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Research paper

Assessment of wind energy resources in Nigeria – a case study of north-western region of Nigeria

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Abstract

This study assesses the wind-energyresources in Nigeria by reviewing the existing literature on the subject matter, and also evaluates the wind potential in six locations in the northwest region of the country. Twenty-two years' (1984 – 2005) wind speed data obtained from the Nigerian Meteorological Agencies (NIMET) were used in this study.Weibull two-parameter and other statistical models were employed in this analysis. Wind speed distribution across Nigeria shows that some locations in the northern part of the country are endowed with higher wind potential than others in the southern part of the country. Moreover, assessment of the wind-energy resources in the study locations reveals that wind energy potential in the region is lowest in Yelwa and highest in Kano; WPD varies from 28.30 Wm^{-2} to 483.72Wm^{-2} at 10 m AGL, 45.33 Wm^{-2} to 775.19 Wm^{-2} at 30 m AGL and 56.43 Wm^{-2} to 964.77 Wm^{-2} at 50 m AGL.Thus Kano, Sokoto and Katsina are suitable for large-scale wind power generation, while Gusau is suitable for small-scale wind power generation; whereas Yelwa and Kaduna may not be suitable for wind power production because of their poor wind potential.

Keywords: *Nigeria; Weibull; Wind Energy; Wind Power; Wind Speed.*

1. Introduction

The need to generate enough electricity to meet the demands of the growing population is one of the major challenges confronting the Nigerian Government. The peak demand forecast in the country as on June 16, 2017 is 17, 720 MW. The total power generation capacity is 6969 MW, while the peak generation output 4240 MW [1]. The peak generation is less than one-quarter of the peak demand forecast. It is also reported that about 85% of the total installed capacity is gas-fired (thermal) while, the remaining 15% is hydro-generated. Aside the environmental consequences of thermal power generation, the source has been bewildered by lots of issues (such as vandalism of gas pipelines and insufficient gas infrastructure) leading to poor power generation. In a bid to increase power generation capacity, and also to provide electricity for the remote rural communities across the country, the government has launched a roadmap to diversify Nigeria's energy mix with the inclusion of energy sources as wind, solar, hydro and coal [2].

Nigeria is endowed with wind energy resource which has not been exploited for power generation. At present, there is no commercial wind power plants connected to the national grid in Nigeria. In 2012, the government initiated the installation of 10 MW wind project in Lambar Rimi, Katsina State, which is still under construction. However, due to recent developments, there is a general growing interest in the wind energy development in Nigeria.

Wind energy can be harnessed for grid and non-grid electricity generation, water pumping, irrigation and milling [3], but the type of wind energy application suitable for a particular location depends on the wind energy potential of such location; hence assessment of wind energy resources in Nigeria is imperative. There is need to accurately determine the wind energy potential in some locations of interest among which is the northwest region of Nigeria. Therefore, this study aims at: (i) reviewing the wind energy resources in Nigeria, and (ii) assessing the wind energy resources in six locations in the north-western region of Nigeria at 10 m, 30 m and 50 m above the sea level.

2. Wind energy resources in Nigeria

As a result of the growing interest in wind energy, many researchers have studied the wind energy distribution in Nigeria. Existing studies on wind energy potential in Nigeria can be classified into three groups based on the area covered by the research. The classification is as follows:

- Studies on wind speed across Nigeria;
- Studies on wind speed for geo-political zone(s) in Nigeria; and
- Studies on wind speed for one location only in Nigeria.

I) **Studies on Wind Speed Across Nigeria**

Studies on wind speed data across Nigeria have been carried out by quite a number of researchers. The findings of some of these researchers are discussed below.

Fagbenle et al. [4], stated that the mean wind speed across the Nigeria is 3ms^{-1}, based on 9 years (1951-1960) wind data from twelve meteorological stations. Besides, they discovered that wind speeds are usually low in the southern areas of the country and high in the northern region. They also noted that Jos had the highest wind speed of about 3.6 ms^{-1}. In another study, Ojosu and

Salawu [5], assessed the wind speed in the country using wind data for 24 years (1951-1975) from twenty-two meteorological stations. They reported that Sokoto had the highest wind speed of about 5.12 ms^{-1} recorded in June and annual average of 3.92 ms^{-1}, while the middle and southern areas have wind speed of about 2 ms^{-1} or less. Furthermore, the same authors [6], used 15 years (1968-1983) wind data to classify wind speeds across the country into four different regimes:1.0-2.0 ms^{-1}, 2.1-3.0 ms^{-1}, 3.1-4.0 $ms^{-1}$and > 4.1 ms^{-1} as shown in Figure 1. All in all, the findings of [5, 6] are in agreement with that of [4].

Other studies which are in agreement with those reported above include: wind speed distribution across Nigeria by [7] and [8]. Adekoya and Adewale [7] used wind data from 30 weather stations, while Fagbenle and Karayiannis [8] used wind data from 18 weather stations between 1979 and 1988 in their study. [8] reported that the average wind speeds in Nigeria vary from 2 ms^{-1} to about 4 ms^{-1} and that the southern and northern areas respectively has the highest mean wind speeds of about 3.5 ms^{-1} and 7.5 ms^{-1} [9].

