WIND ENERGY EVALUATION AND TURBINE IDENTIFICATION FOR POWER GENERATION IN SOME SELECTED AREAS IN NIGERIA

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Abstract: In this paper, the wind power potentials as well as wind speed characteristics of four selected locations in the North-Central (Ilorin and Makurdi) and North-East (Gombe and Maiduguri) parts of Nigeria are investigated. The data used are obtained from Nigeria Meteorological Agency (NIMET) between the durations of 11 and 54 years, measured at an anemometer height of 10m. The analysis of the data is carried out using a two-parameter Weibull Distribution Function (WDF). The most probable wind-speed and the wind-speed carrying the maximum energy were also evaluated. The capacity factor estimation is then used to identify the most suitable turbine for the sites. The results obtained show a monthly mean wind-speed of 4.50 m/s, 3.72 m/s, 4.77 m/s and 5.34 m/s for Ilorin, Gombe, Makurdi and Maiduguri respectively, while the wind-power densities were 67.74 W/m^2, 40.87 W/m^2, 79.52 W/m^2 and 107.49 W/m^2 respectively for the same sites.

Keywords: wind speed, weibull-distribution function, turbine, capacity factor, wind power density

1. INTRODUCTION

It is a known fact that economic development of any nation is tied to its adequate and sustainable energy production [1]. Energy is a very powerful ingredient that is very essential for both social and economic well-being of any nation. Most of the energy supply is usually from fossil fuels, which cause global environmental problems that are not sustainable [2]. This global environmental problem includes ozone layer depletion, global warming, acid rain, etc. Large energy production from pollution free sources is the main solution for resolving this challenge.

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Wind energy can solve this menace caused by the utilization of fossil fuel for energy production [3]. In terms of cost, wind energy is less expensive compared to other renewable energy sources [4]. Today, the most used renewable source of energy, for electricity generation in different countries of the world such as the United States (US), United Kingdom (UK), Holland, Denmark, Sweden and Germany, is offshore wind energy [5]. Ironically, developing countries that are in dire need of energy and blessed in great abundance of this resources are still yet to harness the potential of wind energy.

Nigeria is a nation whose energy need exceeds the supply [6]. However, considering that most rural communities are yet to be connected to the utility grid, which suggests there is the need for an alternative and sustainable means of stand-alone power source. One way of achieving this is to develop its available renewable resources for which wind is in abundance. Wind speed is the most significant parameter when sitting a wind turbine because the generated electric power through a wind turbine is directly proportional to the cube of its associated windspeed [7]. Wind speed, however, varies from month to month, making the prediction of wind energy a significant activity. Understanding a specific site's wind energy potential requires meteorological measurements of the wind speed for a relatively long time in order to ensure accurate prediction of the site's energy potential. Statistical methods are then used to estimate the site's wind power density on the based on this measured data.

The WD function is the most used among these statistical tools because of its simplicity, versatility, and particularly because it is suitable for estimating a large range of data associated with wind.

The likelihood of using wind power to generate electricity in Nigeria has been reported and documented in the open literature. For instance, Zagga and Garda [8] investigated Sokoto's wind potential in north-western Nigeria. The study was based on a two-parameter WD. The density of the wind power obtained was 48.1 W/m^2, which is well below the normal 100 W/m^2 level. Also, Akinsanola et al. [9] explored Koluama's wind potential in Bayelsa State, Nigeria's south-south and the analysis was based on the distribution of weibulls, using the data for the wind speed on monthly basis for an average thirty years. The site's wind density ranges from 82 W/m^2 to 145 W/m^2 respectively for the month of November and August. Udaakah and Ikafia [10] conducted a study to determine the wind power potential of some coastal and non-coastal sites in Akwa-ibom state, Nigeria's south-south based on four-year data distribution. The coaster site's wind density was measured at 181 W/m^2, while the non-coaster density was estimated at 49 W/m^2. Mufutau et al. [11] assessed a location's (Abeokuta and Ijebu-ode) wind energy potential in southwestern Nigeria. Their analysis was also based on the distribution of weibulls. For the study, mean wind speed estimated at a height of 10 m was used every month for fifteen years. The wind power density for the Abeokuta and Ijebu-ode sites ranged from 15-39 W/m^2 and 13-45 W/m^2 respectively. All these studies are concerned with how the wind power potential of sites, in Nigeria can be adequately assessed.

