to various statistical operations. The data were recorded continuously using a cup generator anemometer at a height of 10 m. Figure 2 gives the whole data spread across the period considered, while Figure 3 gives the 21 years' monthly average distribution of the mean speeds, and Figure 4 gives the average annual distribution of mean speeds for the period.

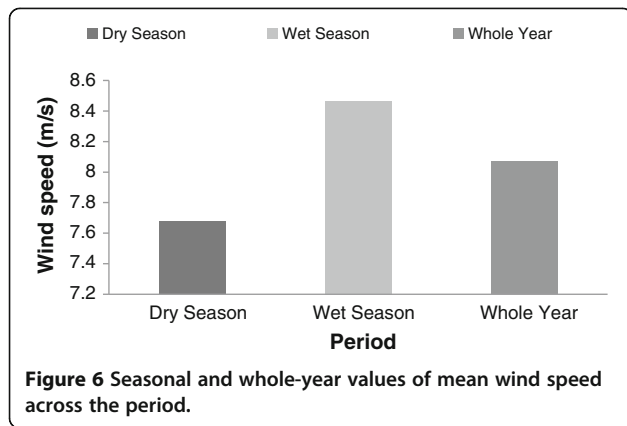
Statistical Analysis

The two-parameter Weibull statistical distribution was employed to characterize the wind profile of the site. This is because the Weibull two-parameter probability density function (PDF) has been proved to be the adequate and accurate of several statistical distributions [28-33]. The two-parameter PDF is given as:

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

where $f(v)$ is the probability of observing wind speed, v . k is the dimensionless Weibull shape parameter and c (m/s), is the Weibull scale parameter.





The corresponding Weibull cumulative density function (CDF) is given as:

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

Equation 2 can be translated into a linear form of $y = mx + C$ as:

$$\ln[-\ln[1-F(v)]] = k \ln v - k \ln c,$$

where $y = \ln[-\ln[1-F(v)]]$, $mx = k \ln v$ and $C = -k \ln c$.

Thus, a plot of $\ln[-\ln[1-F(v)]]$ on the vertical against $\ln v$ on the abscissa gives the shape (k) and scale (c) parameters of the Weibull distribution by evaluating the slope and intercept on the vertical axis.

The mean value of the wind speed v_m and standard deviation σ for the Weibull distribution are given as [4,5]:

$$v_m = c \Gamma\left(1 + \frac{1}{k}\right) \quad (3)$$

and

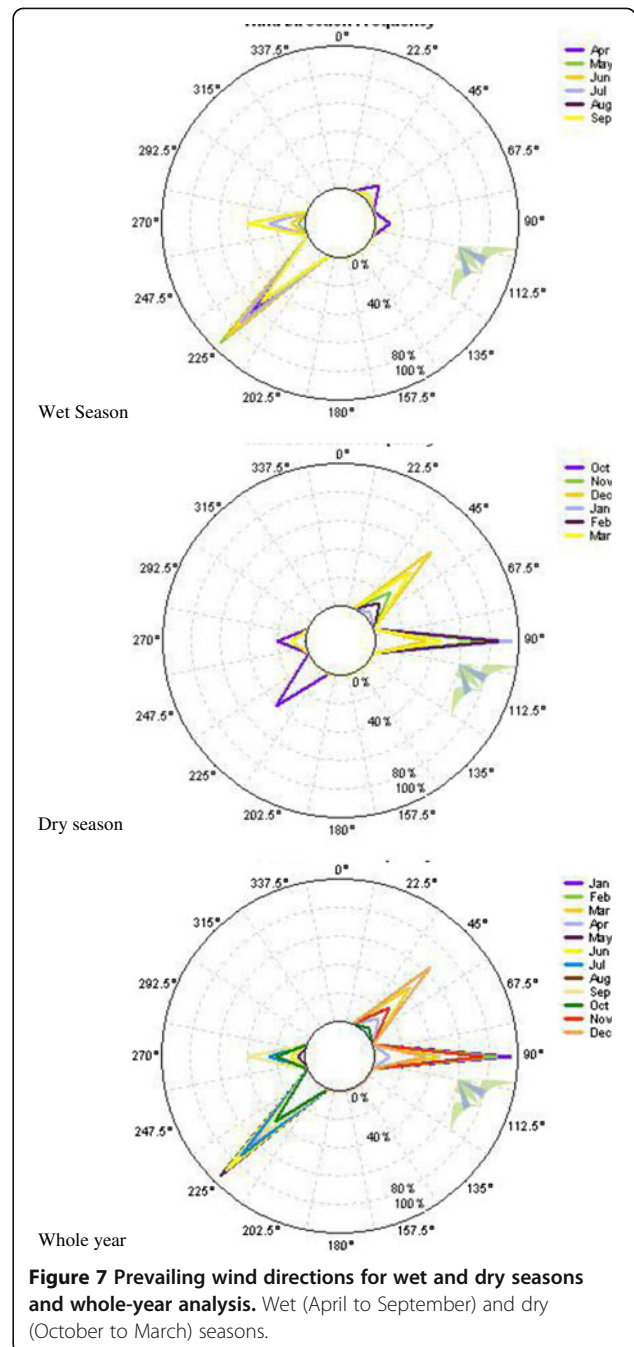
$$\sigma = \sqrt{c^2 \left\{ \Gamma\left(1 + \frac{2}{k}\right) - \left[\Gamma\left(1 + \frac{1}{k}\right) \right]^2 \right\}}, \quad (4)$$

where $\Gamma(\cdot)$ is the gamma function of (\cdot) .

