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Feasibility Assessment of Wind Energy Potential for Electricity Generation in Nigeria

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Abstract— Nigeria is ranked among the lowest countries in terms of per capita energy consumption in the world. It also produces significant CO_2 emissions. Hence, there is a vital need for clean and accessible energy in the country. Wind energy systems are one of such options. In this work, wind speed data measured at 10m above ground level from 2011 to 2016 for thirteen Nigerian sites are analyzed and the two–parameter Weibull distribution probability density function is used for wind power assessment. Moreover, the average wind power density and the corresponding wind energy density are obtained and the potential of electricity generation by means of wind turbines is assessed. The results reveal that Kano and Jos have the highest wind power potential with wind power densities of 79.96 W/m² and 133 W/m², respectively. With about 43 and 20 MWh of annual generated electric energy at Jos and Kano, respectively, these two sites proved to be the most promising candidates for utilizing wind turbines for electricity generation.

Keywords— Wind speed; Wind turbine; Wind power density; Wind energy density; Electricity generation; Feasibility assessment; Nigeria.

Nomenclature

V	Wind speed
C	Weibull scaling parameter
K	Weibull shape parameter
$\bar{V}$	Mean wind speed
v_i	Recorded wind speed
N	Nonzero wind speed data points
Γ	Gamma function and $\bar{V}$ is the mean wind speed
f	Weibull distribution probability density function
V_{rmc}	Root mean cube value of wind speed
ρ	Air density
P_w	Wind power density or wind power/unit area
E_w	Annual wind Energy density
V_1	Wind speed at a known height h_1
V_2	Wind speed at an unknown height higher than h_1
h_1	Known height
h_2	Unknown height higher than h_1
a	Roughness or wind shear factor.
P_{out}	Output power
C_p	Power Coefficient
$E_{WT\text{-}out}$	Annual energy output of the wind turbine
GDP	Gross Domestic Product

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1. INTRODUCTION

Nigeria has been contending with inadequate electric power supply for decades. The poor and erratic nature of electricity supply in Nigeria has been investigated by some researchers [1, 2]. Inspite of Nigeria's poor electricity generation, electricity demand is increasing and is projected to be between 254.1 billion kWh, and 341.7 billion kWh by the year 2040 depending on the analysis scenario [3].

A study estimated that electricity generation is a major contribution to greenhouse gas emission in Nigeria. CO_2 gas emitted from Nigeria's operational thermal power plants was estimated to be 87.3 million metric tons, with an additional 67.9 million metric tons expected from power plants under construction [4]. Another study revealed that there was a relationship between energy consumption, CO_2 emissions and GDP. GDP growth resulted in an increase in CO_2 emissions. To reduce them, it was recommended to explore alternative sources of energy with least CO_2 emissions (i.e. renewable energy sources) [5]. However, the cost of renewable energy systems is failing but wind energy systems have been found to have the lowest capital for producing electricity compared with solar energy source [6]. As the cost of wind energy systems continues to fall due to newer technologies, it will be an important source of future energy demand.

Nigeria has potential for the growth of renewable energy systems including wind energy systems. Wind speed data obtained from 1951-1975 from 22 stations across the country showed that wind speed in Nigeria ranges from about 2 m/s in the southern areas to 5.12 m/s in the northern areas [7]. In the use of artificial neural networks to predict the wind speeds distribution across Nigeria in comparism with measured data from 28 stations over a period that spanned between 1983 and 2003, the predicted monthly average wind speed ranges from a minimum of 0.8 m/s in Ondo (in southern region) to a maximum value of about 13.1 m/s in Kano (in northern region) with an overall average annual wind speed of 4.7 m/s. The highest maximum annual average wind speed of 9.47 m/s was predicted for Jos, closely followed by Kano with wind speed of 9.39 m/s. The lowest minimum annual average value wind speed of 1.77 m/s was predicted for Ondo [8].