This present study goes a step further in selecting adequate wind turbine for the selected locations and additionally determine the effect of wind turbine parameters on capacity factor, thereby providing useful economic information to foster a viable investment in the renewable energy for electricity generation in Nigeria. The remaining parts of the paper are organized as follows: section 2 presents the description of the materials and methods employed in the investigation. The results and discussion of results are presented in section 3 while the study is concluded in section 4.

2. MATERIALS AND METHOD

Assessing wind energy potential through data analysis is critical for proper and efficient deployment of wind energy application and is purely site-dependent (Figure 1). In this study, the daily wind speed data measured with a 10 m height anemometer were used. The data were obtained from the meteorological agency of Nigeria (NIMET), Oshodi, Lagos, Nigeria. Table 1 summarizes the geographical information and data collection intervals of sites. The study uses four sites identified under the country's north-central and north-eastern zone.

Table 1. Selected site geographical information.

Region	Site	Latitude (°N)	Longitude (°E)	Altitude (m)	Data Period
North-central	Ilorin	08.29°	04.35°	307	2000-2010
	Makurdi	07.44°	08.32°	113	1961-2014

North-Eastern	Gombe	10.54°	11.15°	152	1994-2005
	Maiduguri	11.51°	13.05°	354	1994-2005

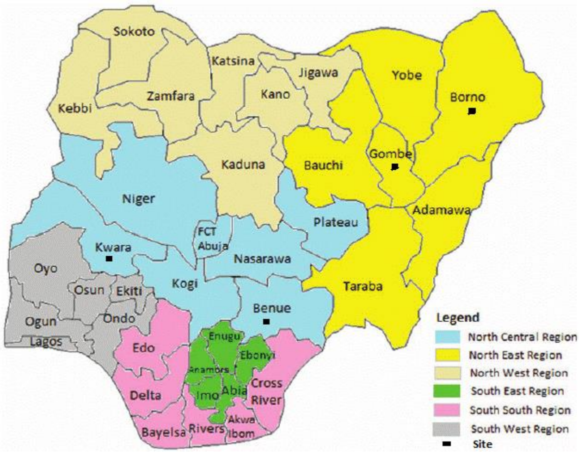


Fig. 1. The Map of Nigeria showing the sites under study.

2.1. Modelling of Weibull distribution parameters

A Probability Distribution (PD) shows the appropriate probability for the observed wind speed at a specified velocity (V_i). The Cumulative Distribution (CD) implies that the probability of wind speed is not greater than V_i, or within a specified wind speed range. The mathematical expression for a two-parameter WD can be written as [12]:

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

The mathematical expression for the CD can also be written as [12]:

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

where υ represents the wind speed (m/s), k represents the shape parameter and c represents scale parameter (m/s). The two Weibull parameters, k and c, may be estimated using equations (3) and (4) expressed as [12]:

$$k = \left[\frac{\sigma}{V_m}\right]^{-1.086} \tag{3}$$

$$c = \frac{V_m}{\Gamma\left(1+\frac{1}{k}\right)} = \frac{V_m k^{2.6674}}{0.184+0.816k^{2.73855}} \tag{4}$$

where σ denotes the Standard Deviation (SD), V_m denotes the Mean Wind Speed (MWS) and Γ is the Gamma Function (GF).

$$\sigma = \left[\frac{1}{n-1}\left(\sum_{i=1}^{n}(V_i - V_m)^2\right]^{\frac{1}{2}} \tag{5}$$

$$V_m = \frac{1}{n}\sum_{i=1}^{n} V_i \tag{6}$$

and

$$\Gamma(x) = \int_0^{\infty} e^{-t}\, t^{x-1} dt \tag{7}$$

The most probable wind speed (V_{mp}) and wind speed associated with the maximum energy (V_{maxE}) can be easily estimated from equations (8) and (9) respectively as [13]:

$$V_{mp} = c\left(\frac{k-1}{k}\right)^{\frac{1}{k}} \tag{8}$$

$$V_{maxE} = c\left(\frac{k+2}{k}\right)^{\frac{1}{k}} \tag{9}$$

The $V_{mp}$is equivalent to the peak probability density function, while V_{maxE} is used to estimate the wind turbine rated wind speed. For optimum utilization of wind turbine in a site, V_{maxE} should be relatively close to the rated wind speed of the turbine [14].