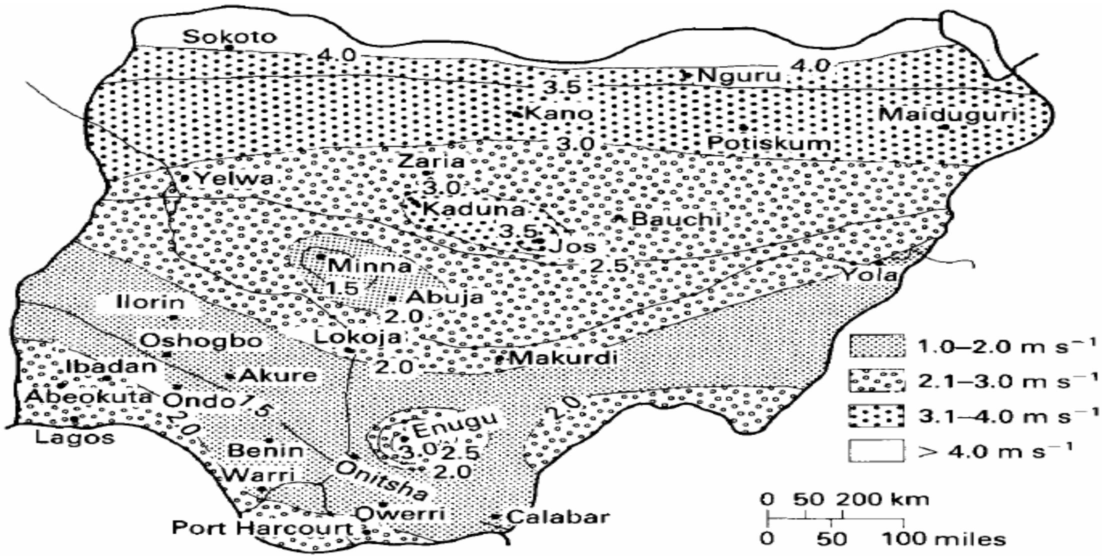

Fig. 1: Annual Mean Wind Speeds Distribution at 10 m Height in Nigeria (Source: [6]).

Chineke [10] reported wind energy potential in 36 state capitals of Nigeria and the Federal capital territory using 29 years (1961-1990) data set retrieved from an International Water Management Institute (IWMI) website. The satellite data presented in his study indicates lowest monthly average wind speeds of about 1.3 ms^{-1} in Osun (South-West) and highest monthly average wind speeds of about 3.9 ms^{-1} in Katsina (North-West) and Jos (North Central). Central. He concluded that the wind speed measured at 10 metres is generally low over the Nigerian environment.

In 2010, [11] used artificial neural networks to determine the wind speeds pattern in 28 stations in Nigeria and compared the predicted wind speeds with measured data between 1983 and 2003. From his result, he predicted an annual average wind speed of 4.7 ms^{-1} for the country, while the minimum and maximum monthly average wind speed of 0.8 ms^{-1} and 13.1 ms^{-1} were predicted for Ondo and Kano respectively. The measured data presented in his study revealed that respectively maximum and minimum annual average wind speed of 9.47 ms^{-1} and 1.77 ms^{-1} were recorded in both Jos and Ondo. The trend of the average annual wind speeds reported by this author is in agreement with other previous studies, but the monthlies measured and predicted mean wind speeds reported are generally higher than previous studies [9]. There is needed for continuous assessment of the wind distribution in the country to get accurate data for wind energy applications.

II) **Studies on wind speed for geo-political zone(s) in Nigeria**

Tijjani [12] used 15 years (1986 - 2000) wind data to present the statistical analysis of wind power density based on the Rayleigh and Weibull models in selected locations in North-West Nigeria (Gusau , Yelwa, Sokoto, Kaduna and Kano) and discovered that the monthly mean wind power density of the region ranged between 1.87 Wm^{-2} and 108.8 Wm^{-2}.

Fagbenle et al. [13] assessed the wind-energy potential of Potiskum and Maiduguri in North-Eastern Nigeria using Weibull distribution function and other statistical analysis. They use twenty-one years (1987-2007) monthly average wind data in their analysis and reported that monthly average wind speed variations for Potiskum and Maiduguri are in the range (3.90 to 5.85 ms^{-1}) and (4.35 to 6.33 ms^{-1}) respectively, while the wind-power densities obtained by using Weibull's method are in the range (102.54 to 300.15 Wm^{-2}) for Potiskum and (114.77 to 360.04 Wm^{-2}) for Maiduguri. They concluded that Maiduguri is a better site in terms of monthly and seasonal variation of average wind speed, but both sites are appropriate for off-grid and medium-scale wind power applications.

Furthermore, [3] evaluated the wind-power density in Maiduguri, Gombe and Yola in North-Eastern Nigeria, based on Rayleigh and Weibull models using twelve-year monthly mean wind speed data. They found out that the region has sufficient wind for wind energy application, with the highest power density of 377Wm^{-2} in Gombe.