However, the two wind speeds of utmost interest for wind resource assessment are the wind speed carrying maximum energy ($v_{E_{max}}$) and the most probable or modal wind speed (v_{mp}). These were evaluated from:

$$v_{E_{max}} = c \left(\frac{k+2}{k}\right)^{\frac{1}{k}} \quad (5)$$

$$v_{mp} = c \left(\frac{k-1}{k}\right)^{\frac{1}{k}}. \quad (6)$$



Estimation of wind power density

The available average power in the wind flowing through a rotor blade with swept area, A (m^2) is known to increase as the cube of its mean wind speed, v_m as:

$$P(v) = \frac{1}{2} \rho A v_m^3. \quad (7)$$

However, in this study, the wind power per unit area is estimated based on the Weibull PDF as:

Table 1 Some Weibull results and estimation parameters for the whole 21 years

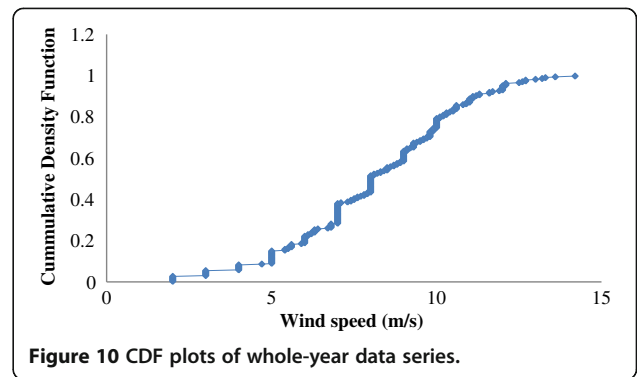
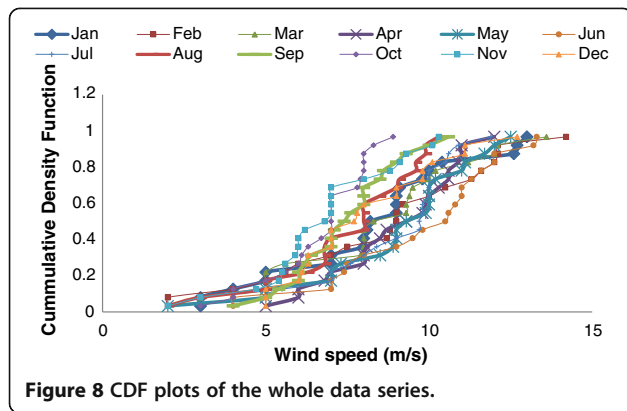
Period	$v_{Weibull}$ (m/s)	k (-)	c (m/s)	$\sigma_{Weibull}$ (m/s)	σ_{actual} (m/s)	R^2	RMSE	COE	K-S P value
Month									
January	8.2	2.7	9.2	3.3	2.9	1.0	0.7	0.9	0.7
February	8.7	2.1	9.8	4.4	3.4	0.9	1.3	0.8	0.6
March	8.4	2.4	9.4	3.7	3.0	0.9	0.9	0.9	0.4
April	8.9	4.9	9.7	2.1	1.9	1.0	0.3	1.0	0.9
May	9.1	2.7	10.2	3.7	2.6	0.9	1.4	0.7	0.5
June	9.6	3.4	10.7	3.2	2.7	0.9	0.8	0.9	0.8
July	8.9	2.4	10.0	3.9	2.5	0.8	1.9	0.4	0.2
August	7.6	2.7	8.5	3.0	2.2	0.9	1.1	0.8	0.4
September	7.4	4.9	8.0	1.7	1.7	1.0	0.2	1.0	1.0
October	6.6	4.1	7.3	1.8	1.6	0.9	0.4	0.9	0.8
November	6.8	2.9	7.6	2.5	2.1	0.9	0.6	0.9	0.6
December	7.9	4.1	8.8	2.2	2.2	0.9	0.5	1.0	0.8
Season									
Dry	7.7	3.0	8.6	2.8	2.7	1.0	0.3	1.0	0.7
Wet	8.5	3.4	9.5	2.8	2.4	1.0	0.6	0.9	0.2
Whole year	8.1	3.2	9.1	2.8	2.6	1.0	0.4	1.0	0.1
Year									
1987	8.5	6.9	9.1	1.4	1.3	0.9	0.4	0.9	0.5
1988	9.1	7.5	9.7	1.4	1.3	0.9	0.4	0.9	0.7
1989	9.2	5.1	10.1	2.1	2.0	0.9	0.6	0.9	0.5
1990	8.9	4.5	9.8	2.2	2.1	1.0	0.4	1.0	1.0
1991	9.1	7.1	9.7	1.5	1.4	0.9	0.4	0.9	1.0
1992	10.2	6.2	10.9	1.9	1.8	0.9	0.6	0.9	0.3
1993	10.6	8.1	11.2	1.5	1.4	1.0	0.2	1.0	1.0
1994	10.2	7.0	10.9	1.7	1.6	0.9	0.4	0.9	0.9
1995	10.4	7.5	11.0	1.6	1.5	0.9	0.3	0.9	0.9
1996	9.7	3.9	10.7	2.8	2.5	1.0	0.5	1.0	1.0
1997	8.6	4.3	9.4	2.3	2.2	0.9	0.5	0.9	0.9
1998	7.9	4.5	8.7	2.0	1.8	0.9	0.4	0.9	0.9
1999	6.5	6.9	6.9	1.1	1.0	1.0	0.2	0.9	1.0
2000	8.5	5.7	9.2	1.7	1.5	0.9	0.4	0.9	0.8
2001	8.4	6.2	9.1	1.6	1.5	1.0	0.3	1.0	1.0
2002	8.5	5.2	9.3	1.9	1.8	1.0	0.3	1.0	1.0
2003	6.0	5.0	6.6	1.4	1.2	0.7	0.6	0.8	0.3
2004	4.4	2.8	4.9	1.7	1.5	0.9	0.4	0.9	0.8
2005	3.6	2.6	4.1	1.5	1.5	0.9	0.4	0.9	0.6
2006	5.8	2.4	6.5	2.6	2.0	0.9	1.0	0.7	0.6
2007	5.4	3.0	6.1	2.0	1.6	0.9	0.7	0.8	0.6

$$p(v) = \frac{P(v)}{A} = \frac{1}{2} \rho c^3 \Gamma \left(1 + \frac{3}{k} \right), \quad (8)$$

where, $P(v)$ is the wind power (W), $p(v)$ is wind power density (W/m^2), and ρ is the air density at the site.