There are many methods for analyzing the measured wind speed data. Abdulkarim et al. used Weibull, Rayleigh and Gamma distribution functions to statistically determine the accurate frequency distribution that fits wind speed data and predict the average wind-power densities for selected sites in northern Nigeria. Based on the percentage error between the predicted and the actual power densities, the Weibull distribution was ranked highest in predicting the average wind power densities, followed by the Gamma and Rayleigh distribution functions [9]. The two-parameter Weibull distribution function was used to analyze wind speed data in Chad. The study revealed that the wind speed increases as one moves from the southern zone to the Saharan zone. Based on the annual averaged data, the most suitable sites for wind energy generation in Chad were Ab´ech´e, Ndjamena, Pala, Mongo, and Faya-Largeau. However, some sites were not suitable for wind power generation, because of their weak wind speed of about 1m/s [10]. The Weibull parameters were also used in estimating the wind power potential in three Australian sites. The study indicated that Hamilton Island is the most feasible site with an annual mean wind speed of 7.5 m/s compared with Proserpine and South JohnStone [11]. The Weibull distribution function has been used across the world in analyzing wind speed data [12 - 16]. The Weibull density function is generally used in evaluating wind speed data because it uses two parameters. Hence it is more accurate and fits wind speed data more broadly [9, 16, 17].

Wind power potential can be obtained from the wind power density in an area. Wind power density has been categorized into seven classes to describe the usefulness of wind power in an area [18, 19]. Wind power densities within class 1 are poor. Class 2 wind power densities are marginal while class 3 wind power densities are suitable for wind energy systems [16]. Wind classes above class 4 are suitable for large scale wind systems [18].

Due to Nigeria's vital need in utilizing renewable energies - especially wind - for electricity generation in order to overcome its energy crisis and to reduce the CO_2 emissions, it is essential to conduct more investigations to assess wind power in Nigeria, especially in its vegetational zones, which have not been explored yet. For this reason, the current work investigates the feasibility of wind power generation for thirteen sites across Nigeria's vegetational zones. For this purpose, the average wind power density and the corresponding wind energy density are estimated. Moreover, the wind energy potential for electricity generation by means of wind turbines is investigated for the selected sites.

2. METHODOLOGY

2.1. The Investigated Sites

The feasibility assessment of the wind energy potential in the considered thirteen sites across Nigeria's vegetational zones were assessed using measured wind speed data for six-year period (2011 to 2016). The data were obtained from the Nigeria's Metrological Agency. The wind speed data were recorded at each location at a height of 10 m. The geographical coordinates of the investigated sites and their elevation from sea level are presented in Table 1, while Fig. 1 represents the map of Nigeria showing the thirteen considered sites.

Table 1. Geographical coordinates and elevation of the thirteen selected cities.

S/N	Site	Latitude	Longitude	Elevation [m]
1	Ikeja	6°35′47″ N	3°20′31″ E	40
2	Port Harcourt	4°46′38″ N	7°00′48″ E	16
3	Calabar	4°57′32″ N	8°19′37″ E	37
4	Ibadan	7°22′39″ N	3°54′21″ E	181
5	Benin City	6°20′17″ N	5°37′32″ E	88
6	Owerri	5°29′01″ N	7°01′59″ E	73
7	Lokoja	7°47′48″ N	6°44′25″ E	53
8	Abuja	9°03′28″ N	7°29′42″ E	476
9	Makurdi	7°44′01″ N	8°31′17″ E	92
10	Jos	9°54′48″ N	8°53′51″ E	1217
11	Sokoto	13°03′45″ N	5°14′35″ E	296
12	Kano	12°00′00″ N	8°31′00″ E	486
13	Maiduguri	11°50′48″ N	13°09′25″E	325