III) **Studies on wind speed for only one location in Nigeria**

Studies that reported wind speed data for one location in Nigeria are many, some of which include: Anyanwa and Iwuagwu [14] for Owerri, Imo State; Medugu and Malgwi [15] for Mubi, Adamawa State; Ngala et al. [16] for Maiduguri in Borno State; Oriaku et al., [17] for Umudike in Anambra State; Fadare [18] for Ibadan, Oyo state and Olayinka [19] for Uyo in Akwa Ibom State. Their findings are generally related and in agreement with studies that reported wind speed distribution across the country. However, [19] assessed the wind energy potential in Uyo based on Weibull and Rayleigh distribution functions using, 21 years data which span between 1986 and 2007. The study revealed that Uyo has an average wind speed of 3.17 ms^{-1} with a maximum value of 3.67 ms^{-1} in April, while the corresponding annual mean wind power density is about 19.19 Wm^{-2}.

Ahmed et al. [20] assessed the wind-energy resource potential in Plateau, North Central, Nigeria using Weibull distribution. Six years (2000-2006) monthly average wind speed data were used in the study, and the highest wind speed for the location was found to be 15.4 ms^{-1} in January while the lowest wind speed was 8.7 ms^{-1} in August. The study also reveals that wind power density for the location varies between 368 and 1056 Wm^{-2}, hence plateau is a good location for wind power generation.

2.1. Study locations

This study covers six locations in North-western states of Nigeria. The selected sites are: Kebbi, Sokoto, Zamfara, Kano, Kaduna and Katsina. The geographical locations and altitudes of the sites are presented in Table 1.

Table 1: Geographical Locations of North-Western States of Nigeria

Location	State	Latitude	Longitude	Altitude (m)
Sokoto	Sokoto	13.05ºN	5.15ºE	285
Yelwa	Kebbi	11.80ºN	4.34ºE	252
Gusau	Zamfara	12.10ºN	6.15ºE	450
Kano	Kano	12.00ºN	8.31º E	484
Kaduna	Kaduna	10.31ºN	7.26º E	612
Katsina	Katsina	12.15ºN	7.30º E	464

3. Methodology

3.1. Measurement and extrapolation of wind speed

Wind speed data used in this study was measured at 10 metres above the ground level by the Nigerian Meteorological Agency (NIMET) using cup anemometer. The dataset span a period of twenty-two years (1984 – 2005). The increase in wind speed with respect to height was estimated using power law, which is used for the extrapolation of wind speeds at various hub heights using the relation:

$$\frac{v}{v_o} = \left(\frac{h}{h_o}\right)^{\alpha} \quad (1)$$

where:
h = extrapolated height
h_o= reference height
v = wind speed at h
v_o= wind speed measured at h_o
α = surface roughness coefficient (usually taken as 0.143).

3.2 Wind Power Density and Wind Energy Density

Wind power density (WPD) indicates how much energy per unit of time and swept area of the blades is available at the selected area for conversion to electricity by a wind turbine [21]. The mean wind power density was calculated by using the Weibull two parameter methods as expressed by [22]:

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

where:
P(v) = Wind Power Density (Wm^{-2})
v=Wind speed (ms^{-1})
c =Weibull scale parameter (ms^{-1})
k =Weibull shape parameter (dimensionless)
Γ(x) is the gamma function, which is defined as:

$$\Gamma(x) = \int_0^{\infty} t^{x-1}e^{-t}dt \quad (3)$$

ρ =Air density at the site, which can be expressed in the form:

$$\rho = \rho o - 1.194 \times 10^{-4} \times H_m \quad (4)$$

Where ρo is the air density value at sea level usually taken as 1.225 kgm^{-3} and H_m is the site elevation in meters.
The wind energy density (WED) is the product of the mean power density and the time (T) in hours. The daily and annual wind energy density can be estimated by multiplying WPD by 24 and 8760 hours respectively. WED is usually expressed in $kWhm^{-2}$ and can be given as:

$$WED = \frac{1}{2}\rho c^3 \Gamma\left(1+\frac{3}{k}\right)T \quad (5)$$

The Weibull parameters k and c were calculated using the standard deviation method given by [23] as:

$$k = \left(\frac{\sigma}{v_m}\right)^{-1.086} \quad (6)$$

$$c = \frac{V_m}{\Gamma\left(1+\frac{1}{k}\right)} \quad (7)$$

$$\sigma = \left[\frac{1}{N-1}\sum_{i=1}^{N}(v_i - v_m)^2\right]^{1/2} \quad (8)$$

where:
σ= standard deviation
v_m= mean wind speed (ms^{-1})
v_i =observed wind speed (ms^{-1})
N = number of months in the period of time considered.