Performance of the Weibull distribution model

The accuracy of the Weibull distribution in estimating the site's actual wind speeds was evaluated using the coefficient of determination, R^2 , the root mean square error (RMSE) and the Nash-Sutcliffe model coefficient of efficiency (COE) [30,34]. These are given by:



$$R^2 = \frac{\sum_{i=1}^N (y_i - z_i)^2 - \sum_{i=1}^N (x_i - y_i)^2}{\sum_{i=1}^N (y_i - z_i)^2}, \quad (9)$$

where

$$R = \sqrt{R^2}; \quad (10)$$

$$RMSE = \left[\frac{1}{N} \sum_{i=1}^N (y_i - x_i)^2 \right]^{\frac{1}{2}} \quad (11)$$

$$COE = 1 - \frac{\sum_{i=1}^N (y_i - x_i)^2}{\sum_{i=1}^N (y_i - \bar{x})^2}, \quad (12)$$

where y_i is the i^{th} actual data, x_i is the i^{th} predicted Weibull result, z is the mean of the actual data, and N is the number of observations.

The accuracy of the Weibull results was evaluated by the proximity of the values of R^2 and COE to unity (or 100%) and the proximity to zero of the values of RMSE.

Suitability/goodness of fit test

To ascertain how closely the measured data follow a Weibull distribution, the Kolmogorov-Smirnov (K-S) goodness of fit test [35-39] was employed to measure the absolute difference between the measured distribution function

$F^*(x)$ and the Weibull distribution function $F(x)$ [40,41]. The expression for the K-S test is given as:

$$d = d(x_1, \dots, x_n) = \sqrt{n} \sup_{-\infty < x < \infty} |F^*(x) - F(x)|,$$

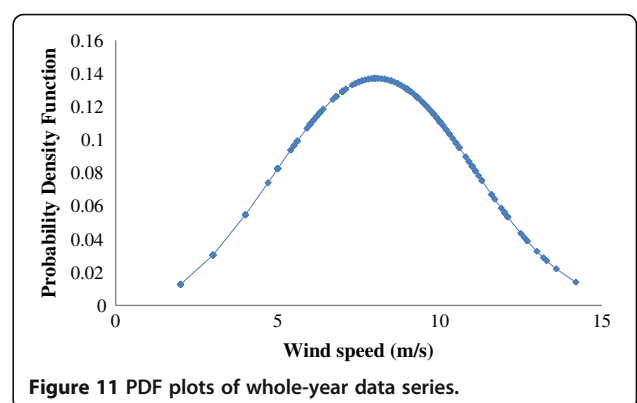
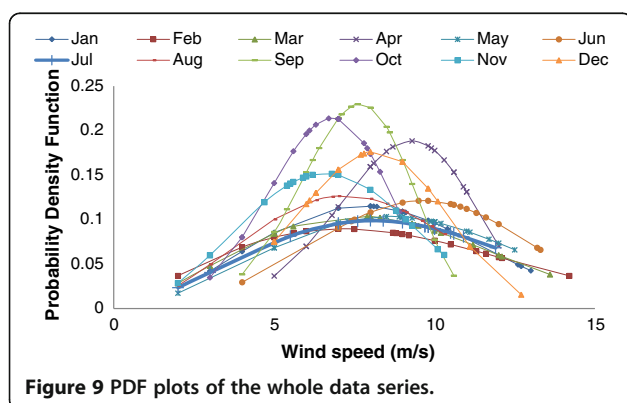
where n is the sample size. From the value of d , the P value of the K-S goodness of fit could be obtained using the relationship given by:

$$P = \begin{cases} P = 1 & \text{for } d < 0.22 \\ P = 1 - \frac{\sqrt{2\pi}}{d} \exp\left(\frac{-\pi^2}{8d^2}\right) & \text{for } 0.22 \leq d \leq 0.80 \\ P = 2\exp(-2d^2) + \exp(-8d^2) - \exp(-18d^2) & \text{for } 0.80 < d \leq 3.15 \\ P = 0 & \text{for } d > 3.15 \end{cases} \quad (13)$$

Therefore, at a significance level $\alpha = 0.05$, the P value can be compared directly with α to test the hypotheses as:

$$\begin{aligned} H_0 &: P \geq \alpha \\ H_A &: P < \alpha \end{aligned}$$

where H_0 is the null hypothesis, suggesting that the two-parameter Weibull distribution suitably approximates the Kano wind speed profiles. H_A is the alternative hypothesis indicating otherwise.



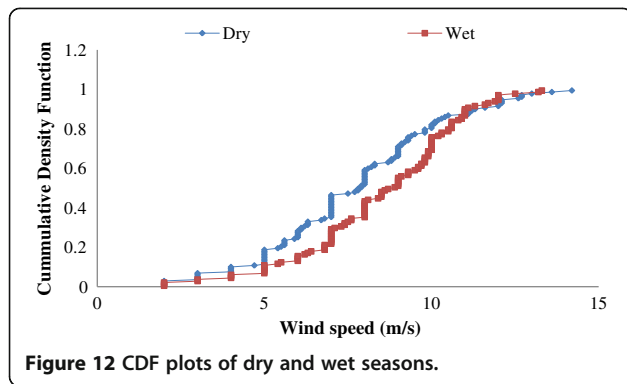


Figure 12 CDF plots of dry and wet seasons.

Simulating the electrical power output from a wind turbine model

The magnitude of wind power that can be produced from a practical wind turbine applied at the site was simulated using Equation 14 [31]:

$$P_e = \begin{cases} 0 & (v < v_c) \\ P_{eR} \frac{v^k - v_c^k}{v_R^k - v_c^k} & v_c \leq v \leq v_R \\ P_{eR} & v_R \leq v \leq v_F \\ 0 & v > v_F \end{cases} \quad (14)$$

The average power output ($P_{e,ave}$) from a turbine corresponding to the total energy production and related to the total income/cost analysis was evaluated from:

$$P_{e,ave} = P_{eR} \left\{ \frac{e^{-(v_c/c)^k} - e^{-(v_R/c)^k}}{(v_R/c)^k - (v_c/c)^k} - e^{-(v_F/c)^k} \right\} \quad (15)$$

The capacity factor (CF) of generation is evaluated from:

$$CF = \frac{P_{e,ave}}{P_{eR}}, \quad (16)$$

where P_{eR} = rated electrical power, v_c = cut-in wind speed, v_R = rated wind speed and v_F = cut-off wind speed.