2.2. Estimation of Wind Power Density (WPD) and Wind Energy Density (WED)

The WPD is a measure of how much power can be harnessed in a particular site for conversion by wind turbine. It can be estimated by [14]:

$$WPD = \frac{p(V)}{A} = \frac{1}{2}\rho V_m^3 \tag{10}$$

where $p(V)$ is the wind power in Watt, A is the turbine blades swept area (m^2) and ρ is air density of the site whose value is considered to be 1.225 kg/m^3 in this paper [14]. The WPD is used for the classification of the wind energy resource [12]. However, the WPD can be obtained from the weibull distribution function using [14]:

$$WPD = \frac{p(V)}{A} = \frac{1}{2}\rho c^3 \Gamma\left(1 + \frac{3}{k}\right) \tag{11}$$

2.3. Estimation of wind turbine power output and capacity factor

When designed based on the location's wind characteristics, a wind turbine will operate optimally. This is due to the cut-in wind speed, cut-out wind speed and rated wind speed, which must correspond to the site's wind regime [15]. A wind turbine's power output is of a paramount importance in the conversion method for wind energy. It's a good indicator of economic value than the rated power of a turbine. The capacity factor (CF) of a wind turbine is defined as the ratio of power output to the rated power (P_R) of the wind turbine. The mean power output (P_{mpo}) and CF of a wind turbine can be determined based on weibull distribution function using [16]:

$$P_{mpo} = P_R\left[\frac{e^{-\left(\frac{V_{ci}}{c}\right)^k} - e^{-\left(\frac{V_r}{c}\right)^k}}{\left(\frac{V_r}{c}\right)^k - \left(\frac{V_{ci}}{c}\right)^k} - e^{-\left(\frac{V_{co}}{c}\right)^k}\right] \tag{12}$$

and

$$CF = \frac{e^{-\left(\frac{V_{ci}}{c}\right)^k} - e^{-\left(\frac{V_r}{c}\right)^k}}{\left(\frac{V_r}{c}\right)^k - \left(\frac{V_{ci}}{c}\right)^k} - e^{-\left(\frac{V_{co}}{c}\right)^k} \tag{13}$$

where V_{ci}, V_{co} and V_r represents the cut-in, cut-out and rated wind speeds of the turbine respectively. One major condition to be satisfied, for an economic viability of wind turbine grid application, requires that the CF must be ≥ 0.25 [17].

Seven wind turbines of different ratings were considered, ranging from 10 kW to 850 kW from several manufacturers available in the market. The turbines were grouped into mini and medium wind turbine as shown in Table 2.

Table 2. Characteristics of wind turbine models.

Wind turbine model	Designation	Cut-in wind speed V_{ci}(m/s)	Cut-in wind speed V_{co}(m/s)	Rated wind speed V_r(m/s)	Rated power output P_R(KW)	Area (m^2)	Class
Aircon-10	WT1	2.5	32	11	10	40	Mini

Polaris P20	WT2	2.7	25	10	20	71	
Polaris P50	WT3	2.7	25	9	50	290	
Norwin	WT4	4	25	13	500	1735	Medium
Vestas V42	WT5	4	25	16	600	1385	
Norwin 47/750	WT6	4	25	15	750	1735	
Gamesa G58	WT7	3.5	21	12	850	2642	