3.3. Extrapolation of Weibull parameters

As the wind speed is extrapolated from the measured height to any desired height, the shape factor (k) and scale factor (c) of the Weibull distribution will vary as a function of height. The relationship between the Weibull parameters at the anemometer height and at any desired height as proposed by [23] can be expressed as:

$$C_h = C_o \times \left({}^{z_h}/{}_{z_o}\right)^n \quad (9)$$

$$k_h = \frac{k_o[1-0.0881In({}^{z_o}/{}_{10})]}{[1-0.0881In({}^{z_h}/{}_{10})]} \quad (10)$$

where: C_o and k_o are C and k determined at the anemometer height (z_o= 10 metres), C_h and k_h are C and k to be determined at the desired height z_h.The power law exponent n is given by:

$$n = [0.37 - 0.0881In(C_{10})]/[1 - 0.0881In({}^{z_h}/{}_{10})] \quad (11)$$

Where C_{10} is the value of Weibull scale parameter determined at 10 meters height above ground level.

3.4. Classification of wind power using WPD

A classification zone for wind with respect to its WPD in Wm^{-2} has been developed by the Battelle-Pacific Northwest Laboratory (PNL). This classification was made for three heights of 10m, 30m and 50m and divided the wind power to seven different classes as shown in Table 2. In general, wind power Class 4 or higher are considered to be suitable for generating at large and small-scale. Areas classified as Class 2 are considered marginal for the development of wind power projects, while Class 1 areas are not suitable for wind energy investment [24].

Table 2:PNL Wind Power Classification

Wind PowerClass	WPD at 10 m(Wm^{-2})	WPD at 30 m (Wm^{-2})	WPD at 50 m(Wm^{-2})
1	0-99	0-159	0-199
2	100-149	160-239	200-299
3	150-199	240-319	300-399
4	200-249	320-399	400-499
5	250-299	400-479	500-599
6	300-399	480-639	600-799
7	400-1000	640-1600	800-2000

Source: [25]

4. Results and discussion

4.1. Variation of wind speed

The variation of the monthly mean wind speed in the selected sites is presented in Fig. 2.

Fig. 2, shows that the highest and lowest monthly mean wind speed values for the period of the study are between 9.60 ms^{-1}(in June) and 5.84 ms^{-1} (in October) for Sokoto, 8.46 ms^{-1} (in January) and 3.54 ms^{-1} (in October) for Gusau, 7.03 ms^{-1}(in February) and 3.34 ms^{-1} (in October) for Kaduna,11.17 ms^{-1}(in June) and 7.59 ms^{-1} (in October) for Kano, 10.55 ms^{-1}(in June) and 5.82 ms^{-1} (in November) for Katsina, 4.69 ms^{-1}(in April) and 2.59 ms^{-1}(in November) for Yelwa. The lowest and the highest monthly mean measured wind speeds are respectively 2.59ms^{-1} in Yelwa and 11.17 ms^{-1} in Kano. The annual mean wind speed recorded for the period of the study are: 7.99 ms^{-1} for Sokoto, 6.52 ms^{-1} for Gusau, 5.31 ms^{-1} for Kaduna, 9.27 ms^{-1} for Kano, 8.15 ms^{-1} for Katsina and 3.48 ms^{-1} for Yelwa, while the annual mean value for the region is 6.79 ms^{-1}. This value is in agreement with previous study by [8], but is higher than the values reported by [4] and [10].

It can be further observed that wind speed is lower in the rainy season months (August – October) than in the dry season months. Kano has the highest wind speed all round the year in the region. This is in agreement with the findings of previous works in the region and clearly indicates that Kano, Sokoto, Gusau, Katsina and Kaduna experience wind speeds that are viable for economically beneficial wind energy power generation at 10 m heights and above [26].

Wind speed increases with height; hence the variation of wind speed with height in each of the locations was examined. The measured wind speeds at 10 m above the ground level (AGL) were extrapolated to 30 m and 50 m AGL using power law. A comparison of the monthly mean wind speed for Sokoto and the annual mean wind speeds for the study sites, at 10m, 30m and 50m are respectively presented in Figs. 3 and 4.

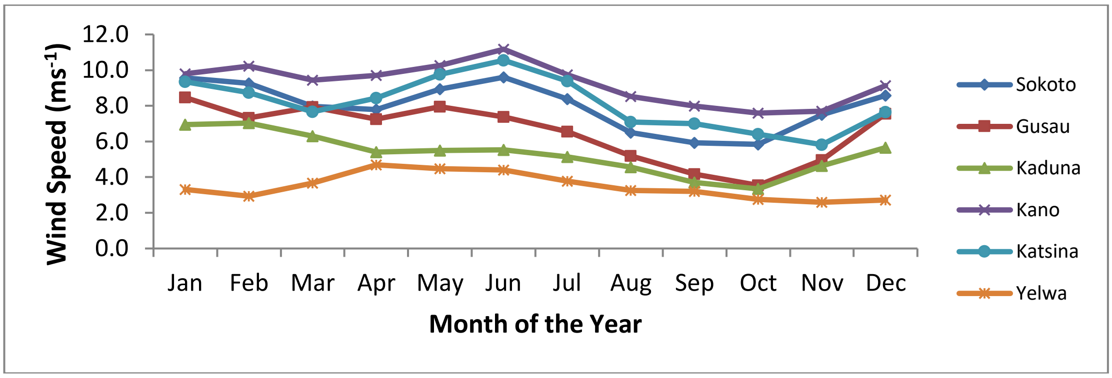

Fig. 2: Monthly Average Wind Speeds (At 10 m Height) Over Sokoto, Gusau, Kaduna, Kano, Katsina, Yelwa and Dutse.