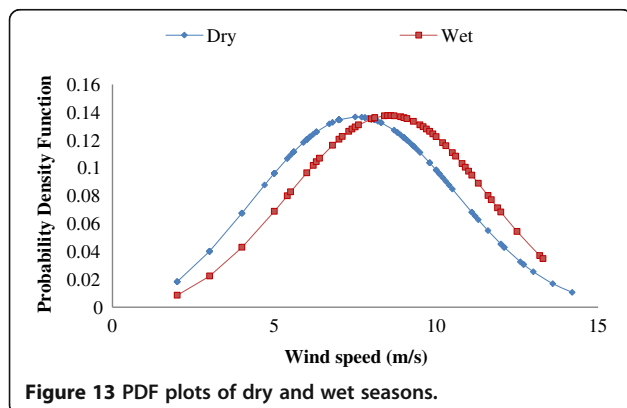


Figure 13 PDF plots of dry and wet seasons.

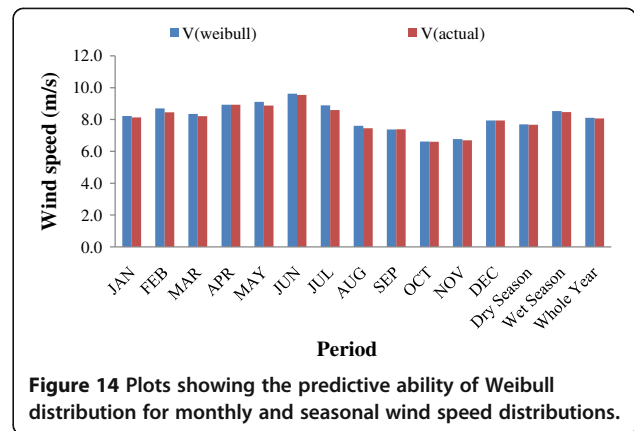


Figure 14 Plots showing the predictive ability of Weibull distribution for monthly and seasonal wind speed distributions.

Results and discussion

Wind profile assessment

Figure 2 indicates that there was a general decline in the values of the wind speed profiles across the years considered while October and November appear to be the months with the least wind supply of the station. The reason behind the drop is not immediately assumable. It is however believed that it may be due to developmental changes around the site. These changes have introduced wind brakes (e.g. tall buildings) that were absent some years back. Furthermore, these changes are notable because of the site's location, which is in the heart of the capital city of Kano. Based on this, the vertical wind shear profile was determined using the Windographer® software [42] and the observable site's characteristics. This gave Figure 5. Thus, even though there was a decline in the observable wind speeds across the periods shown in Figure 2, wind speed profile increased with heights at the site.

The magnitude of the monthly mean measured wind speeds from January to December across the whole 21-year period lay within the range of 2.0 to 14.2 m/s and those of the seasons from dry (October to March) to wet (April to September) every year lay within the range 2.0 to 14.2 and 2.0 to 13.3 m/s, respectively, at the 10-m height. Yearly,

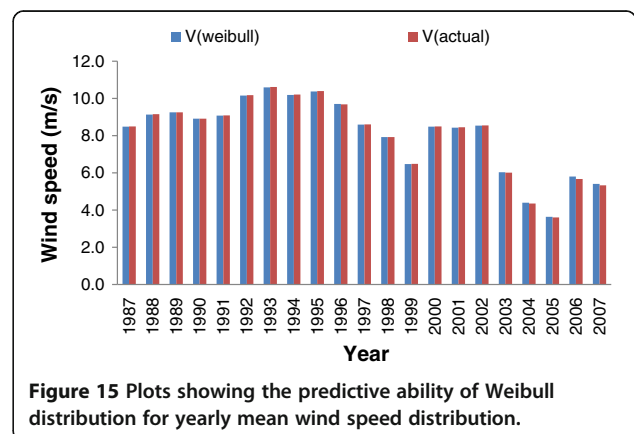


Figure 15 Plots showing the predictive ability of Weibull distribution for yearly mean wind speed distribution.

the mean measured wind speeds from 1987 to 2007 also ranged from 2.0 to 14.2 m/s. However, to determine the fluctuations in the wind speed profiles, the 21-year average of all monthly and yearly mean wind speeds of Figure 2 were estimated and plotted as shown in Figures 3 and 4. Figures 3 and 4 show similar trends with Figure 2 across the months and 2005 experienced the lowest wind speed values, between 2.0 and 6.3 m/s. In addition, the period with the highest energy potential was from January to June, while June appears to have the greatest potential with speed range of 4.0 to 13.3 m/s. The average monthly wind speed range was from 6.6 (in October) to 9.5 m/s (in June). Seasonally, the wet season appears to have more wind energy potential than the dry (Figure 6), while the 21-year average for all of the data was 8.1 m/s. Seasonal mean speed range for dry, was from 6.6 (in October) to 8.5 m/s (in February), while for wet, it ranged from 7.4 (in September) to 9.5 (in June), respectively. These clearly indicate that Kano experiences wind speeds that are viable for economically beneficial wind energy production at 10-m heights and above.

Figure 7 shows the prevailing wind directions across the months and seasons. It shows that the wind directions in the dry period (October to March) vary differently from those of the wet (April to September). The prevailing wind directions tend toward the east during the dry period and south westerly during the wet. Worthy of note however is the fact that as the period tends toward seasonal changes, the wind directions also changes until the prevailing direction is achieved.

The site's characteristics analysis gave wind power class of 7, surface roughness of 0.906 m and a roughness class of 3.83. The wind power class signifies an excellent wind profile [43,44] for the site while the roughness class signifies a site with landscape having many trees and buildings [45].

The result of a Weibull statistical analysis on the wind speed data are displayed in Table 1, and the corresponding CDF and PDF plots for the whole years' data and seasons are shown in Figures 8, 9, 10, 11, 12, and 13. These figures demonstrate that the wind profiles for these periods and whole year data series follow the same cumulative distribution pattern.