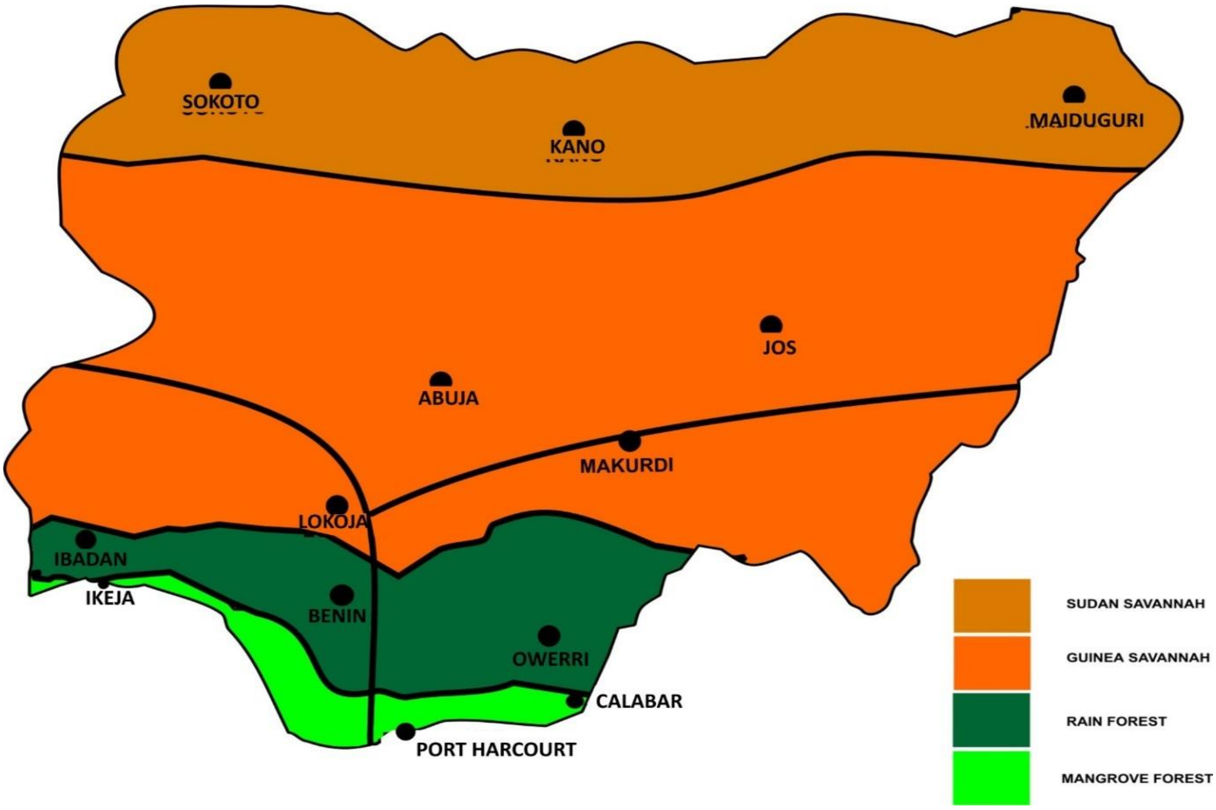

Fig. 1. Map of Nigeria showing the investigated sites.

2.2. Statistical Analysis of Wind Data

The Weibull distribution probability density function for wind speed is expressed by [17]:

$$f(v) = \left(\frac{K}{C}\right)\left(\frac{V}{C}\right)^{k-1} e^{\left(\frac{V}{C}\right)k} \quad (K > 0, V > 0, C > 0) \tag{1}$$

The weibull shape factor can be evaluated using [20]:

$$K = 0.83\, \bar{V}^{0.5} \tag{2}$$

The weibull scale factor can be evaluated from the following equation [17]:

$$C = \frac{\bar{V}}{\Gamma\left(1+\frac{1}{k}\right)} \tag{3}$$

It should be noted that the annual average wind power is proportional to the cube of the wind speed. Clearly, the effective value of the wind speed will be the root mean cube value instead of the average value. It is comparable to the relationship that exist between the average value and the root mean square value of voltage. Therefore, better results will be obtained if the root mean cube value of V_{rmc}, expressed in the following equation is used in place of $\bar{V}$ in Eq. (3) [21, 22].

$$V_{rmc} = \sqrt[3]{\frac{1}{N}\sum_{i=1}^{N} V_i^3} \tag{4}$$

The average wind-power/unit area (available wind power/unit area) at a particular site is given by::

$$P_w = \frac{1}{2}\,\rho\, V_{rmc}^3 \tag{5}$$

Here, ρ is assumed to be 1.225 kg/m^3 [19].

The average wind power density per unit area or available wind power/swept area by a wind generator blade from a Weibull probability density function can be obtained using the following euation [16]:

$$P_w = \frac{1}{2}\rho C^3 \Gamma\left(1+\frac{3}{k}\right) \quad (6)$$

The average annual wind energy density/unit area can be obtained by multiplying the average wind power density by the number of hours in one day and the number of days in a year as given by:

$$E_w = P_w \, x \, 24 \times 365 = P_w \, x \, 8760 \quad (7)$$

Wind speed is usually measured at a height of 10 m, while the hub height of most wind turbines are usually higher than that. Thus, wind speed at a height greater than 10 m can be evaluated using [23]:

$$V_2 = V_1 \left(\frac{h_2}{h_1}\right)^{\alpha} \quad (8)$$

2.3. Potential of Wind Energy for Electricity Generation

In order to assess the potential of wind energy for electricity generation, a wind turbine with the specifications shown in Table 2 was selected [24]. The average wind speed at the turbine's hub height of 25m were extrapolated from the measured at 10m wind speed data using Eq. (8). The power law exponents for varying terrain were 0.3 in the forested area, 0.22 in the Guinea savannah area and 0.2 in the Sudan savannah area [25]. The turbine's parameters were applied in Eq. (9) in order to calculate the annual electric energy output of the wind turbine.

$$E_{WT-out} = \frac{1}{2}\rho A V^3 C_p \, x \, 8760 \quad (9)$$

Table 2. Specifications of Atlantis wind turbine ASWT 9.0-20 kW.