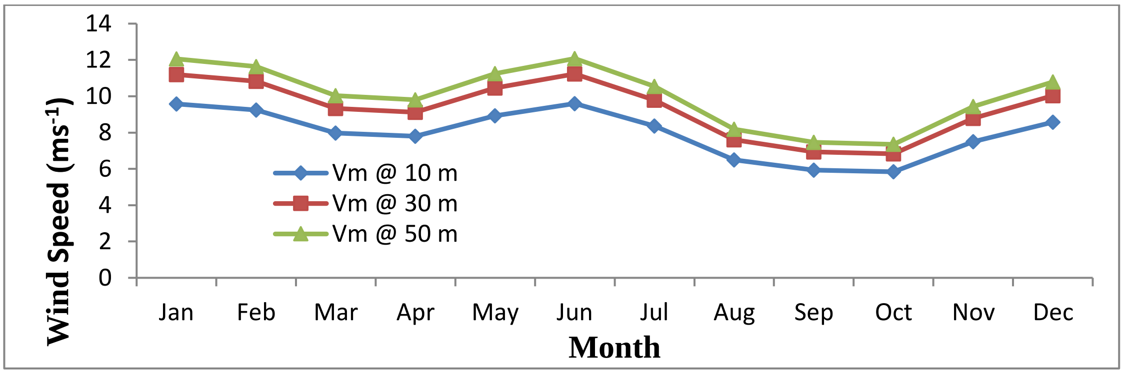

Fig. 3: Mean Monthly Wind Speed (V_m) For Sokoto at 10 m, 30 m and 50 m.

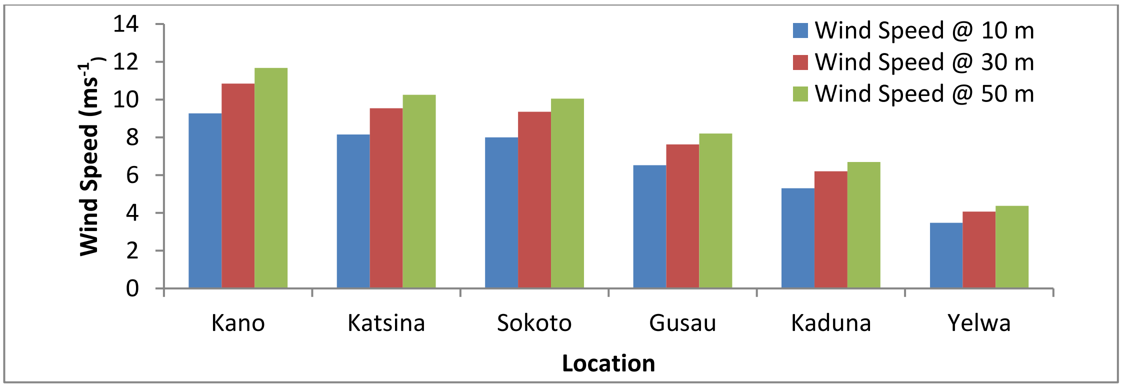

Fig. 4: Mean Annual Wind Speed at 10 m, 30 m and 50 m.

From the result of wind speed extrapolation shown in Fig. 3, it can be observed that the extrapolated wind speed varied in same trend with the measured data in all the months of the year. However, the increase in wind speed between 10 m and 30 m is greater in magnitude than the increase estimated between 30 m and 50 m. Also, it can be noted that the highest and lowest annual mean wind speeds were recorded in Kano and Yelwa respectively. The magnitudes of the annual mean speed at 10 m AGL are: 9.27 ms^{-1} for Kano, 8.15 ms^{-1} for Katsina, 7.99 ms^{-1} for Sokoto, 6.52 ms^{-1} for Gusau, 5.31 ms^{-1} for Kaduna and 3.48 ms^{-1} for Yelwa. The extrapolation of the wind speed from 10 m to 30 m resulted in 17% increase in the wind speed in all the locations while, the extrapolation from 30 m to 50 m brought about 7.5 – 9% increase in the wind speed (which is about half of the value of the first 20 m extrapolation). This implies that the first 20 m extrapolation leads to higher increase in wind speed than the next 20 m extrapolation, thus wind speed does not increase linearly with height.

4.2. Wind energy potential

The wind energy potential of a site can be described in terms of its mean wind speed (v_m), wind power density and wind energy density. The monthly and annual average values of the wind speed wind, Weibull parameters (c and k), wind power density (WPD) and wind energy density (WED) of the study sites at a height of 10 m AGL are presented in Tables 3 – 8.