Moreover, Figures 8 and 9 reveal that up to 60% of the whole data series were values that ranged from about 7.0 to 10.8 m/s and below, while up to 90% of the data series was values that ranged from about 8.3 to 13.2 m/s.

The dry and wet seasons' Weibull plots of Figure 12 indicate that between 60% and 90% of the dry season's data falls within the range 8.2 to 11.6 m/s and below, while those of the wet season ranged from 9.6 to 11.1 m/s and below. From Table 1, the Kolmogorov-Smirnov *P* values show that the two-parameter Weibull distribution was adequate for approximating the wind profiles at Kano.

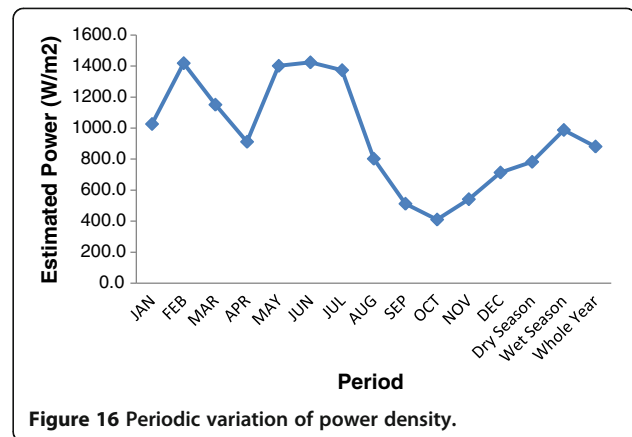


Figure 16 Periodic variation of power density.

The Weibull results (Table 1) were compared with the actual data to assess the degree of convergence. The results are displayed in Figures 14 and 15.

Figures 14 and 15 therefore show that the Weibull statistical distribution predicted the mean wind speed profiles of the station quite adequately. This was corroborated by the associated values of R^2 and COE of Table 1.

However, the RMSE values of Table 1 show some values closer to or greater than 1.0. The reason behind this was the value of the prediction from the Weibull results. This phenomenon is interpreted as when the predicted result is greater than the actual data, the value of RMSE will be closer to or greater than 1.0. Thus, high RMSE values indicate Weibull result greater than actual measured value thus implying over prediction. Overall the, Weibull was adequate at predicting both annual variations and periodic variations of wind profiles going by the R^2 , *P*, and COE values.

On the wind power density across the period and years considered (Figures 16 and 17), June had the highest wind power potential. Also, the period of February, and those between May and July every year can be regarded as the period with very good potential for wind power

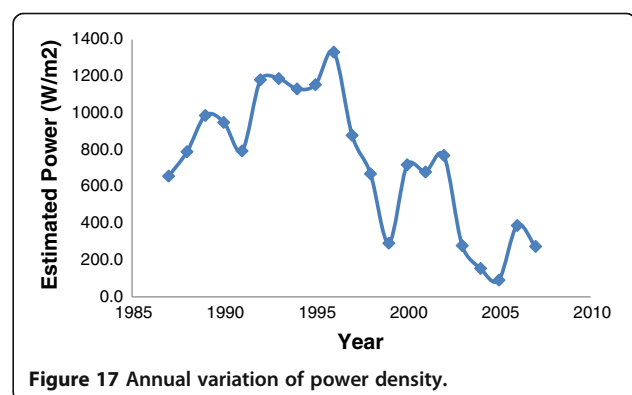


Figure 17 Annual variation of power density.

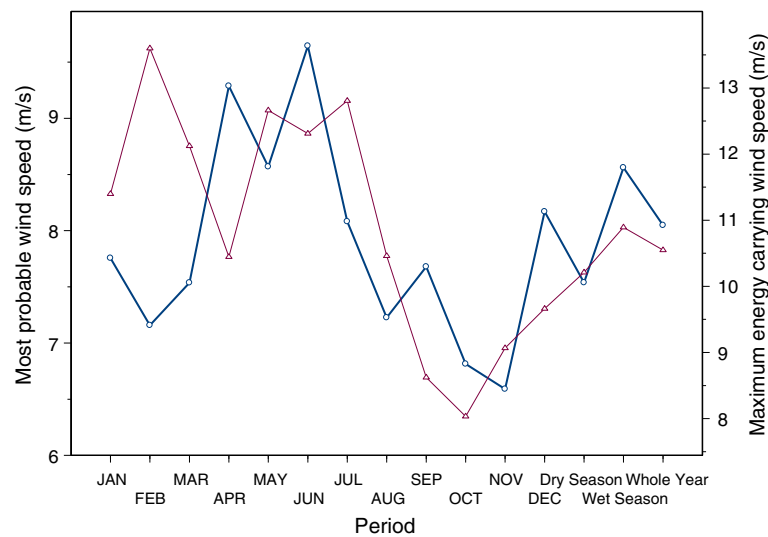


Figure 18 Plot comparing the periodic most probable and maximum energy carrying wind speeds.

harvest. The monthly values ranged between 410.8 (in November) and 1,424.4 W/m² (in June), while the dry and wet seasons and whole-year values ranged from 782.9 (dry) to 988.4 W/m² (wet). This significant monthly change in power density according to Keyhani et al. [46] underscores the importance of distinguishing different months and periods of the year when a wind power project is assessed or designed to produce maximum power. Furthermore, the values of k and c from the analysis across all period ranged between $2.1 \leq k \leq 4.9$ and $7.3 \leq c \leq 10.7$, respectively. These high values of k and c ($k \geq 2$ and $c \geq 2$) indicate a data spread in a perfectly normal distribution [29], and also show that the data spread exhibits good uniformity with relatively small scatter [47]. The scale parameter, c , further indicates how windy a location under

consideration is, whereas the shape parameter, k , indicates how peaked the wind distribution is [46]. Thus, if the wind speeds tends to spike steeply at a certain value, the distribution will have a high k value.