Parameter	Value
Rated power [kW]	20
Maximum output power [kW]	28
Cut-in wind speed [m/s]	3
Rated wind speed [m/s]	11.5
Cut-out wind speed [m/s]	3-25
Hub height [m]	25
Generator's efficiency	> 0.85
Number of blades	3
Blade diameter [m]	9

3. RESULTS AND DISCUSSION

The mean wind speed for the considered period and the corresponding results of V_{rmc} are presented in Table 3. Figs. 2–5 exhibit the monthly average of Weibull shape parameter, the monthly average of the scale parameter, the average power densities and the annual wind energy density for the investigated sites.

Table 3. Mean and root mean cube values of wind speed at the investigated sites.

Site	Parameter	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Ikeja	$\bar{V}$	1.86	2.10	2.19	2.03	1.81	1.96	2.36	2.90	2.60	1.58	1.54	1.89
	V_{rmc}	1.92	2.14	2.23	2.19	1.85	2.03	2.48	3.14	2.91	1.65	1.60	1.99
Port Harcourt	$\bar{V}$	1.23	1.39	1.39	1.34	1.28	1.19	1.39	1.46	1.37	1.26	1.15	1.18
	V_{rmc}	1.28	1.48	1.50	1.36	1.29	1.23	1.44	1.53	1.48	1.36	1.27	1.32
Calabar	$\bar{V}$	1.42	1.75	1.68	1.68	1.88	1.63	1.49	1.63	1.82	1.83	1.65	1.59
	V_{rmc}	1.50	1.84	1.77	1.76	2.17	1.72	1.59	1.66	1.88	1.97	1.70	1.65
Ibadan	$\bar{V}$	2.24	2.31	2.42	2.49	2.21	2.23	2.47	2.40	2.13	1.65	1.65	1.75
	V_{rmc}	2.30	2.36	2.47	2.56	2.25	2.23	2.48	2.52	2.16	1.86	1.73	1.84
Benin City	$\bar{V}$	1.67	1.88	2.12	2.02	1.88	1.88	2.00	2.03	1.81	1.99	1.45	1.57
	V_{rmc}	1.81	2.01	2.22	2.18	1.95	1.91	2.06	2.15	1.82	2.15	1.46	1.58
Owerri	$\bar{V}$	1.96	1.76	1.79	1.85	1.75	1.67	1.58	1.60	1.62	1.54	1.44	1.59
	V_{rmc}	2.12	1.79	1.85	1.91	1.79	1.68	1.60	1.64	1.62	1.57	1.48	1.69
Lokoja	$\bar{V}$	1.30	1.98	2.10	2.36	1.97	1.67	1.70	1.88	1.51	1.74	1.35	1.17
	V_{rmc}	1.45	1.99	2.21	2.42	2.02	1.77	1.83	1.93	1.54	1.79	1.46	1.34
Abuja	$\bar{V}$	2.35	2.27	2.45	2.43	2.25	1.85	2.19	1.99	2.00	2.01	2.01	2.31
	V_{rmc}	2.35	2.28	2.45	2.44	2.25	2.08	2.21	1.99	2.01	2.02	2.02	2.32
Makurdi	$\bar{V}$	3.05	2.63	2.65	2.51	2.30	2.18	2.33	2.36	2.15	2.21	2.22	2.68
	V_{rmc}	3.12	2.66	2.68	2.52	2.32	2.21	2.35	2.38	2.18	2.23	2.27	2.85
Jos	$\bar{V}$	5.40	5.77	5.31	5.76	5.68	5.43	5.01	5.13	4.44	4.17	4.77	6.01
	V_{rmc}	5.77	6.05	5.35	5.77	5.70	5.45	5.06	5.17	4.47	4.27	4.88	6.20
Sokoto	$\bar{V}$	3.78	3.99	3.81	4.10	4.66	4.42	3.73	2.85	2.48	3.01	3.35	3.62
	V_{rmc}	3.90	4.03	3.84	4.45	4.68	4.45	3.77	2.90	2.54	3.12	3.93	3.77
Kano	$\bar{V}$	4.46	3.74	4.05	4.36	5.32	5.65	4.83	3.88	3.28	2.90	3.14	4.10
	V_{rmc}	4.49	3.86	4.21	4.43	5.33	5.73	4.94	3.99	3.46	3.06	3.21	4.15
Maduguri	$\bar{V}$	2.54	2.94	3.83	3.25	3.40	3.93	3.67	3.03	2.49	2.37	2.56	2.85
	V_{rmc}	2.61	3.01	3.86	3.33	3.47	4.02	3.80	3.10	2.57	2.41	2.59	2.97