Tables 3-8, show that the values of the monthly Weibull shape parameter, k, is in the range of 2.94 – 6.74 for Yelwa, 4.06 – 9.86 for Sokoto, 2.74 – 9.91 for Gusau, 4.65 – 9.89 for Kaduna, 5.30 – 16.17 for Kano and 2.12 – 6.14 for Katsina. The shape parameter, k, indicates how peak the wind distribution is when plotting the cumulative frequency curve, and it is useful in determining the most-probable wind speed from the cumulative frequency curve.

Also, it can be observed from Tables 3-8, that the values of monthly Weibull scale parameter, c, correspond to the monthly mean wind speeds in all the study sites. The monthly Weibull scale parameter, c, is in the range of 2.85 – 5.25 ms^{-1} for Yelwa, 6.40 – 10.32 ms^{-1} for Sokoto, 3.90 – 9.42 ms^{-1} for Gusau, 3.63 – 7.61 ms^{-1} for Kaduna, 7.84 – 11.60 ms^{-1} for Kano and 6.28 – 11.44 ms^{-1} for Katsina. The Weibull scale parameter determines the spread of the wind distribution in each location. Thus, Gasau has the highest spread of wind speed in the region.

Furthermore, the monthly wind power density (WPD) and annual average wind energy density (WED) for each of the study sites are as follows: Monthly WPD for Yelwa is in the range of 12.55 – 85.85 Wm^{-2}, which falls into the Wind Class 1 of the PNL wind classification. The annual average WED was estimated to be 0.886 $kWhm^{-2}day^{-1}$ (Table 3). For Sokoto (Table 4), monthly WPD is in the range of 138.07 – 579.48 Wm^{-2}, which falls into the Wind Classes of 2 and 7 of the PNL wind classification. The annual average WED was estimated to be 8.639 $kWhm^{-2}day^{-1}$. For Gusau, monthly WPD is in the range of 31.83 – 467.59 Wm^{-2}, which falls into the Wind Classes between 1 and 7 of the PNL wind classification with an annual average WED estimated to be 5.386 $kWhm^{-2}day^{-1}$ (Table 5). Kaduna's monthly WPD is in the range of 24.61 – 225.66 Wm^{-2}, which falls into the Wind Classes between 1 and 4 of the PNL wind classification and the annual average WED is estimated to be 2.610 $kWhm^{-2}day^{-1}$ (Table 6). The annual average WED for Kano is estimated to be 12.372 $kWhm^{-2}day^{-1}$, while the monthly Weibull WPD is in the range of 259.52 – 832.60 Wm^{-2}, which falls into the Wind Classes between 5 and 7 of the PNL wind classification (Table 7).The annual average WED for Katsina is estimated to be 12.372 $kWhm^{-2}day^{-1}$, while the monthly WPD is in the range of 128.47 – 778.63 Wm^{-2}, which falls into the Wind Classes between 2 and 7 of the PNL wind classification (Table 8).

Table 3: Wind Speed and Other Parameters at 10 m in Yelwa

Period	$V_m(ms^{-1})$	k	$c(ms^{-1})$	$WPD(Wm^{-2})$	$WED(kWhm^{-2}d^{-1})$
Jan	3.30	3.73	3.66	27.19	0.653
Feb	2.93	3.05	3.28	20.90	0.502
Mar	3.67	4.71	4.01	34.63	0.831
Apr	4.69	3.05	5.25	85.85	2.06
May	4.47	2.94	5.01	75.77	1.818
Jun	4.41	3.38	4.91	67.74	1.626
Jul	3.78	3.82	4.18	40.52	0.972
Aug	3.25	3.43	3.62	26.95	0.647
Sep	3.21	4.89	3.50	22.95	0.551
Oct	2.76	4.55	3.02	14.87	0.357
Nov	2.59	4.25	2.85	12.55	0.301
Dec	2.71	6.74	2.90	12.95	0.311
Average	3.48	4.04	3.85	36.91	0.886

Table 4: Wind Speed and Other Parameters at 10 m in Sokoto

Period	$V_m(ms^{-1})$	k	$c(ms^{-1})$	$WPD(Wm^{-2})$	$WED(kWhm^{-2}d^{-1})$
Jan	9.57	5.99	10.32	579.48	13.907
Feb	9.25	4.88	10.09	547.48	13.140
Mar	7.97	5.82	8.61	336.53	8.077
Apr	7.79	6.04	8.39	312.06	7.490
May	8.93	9.86	9.39	442.50	10.620
Jun	9.60	9.84	10.10	549.82	13.196
Jul	8.37	7.45	8.92	374.86	8.997
Aug	6.50	6.61	6.97	178.55	4.285
Sep	5.93	5.94	6.40	138.07	3.314
Oct	5.84	4.06	6.44	145.58	3.494
Nov	7.50	4.85	8.18	292.19	7.013
Dec	8.57	5.55	9.28	422.42	10.138
Average	7.99	6.41	8.59	359.96	8.639