The most probable (v_{mp}) and maximum energy carrying wind speeds (v_{Emax}) analyses for the periods and years are given by Figures 18 and 19. The values of v_{mp} ranged from 6.6 to 9.6 m/s (for January to December), 7.5 m/s (dry season), 8.6 m/s (wet season), and 8.0 m/s (whole years). For the yearly analysis, it ranged from 3.4 to 11.1 m/s. Also, the values of v_{Emax} ranged from 2.1 to 13.6 m/s (for January to December), 10.2 m/s (dry season), 10.9 m/s (wet season), and 10.5 m/s (whole years). For the whole years' it ranged from 5.1 to 11.9 m/s (1987 to 2007), respectively.

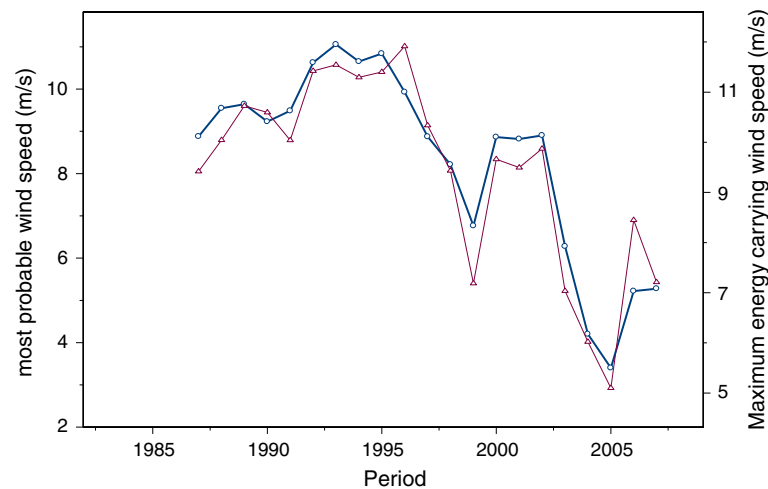


Figure 19 Plot comparing the annual most probable and maximum energy carrying wind speeds.

Table 2 Turbines' technical parameters

Wind machine	v_c (m/s)	v_F (m/s)	v_R (m/s)	P_{eR} (kW)	Hub height (m)	Rotor diameter (m)
GE 1.5sle	3.5	25	14	1,500	65/80	77
GE 1.5xle	3.5	20	11.5	1,500	80	82.5
AV 928	3	25	11.6	2,500	80	93.2
V90	4	25	15	3,000	80	90
SWT-3.6-107	3	25	13	3,600	80	107

Adapting real wind turbines to the Kano site

According to Ajayi et al. [12], installing a wind turbine is capital intensive. Therefore it is worthwhile to first match a turbine parameter to the site's wind profile. Initially, this entails estimating the amount of electrical power that a particular wind turbine will likely generate. The estimated capacity factor (CF) is a pointer to the turbine's generation capacity.

Based on the above, this study employed five different turbines with technical parameters given in Table 2. Equations 14, 15, and 16 were then used to evaluate the power output from each of the turbines. However, because the turbine hub heights are at 80 m, the wind profile characteristics were estimated for this height using Equation 17 [12]. The speeds at this new height were then employed for Weibull re-analyses. It is worthy of note that although it is thought that recent developments may have led to the development of wind brakes around the site's location within the capital city of Kano, the hub heights of practical wind turbines are moreover much more than 10 m. Thus at heights above 20 m, the economic viability of wind energy at the site can be demonstrated.

$$v_{ref} = v_{10} \left(\frac{h_{80}}{h_{10}} \right)^\alpha = v_{10}(8)^\alpha = v_{80}, \tag{17}$$

where $v_{ref} = v_{80}$ = wind speed at 80 m, v_{10} = wind speed at 10-m height, h_{80} = 80 m height, h_{10} = 10-m height, and α = wind shear coefficient for the sites = 0.143.

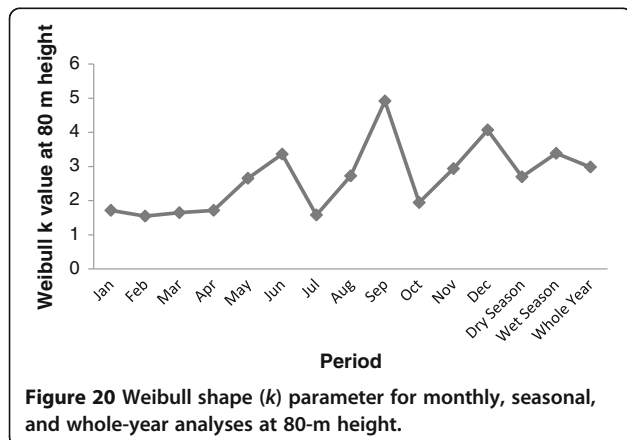


Figure 20 Weibull shape (k) parameter for monthly, seasonal, and whole-year analyses at 80-m height.

The value of α (wind shear coefficient) was used to determine the wind speeds at higher height instead of the roughness length, z_0 . This is because, while α is a dynamic value that varies according to a large number of factors which include time of day, season, atmospheric stability, and regional topography, the z_0 , obtained from the log law, is only valid under certain assumptions regarding atmospheric stability. Actual values may however deviate from the log law. Thus, it is difficult to argue that the wind profile at the site follow the log law or power law. The power law gives better fit to wider range of speed including high wind speeds. However, the value of α has been reported to be suitable for all sites. Also α is approximately equal to 0.143 for neutral stability and regarded as a reasonable but conservative estimate [48-53]. Thus, the commonest and widely accepted value of α for most sites is 0.143 [12].

The results of the Weibull analyses at 80-m heights for monthly, seasonal, and whole-year analyses are presented in Figures 20 and 21. These reveal that the wind speeds at this height ranged from 9.12 to 12.95 m/s. The values of the scale (c) and shape (k) parameters were $10.22 \leq c \leq 14.42$ and $1.55 \leq k \leq 4.91$, respectively. The range of wind speeds at this height further strengthens the economic viability of wind energy projects and wind farm development at Kano. The capacity factors of deploying the five wind turbines at the site are presented in Figure 22.