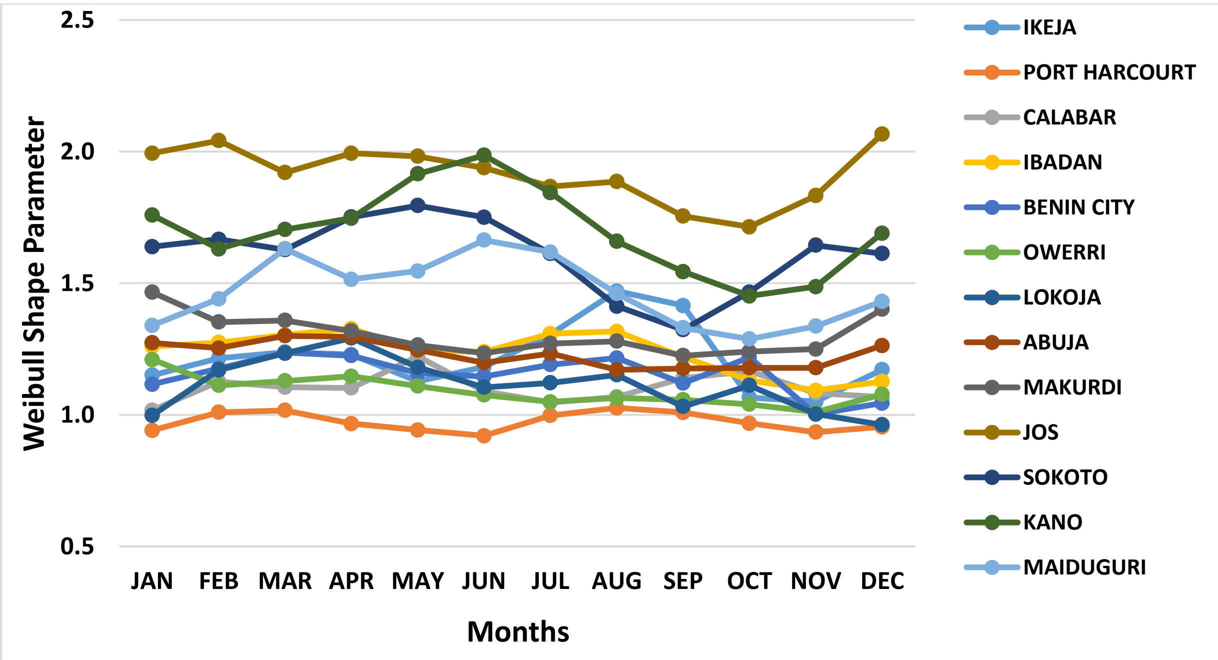

Fig. 2. Monthly Weibull shape parameter for the investigated sites.