Table 5: Wind Speed and Other Parameters at 10 m in Gusau

Period	$V_m(ms^{-1})$	k	$c(ms^{-1})$	$WPD(Wm^{-2})$	$WED(kWhm^{-2}d^{-1})$
Jan	8.46	3.40	9.42	467.59	11.222
Feb	7.33	2.74	8.24	341.79	8.203
Mar	7.93	4.41	8.70	349.11	8.379
Apr	7.25	7.34	7.73	240.04	5.761
May	7.94	9.91	8.35	305.77	7.339
Jun	7.37	7.91	7.83	249.85	5.996
Jul	6.55	6.17	7.05	181.77	4.362
Aug	5.19	4.64	5.68	96.37	2.313
Sep	4.16	3.88	4.60	52.62	1.263
Oct	3.54	4.08	3.90	31.83	0.764
Nov	4.96	5.28	5.39	81.43	1.954
Dec	7.56	4.82	8.25	294.83	7.076
Average	6.52	5.38	7.09	224.42	5.386

Table 6: Wind Speed and Other Parameters at 10 m in Kaduna

Period	V_m(ms^{-1})	k	c(ms^{-1})	WPD(Wm^{-2})	WED($kWhm^{-2}d^{-1}$)
Jan	6.95	4.79	7.59	225.66	5.416
Feb	7.03	5.57	7.61	225.37	5.409
Mar	6.30	4.65	6.89	169.43	4.066
Apr	5.40	6.87	5.78	98.45	2.363
May	5.50	6.93	5.88	103.88	2.493
Jun	5.53	9.53	5.83	101.92	2.446
Jul	5.14	9.89	5.41	81.59	1.958
Aug	4.56	8.07	4.84	58.07	1.394
Sep	3.71	7.26	3.96	31.68	0.760
Oct	3.34	5.14	3.63	24.61	0.591
Nov	4.64	5.42	5.03	65.17	1.564
Dec	5.65	5.10	6.15	119.35	2.864
Average	5.31	6.60	5.72	108.76	2.610

Table 7: Wind Speed and Other Parameters at 10 m in Kano

Period	V_m(ms^{-1})	k	c(ms^{-1})	WPD(Wm^{-2})	WED($kWhm^{-2}d^{-1}$)
Jan	9.80	5.30	10.64	625.48	15.012
Feb	10.22	6.02	11.01	690.97	16.583
Mar	9.44	6.22	10.16	541.47	12.995
Apr	9.70	10.55	10.17	553.02	13.272
May	10.26	10.20	10.78	656.02	15.744
Jun	11.17	13.60	11.60	832.60	19.982
Jul	9.74	12.06	10.16	555.29	13.327
Aug	8.52	10.29	8.95	375.42	9.010
Sep	7.99	8.21	8.47	315.93	7.582
Oct	7.59	16.17	7.84	259.52	6.228
Nov	7.70	7.55	8.20	285.53	6.853
Dec	9.14	6.00	9.85	494.68	11.872
Average	9.27	9.35	9.82	515.49	12.372

Table 8: Wind Speed and Other Parameters at 10 m in Katsina

Period	V_m(ms^{-1})	k	c(ms^{-1})	WPD(Wm^{-2})	WED($kWhm^{-2}d^{-1}$)
Jan	9.34	3.38	10.40	630.14	15.123
Feb	8.73	3.12	9.76	534.61	12.831
Mar	7.66	4.09	8.44	321.83	7.724
Apr	8.43	5.73	9.11	392.33	9.416
May	9.76	6.14	10.51	601.00	14.424
Jun	10.55	5.40	11.44	778.63	18.687
Jul	9.38	4.48	10.28	573.91	13.774
Aug	7.08	4.93	7.72	240.45	5.771
Sep	7.00	5.10	7.62	230.40	5.530
Oct	6.41	2.12	7.24	278.33	6.680
Nov	5.82	5.87	6.28	128.47	3.083
Dec	7.65	4.41	8.39	312.83	7.508
Average	8.15	4.56	8.93	418.58	10.046

Tables 3-8, show that the values of the monthly Weibull shape parameter, k, is in the range of 2.94 – 6.74 for Yelwa, 4.06 – 9.86 for Sokoto, 2.74 – 9.91 for Gusau, 4.65 – 9.89 for Kaduna, 5.30 – 16.17 for Kano and 2.12 – 6.14 for Katsina. The shape parameter, k, indicates how peak the wind distribution is when plotting the cumulative frequency curve, and it is useful in determining the most-probable wind speed from the cumulative frequency curve.

Also, it can be observed from Tables 3-8, that the values of monthly Weibull scale parameter, c, correspond to the monthly mean wind speeds in all the study sites. The monthly Weibull scale parameter, c, is in the range of 2.85 – 5.25 ms^{-1} for Yelwa, 6.40 – 10.32 ms^{-1} for Sokoto, 3.90 – 9.42 ms^{-1} for Gusau, 3.63 – 7.61 ms^{-1} for Kaduna, 7.84 – 11.60 ms^{-1} for Kano and 6.28 – 11.44 ms^{-1} for Katsina. The Weibull scale parameter determines the spread of the wind distribution in each location. Thus, Gasau has the highest spread of wind speed in the region.