Figure 22 shows that the AV 928 turbine produced at the highest CF with values between 51.95 and 78.99%. It is closely followed by the GE 1.5xle and SWT-3.6-107 with the production CF ranged from 48.91 to 74.54%

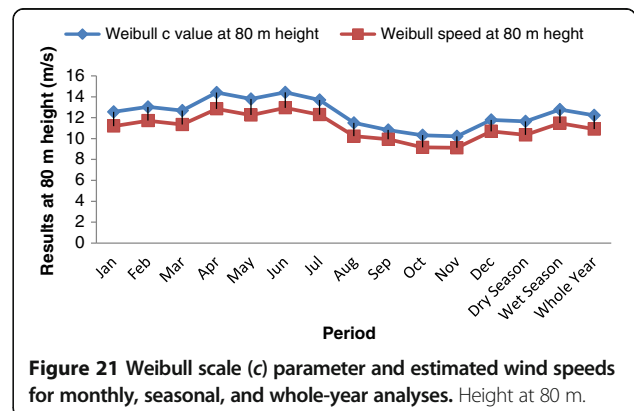


Figure 21 Weibull scale (c) parameter and estimated wind speeds for monthly, seasonal, and whole-year analyses. Height at 80 m.

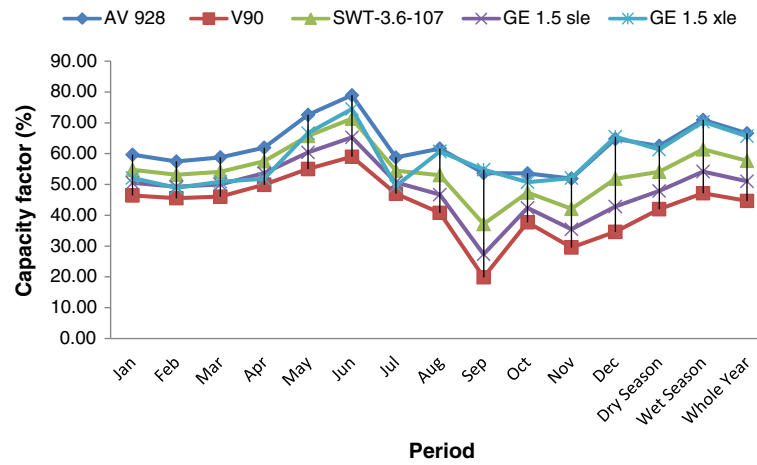


Figure 22 Capacity factors of generation using the turbines at the site.

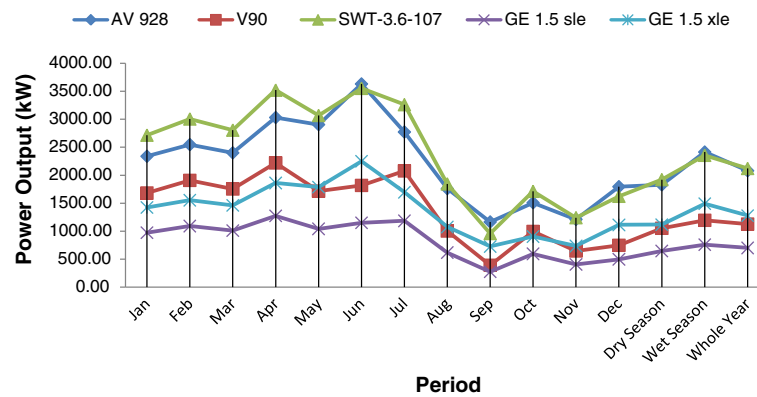


Figure 23 Power output from turbines based on the site's mean wind speed profile at 80-m height.

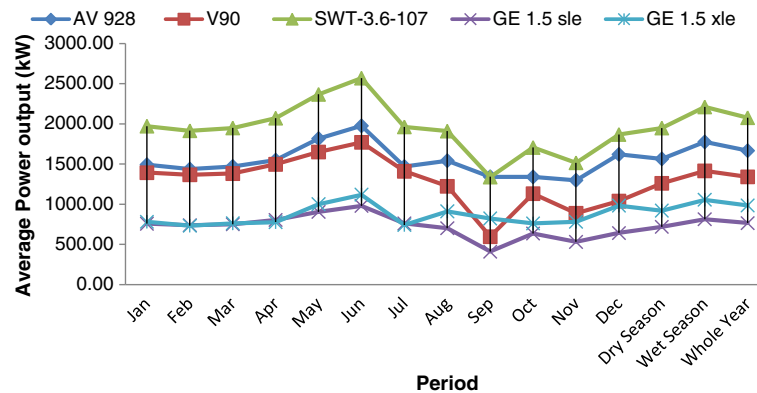


Figure 24 Average power output from turbines based on site's wind speed profile at 80-m height.

Table 3 Range of values from January to December across the period

Item	Wind machine														
	AV 928			V90			SWT-3.6-107			GE 1.5sle			GE 1.5xle		
	P_e (kW)	$P_{e,ave}$ (kW)	CF (%)	P_e (kW)	$P_{e,ave}$ (kW)	CF (%)	P_e (kW)	$P_{e,ave}$ (kW)	CF (%)	P_e (kW)	$P_{e,ave}$ (kW)	CF (%)	P_e (kW)	$P_{e,ave}$ (kW)	CF (%)
Minimum	1164.27365	1298.52	51.94	391.77	597.08	19.90	957.26	1338.82	37.19	276.35	410.93	27.395465	727.7756	733.7201	48.914673
Maximum	3631.51342	1974.86	78.99	2219.23	1770.06	59.00	3553.76	2569.39	71.37	1273.60	979.64	65.309319	2249.5683	1118.1235	74.541568

P_e , power output, $P_{e,ave}$ average power output, and CF capacity factor.