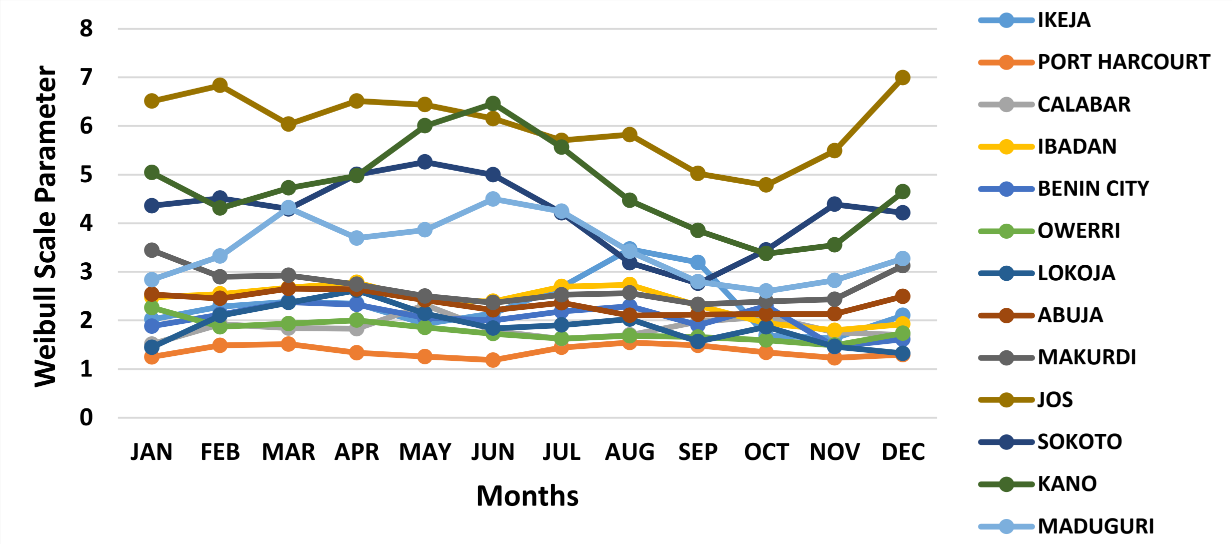

Fig. 3. Monthly Weibull scale parameter for the investigated sites.

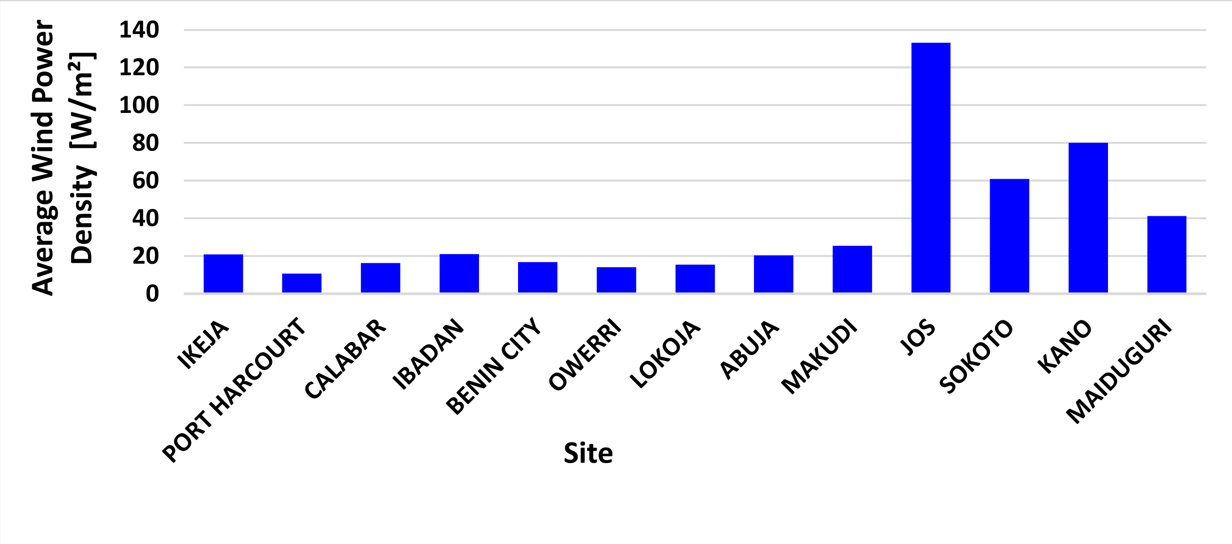

Fig. 4. Average wind power densities for the investigated sites.