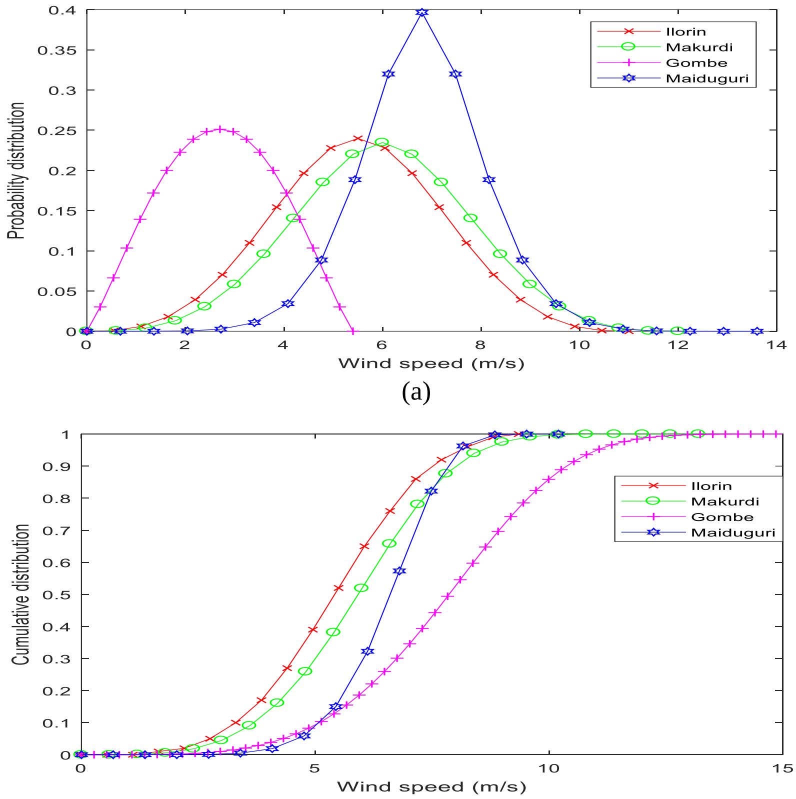
The annual average energy output of a wind turbine can be estimated by [18]:

$$WPD = \mathrm{CF} * \mathrm{P_r} * 8760 \quad (14)$$

3. RESULTS AND DISCUSSION

3.1. Wind speed characteristics and power density

The Probability Density Function (PDF) and Cumulative Density Function (CDF) of the wind speeds for the four sites obtained based on WD for the period under investigation are shown in Figures 2(a-b).



(a)

(b)

Fig. 2. Speed distribution over the investigated duration for (a) PDF (b) CDF

The PDF is used to describe the fraction of time that might occur at a location for a given wind speed. As can be seen from Figure 2(a), the PDF value skewed to the higher wind velocity; the average also indicates the most regular velocity. In Ilorin, Makurdi, Gombe and Maiduguri, the most frequent wind speed is around 5.5 m/s, 6.0 m/s, 2.7 m/s and 6.8 m/s respectively. It can be inferred from Figure 2(a) that Maiduguri has the biggest spread of wind speed compared to other sites. Similar trend is also noticed in the CDF of Figure 2(b). For wind speeds more than or equal to 3.0 m/s cut-in wind speed, Maiduguri, Gombe, Makurdi and Ilorin have frequencies of about 99.80 %, 98.94 %, 95.53 % and 93.00 % respectively, while for a cut-in wind speed of 4.0m/s, the frequencies are 98.35 %, 96.35 %, 86.66 % and 80.00 % for the same locations respectively.

The monthly mean wind speed (V_m), weibull parameters (k and c) and wind power density at a height of 10 m are shown in Figures 3-6.

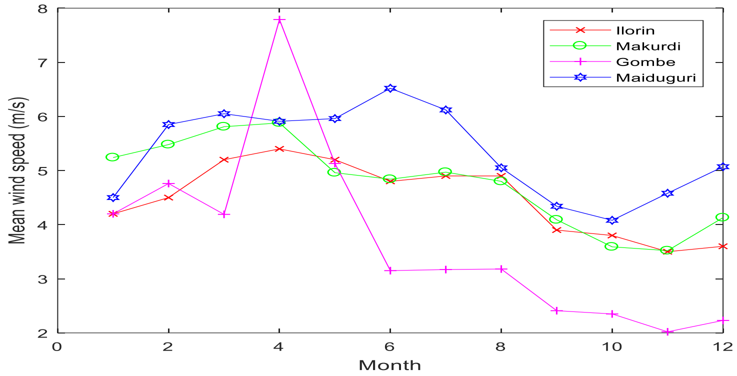


Fig. 3. Monthly mean wind speed.

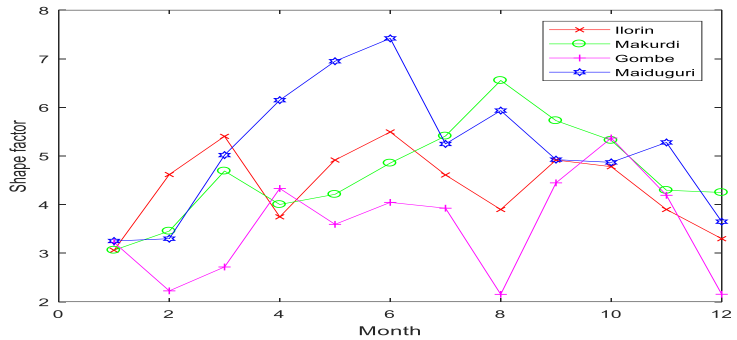


Fig. 4. Monthly shape factor.