Furthermore, the monthly wind power density (WPD) and annual average wind energy density (WED) for each of the study sites are as follows: Monthly WPD for Yelwa is in the range of 12.55 – 85.85 Wm^{-2}, which falls into the Wind Class 1 of the PNL wind classification. The annual average WED was estimated to be 0.886 $kWhm^{-2}day^{-1}$ (Table 3). For Sokoto (Table 4), monthly WPD is in the range of 138.07 – 579.48 Wm^{-2}, which falls into the Wind Classes of 2 and 7 of the PNL wind classification. The annual average WED was estimated to be 8.639 $kWhm^{-2}day^{-1}$. For Gusau, monthly WPD is in the range of 31.83 – 467.59 Wm^{-2}, which falls into the Wind Classes between 1 and 7 of the PNL wind classification with an annual average WED estimated to be 5.386 $kWhm^{-2}day^{-1}$ (Table 5). Kaduna's monthly WPD is in the range of 24.61 – 225.66 Wm^{-2}, which falls into the Wind Classes between 1 and 4 of the PNL wind classification and the annual average WED is estimated to be 2.610 $kWhm^{-2}day^{-1}$ (Table 6). The annual average WED for Kano is estimated to be 12.372 $kWhm^{-2}day^{-1}$, while the monthly Weibull WPD is in the range of 259.52 – 832.60 Wm^{-2}, which falls into the Wind Classes between 5 and 7 of the PNL wind classification (Table 7). The annual average WED for Katsina is estimated to be 12.372 $kWhm^{-2}day^{-1}$, while the monthly WPD is in the range of 128.47 – 778.63 Wm^{-2}, which falls into the Wind Classes between 2 and 7 of the PNL wind classification (Table 8).

4.3. Wind power density

The estimated wind power density at 10 m, 30 m and 50 m above the ground level are presented in Table 9.

Table 9: Wind Power Density at Different Heights above the Ground Level

Location	WPD (Wm^{-2})@ 10m	Class	WPD(Wm^{-2})@ 30m	Class	WPD(Wm^{-2})@ 50m	Class	Resource Potential
Yelwa	28.30	1	45.33	1	56.43	1	Very Poor
Kaduna	97.21	1	155.76	1	193.87	1	Poor
Gusau	188.93	3	302.63	3	376.95	3	Marginal
Sokoto	325.72	6	521.92	6	649.61	6	Very Good
Katsina	344.26	6	551.41	6	686.81	6	Very Good
Kano	483.72	7	775.19	7	964.77	7	Excellent

From Table 9, it can be observed that the annual mean wind power density in North-Western Nigeria is lowest in Yelwa and highest in Kano. The values of the WPD vary from 28.30 Wm^{-2} to 483.72Wm^{-2} at 10 m hub height, 45.33 Wm^{-2} to 775.19 Wm^{-2}at 30 m hub height and 56.43 $Wm^{-2}$to 964.77 Wm^{-2} at 50 m hub height. Also, the values of the wind-power density increase with height, nevertheless, the wind-power class for each location remains constant irrespective of the height at which the wind power is estimated. According to PNL classification, Yelwa and Kaduna fall into class1. Gusau falls into class 3, Sokoto, and Katsina fell into class 6, while Kano falls into class 7. This indicates that Kano, Sokoto and Katsina have sufficient wind energy that is suitable for economic large-scale wind power generation. Also, Gusau which falls into class 3 is considered marginal for wind power generation. However, this site will be suitable for small-scale electricity generation by using special wind turbines, which have low cut-in speeds, water pumping and other low-energy capacity applications that require intermittent power supply. Yelwa and Kaduna have poor wind potential, and may not be suitable for wind power generation.

5. Conclusion

Nigeria has reasonable amount of wind energy resources which can be harnessed for power generation. Studies show that some locations in the northern part of the country are more favourable to wind power generation because they have higher wind speeds compared to most locations in the southern region. This assessment of wind energy resources at the selected sites in the north-western region of Nigeria reveals that:

i) The highest and lowest annual mean wind speeds at 10 m AGL in the region are respectively recorded in Kano (9.27 ms^{-1}) and Yelwa (3.48 ms^{-1}), while the annual mean value of wind speed for the region is 6.79 ms^{-1}.

ii) The wind speed at 30 m above the ground level is 17% higher than wind speed at 10 m in all the locations, while the extrapolation from 30 m to 50 m resulted to about 7.5 – 9% increase in the wind speeds.

iii) The wind-energypotential in the region is lowest in Yelwa and highest in Kano. The value of the WPD varies from 28.30 Wm^{-2} to 483.72Wm^{-2} at 10 m AGL, 45.33 Wm^{-2} to 775.19 Wm^{-2} at 30 m AGL and 56.43 Wm^{-2} to 964.77 Wm^{-2} at 50 m AGL.

iv) The result of this study indicates that Kano, Sokoto and Katsina are suitable for economic large-scale wind power generation. Gusau is suitable for small-scale wind power generation, but Yelwa and Kaduna may not be suitable for wind power production because of their poor wind potential.

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