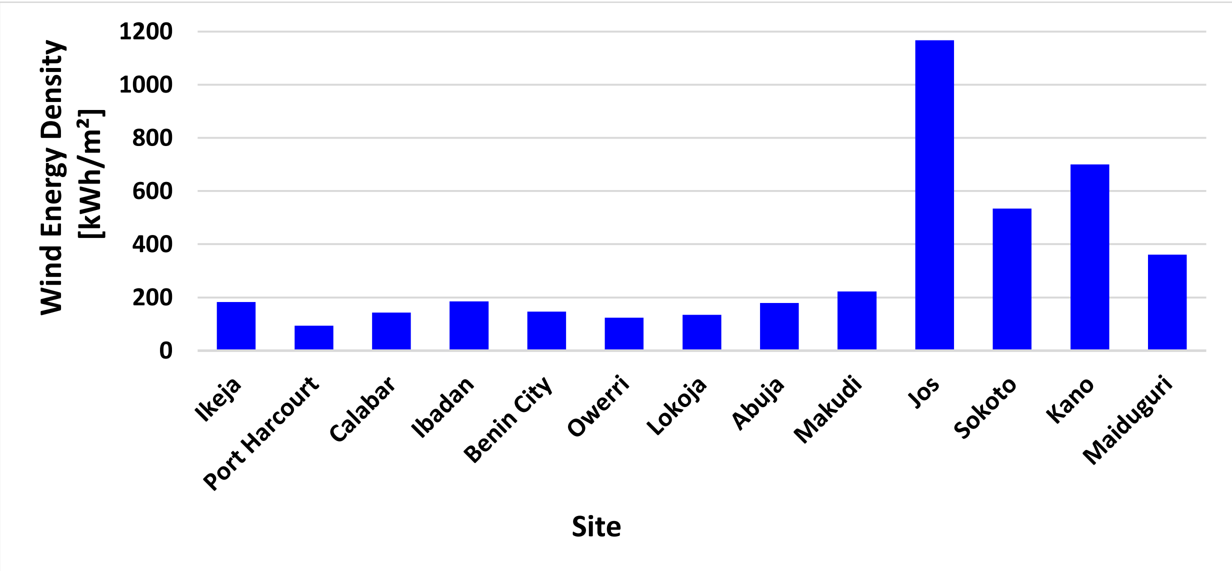

Fig. 5. Wind energy densities for the investigated sites.

From the obtained results, the average wind speed increases as it moves from the southern to the northern parts of Nigeria. The only exception is Jos, in which the high wind speed can be attributed to its elevation of 1217 m. The wind speed in the savannah region (an open area) is higher than the wind speed in the forested region. The low wind speed in the southern part of the country can be attributed to the forested vegetation that also acts as an obstruction to wind flow.

On the average, the wind speed in the forested region (Ikeja, Port Harcourt, Calabar, Ibadan, Benin City and Owerri) ranges between 1.3 m/s and 2.23 m/s while their wind power density ranges between 10 W/m^2 and 21 W/m^2. The wind speed in the Guinea Savanah region (Abuja, Lokoja and Makurdi) ranges between 1.8 m/s to 2.48 m/s while their wind power density ranges between 14 W/m^2 and 25 W/m^2. The wind speed in the Sudan Savannah region (Sokoto, Kano and Maiduguri) ranges between 3.14 m/s and 4.24 m/s and their corresponding wind power density ranges between 41 W/m^2 and 79.96 W/m^2. The average wind speed for Jos is 5.34 m/s and the wind power density is 133 W/m^2.

Fig. 6 represents wind speed at 25 m (the wind turbine's hub height) for the investigated sites, calculated using Eq. (8). It is noted that the wind potential in these areas is improved if vertically extrapolated above 10 m.

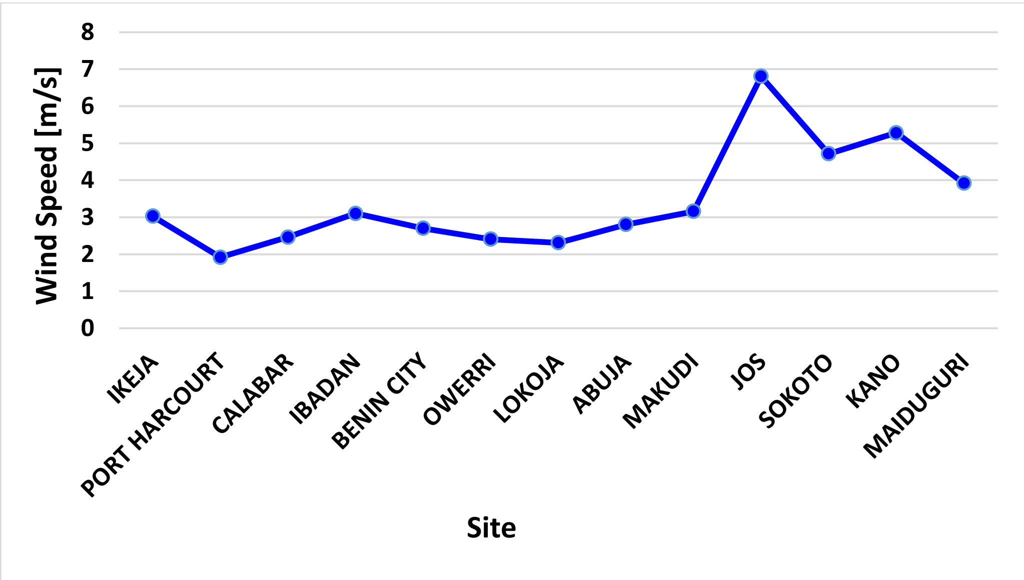

Fig. 6. Wind speed at 25m height for the selected sites.