Table 4 Assumptions used for the econometrics analysis [12; 59]

Item	Assumed value
R_C	20.0%
R_{OM}	25.0%
R_I	12.0%
I_R	8.6%
R_{SC}	10.0%
t	20.0 years

Table 5 Assumed turbine model price

Turbine model	Assumed price (€)
GE 1.5sle	1,500,000
GE 1.5xle	1,500,000
AV 928	2,500,000
V90	3,000,000
SWT-3.6-107	3,500,000

and 37.19 to 71.37%, respectively. In term of production capacity, the producible wind powers at the site are presented in Figures 23 and 24. Figures 23 and 24 in comparison with Figure 22 demonstrate that, although the model SWT-3.6-107 was third best in terms of the CF of average production over the rated power, its production capacity is the best. This is closely followed by AV 928. The reason can be adduced to the fact that, for all values greater than the cut-in speed, their power-producing potential is more than the AV 928 and other models. This is due to its power rating (P_{ER}). Consequently, a turbine speed rating (v_R) of between 11.0 and 13.0 m/s, and also cut-in (v_C) and cut-off (v_F) speeds of 3.0 and 25 m/s, respectively, will be valuable for the site. The range of results (minimum and maximum) obtained when the five wind turbines were adapted to the site are presented in Table 3.

Economic benefit of wind power generation at the site

The econometrics analysis was carried out with Equations 18 and 19 [12] using the assumptions stated in Tables 4 and 5. The results are presented in Table 6.

Table 6 Econometrics analysis of wind electricity generation at the site

Turbine model	Present value cost (€)	Average P_{erave} per annum (from Table 5) $\times 10^6$ kWh	20 years average P_{erave} ($t \times P_{erave}$) $\times 10^6$ kWh	Specific cost per kWh (€)	Specific cost per kWh (Nigeria naira)
GE 1.5sle	1,978,445	6.7	134	0.015	3.06
GE 1.5xle	1,978,445	8.6	172	0.012	2.38
AV 928	3,297,409	14.6	292	0.011	2.34
V90	3,956,891	11.7	234	0.017	3.50
SWT-3.6-107	4,616,372	18.8	376	0.012	2.54

$$C_{pv} = x(1 + R_C) + \frac{x}{t} R_{om} \left[\frac{1 + I_R}{R_I - I_R} \right] \times \left[1 - \left(\frac{1 + I_R}{1 + R_I} \right)^t \right] - x R_{sc} (1 + R_C) \left(\frac{1 + I_R}{1 + R_I} \right)^t \tag{18}$$

$$C_{SC/kWh} = \frac{C_{PV}}{\text{Annual } P_{e,ave} \times t} \tag{19}$$

where C_{PV} = present value cost, x = turbine price, R_C = rate chargeable on turbine price to arrive at the cost for civil/structural works, R_{OM} = rate chargeable on annual turbine price to arrive at the cost for Operation and Maintenance, R_I = prevailing interest rate, I_R = prevailing inflation rate, R_{SC} = rate chargeable on total investment cost, t = turbine life or period of operation of turbine, and $C_{SC/kWh}$ = specific cost per kWh of wind electricity.

Turbine prices have been varying for some years. There is no specific fixed price because of the interplay between demand and supply and other variables which include the cost of materials. Various prices have been quoted around € 900 to 1,300 per kW by suppliers. However, a price of € 1,000/kW was adopted as the assumed rule of thumb [54-56]. An average of 20% of turbine cost price is usually associated with the cost for civil/structural works [57]. The R_{OM} value includes the costs for insurance, regular maintenance, repair, spare parts and administration [58]. The current inflation and interest rates in Nigeria are 8.6% and 12.0% (according to CBN report [59]).

Table 6 shows the model AV 928 provides the lowest production cost per kWh. However, since the model SWT-3.6-107 produces more power per wind speed greater than the cut-in speed, it may seem the preferred choice. Therefore, prior to any conclusion, an economic decision should be made based on whether to compromise the potential for more power output by choosing the lowest cost of power or vice versa [12]. Worthy of note is the fact that the econometrics result gives the specific cost per kWh of generating wind electricity from the site. It is at variance with electricity tariff in Nigeria which is between N 4 and N 23.71 (€ 0.02 and € 0.15) depending on the location and the cost of living of the area. In order to carry out adequate comparison, the factors such as cost of grid connection,

cost of transmission and distribution, control system cost, and cost incurred from losses in transmission would have to be included in the analysis for Nigeria.

Conclusions

An assessment of the potential of wind power generation at Kano, Nigeria was carried out. Twenty one years of three-hourly mean wind data at 10-m height from the Nigeria meteorological department, Oshodi, Nigeria were assessed and subjected to Weibull two-parameter and other statistical analyses. It was discovered that:

1. The two-parameter Weibull probability distribution adequately predicts the mean wind speed distribution at Kano.
2. From direct data analysis, of 252 recorded monthly mean wind speeds, representing whole 21 years of monthly mean data measurements, the cumulative frequency of mean wind speeds from 4.0 m/s and below was only 23 and that for 5.0 m/s and below was 20, suggesting that monthly mean wind speed values greater than 5.0 m/s were prevalent in Kano. The 21 years' monthly average wind speed variation ranged from 6.6 to 9.5 m/s. Seasonally, the magnitude of mean wind speed ranged from 7.7 (dry) to 8.5 (wet), while the whole year average gave wind speed value of 8.1 m/s, respectively.
3. The cumulative density function of the Weibull statistical distribution revealed that up to 60% of the whole data series were values that ranged from about 7.0 to 10.8 m/s and below, while up to 90% of the data series were values that ranged from about 8.3 to 13.2 m/s. The dry and wet seasons Weibull plots also indicate that between 60% and 90% of the dry season's and wet season's data series were values that ranged from at most 8.2 to 11.6 m/s, and 9.6 to 11.1 m/s respectively.
4. For the wind power density variation based on the Weibull analysis, January to June every year may be considered as the periods with good potential for wind energy harvest. However, the months of February and periods of May and July appeared to have better potential while June had the highest potential for wind energy harvest. The range of monthly wind power density lay between 410.8 and 1424.4 W/m².

Competing interests

The authors declare that they have no competing interests.

Authors' contributions

OOA collected the wind data and drafted the manuscript. OOA, SAA, and JOO carried out the comprehensive analysis. ROF and JK supervised the study and approved the original draft. All authors read and approved the final manuscript.

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