Fig. 7 exhibits the annual electric energy, generated by the 20 kW wind turbine. At 25 m, this energy is significantly higher than the predicted annual wind energy density at 10 m even at a capacity factor of 0.4. Since the cut-in wind speed for most of wind turbines - including the one utilized in this investigation - is 3 m/s, Ikeja, Ibadan, and Makurdi can produce marginal energy from the 20 kw turbine, because the adjusted wind speed at the hub height of 25 m is less than or equal to 3 m/s. On the contrary, Sokoto, Kano, Maiduguri and Jos constitute good candidates for utilizing a small size wind turbines for electricity generation. Among these sites, Jos is the most promising with about 43 MWh annual electricity followed by Kano, Sokoto and Maiduguri with annual electricity generation of 20 MWh, 14 MWh and 8 MWh, respectively.

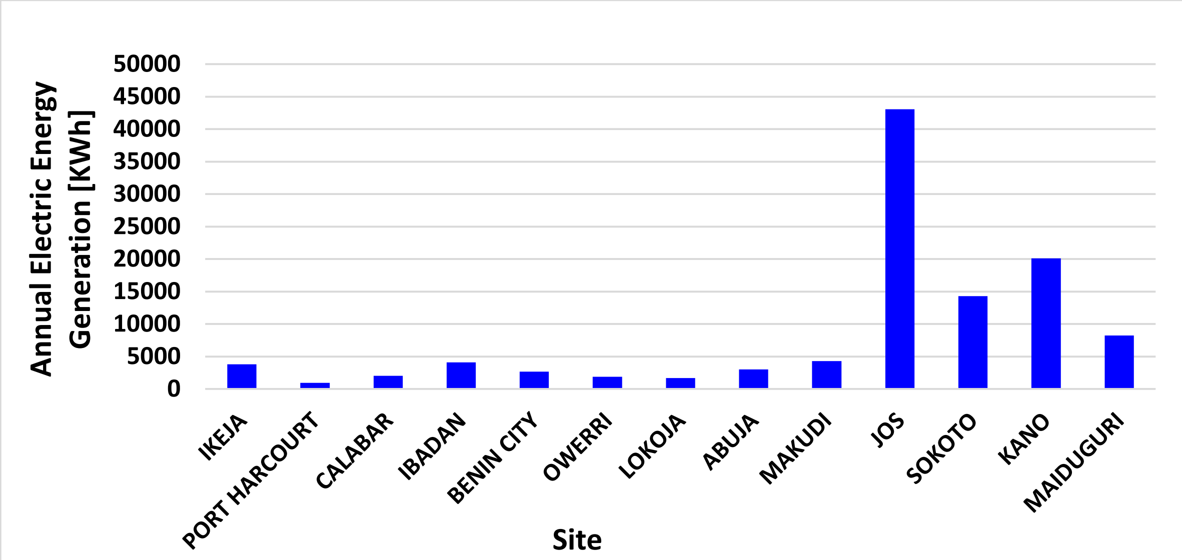

Fig. 7. Annual electric energy, generated by the 20 kw wind turbine at the selected sites.

4. CONCLUSIONS

Measured wind speed data for a six-year period (2011 – 2016) was analyzed using the Weibull shape and scale parameters in order to assess the wind power potential at thirteen Nigerian sites.

The results showed that the wind power densities at the investigated sites were generally poor (at class 1), with the exception of Jos that is in class 2. However, the average wind speed measured at 10 m above ground level in Jos, Sokoto, Kano and Maiduguri were above 3.0 m/s - the cut-in wind speed for most wind turbines. The annual electricity, generated by the 20 kW wind turbine at its hub height of 25 m was found to be 3884, 4070, 4296, 8209, 14276, 20077 and 43042 kWh for Ikeja, Ibadan, Makurdi, Maiduguri, Sokoto, Kano and Jos, respectively. For the rest of the investigated sites, the correlated wind speed at 25 m hub height was found to be less than the cut-in wind speed of the wind turbine; hence they are not suitable for electricity generation.

The above results reveal that electricity generation from small stand-alone wind energy systems in Jos, Sokoto, Kano and Maiduguri is quite promising. Therefore, potential exists for small stand-alone wind systems in some parts of Nigeria. Such systems can fulfill the energy needs of many households, especially in rural areas, where the energy demand is low. They can also replace the existing small petrol/diesel generators in Nigeria and consequently contribute to a more pollution free environment.

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