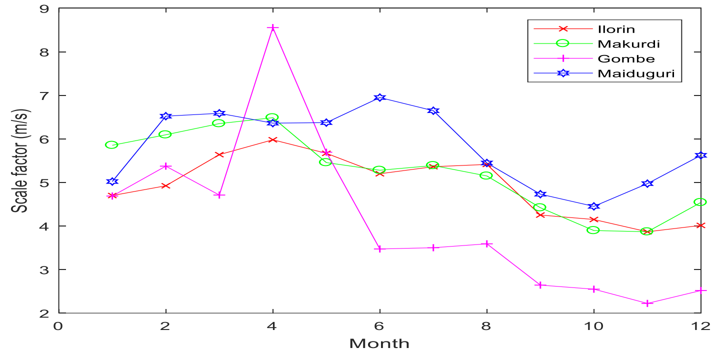


Fig. 5. Monthly scale factor.

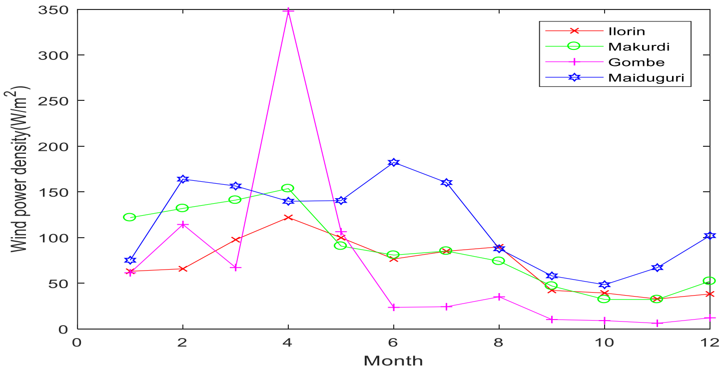


Fig. 6. Monthly wind power density.

The monthly mean wind speed was found to varies between 3.5 m/s and 5.4 m/s in Ilorin (Figure 3). The k and c parameter values varies between 3.1 m/s to 5.5 m/s and 4.0 m/s to 5.7 m/s respectively(Figure 4 and 5), while the monthly power density ranges between 32.7 W/m^2 and 122 W/ m^2 (Figure 6) for the same location. The monthly mean wind speed ranges between 3.52 m/s and 5.88 m/s for Makurdi, the monthly k and c parameters varies between 3.1 to 6.6 and 3.87 m/s to 5.7 m/s respectively. Also, the power density varies between 32 W/m^2 and 154 W/m^2 for the same site. In the case of Gombe, the monthly average wind speed varies between 2.02 m/s and 7.8 m/s, while the k parameter varies between 2.15 to 5.36 and c parameter between 2.2 m/s and 8.55 m/s. The power density values ranges from 6.1 W/$m^2$and 348 W/m^2. The minimum and maximum monthly mean wind speed are 4.08 m/s 6.52 m/s for Maiduguri, while the k and c parameters and power density varies from 3.25 to 7.42, 4.45 m/s to 6.94 m/s and 48 W/m^2 in November to 182 W/m^2in June respectively.

The results of the whole year wind characteristics (V_m, $V_{mp}$and V_{maxE}), weibull parameters (k and c) and wind power density of sites are depicted in Table 3.

Table 3. Wind speed characteristics and power density.

Site	**Vm**	**K**	**c**	V_{mp}	V_{maxE}	**WPD**	**Class**
Ilorin	4.500	4.201	4.951	4.641	5.431	67.736	1
Makurdi	4.770	4.396	5.234	4.936	5.700	79.517	1
Gombe	3.720	3.240	4.151	3.704	4.815	40.874	1
Maiduguri	5.340	4.926	5.821	5.559	6.238	107.485	2

Table 3 reveals that the average wind speed (V_m) ranges from 3.72 m/s in Gombe and 5.34 m/s at Maiduguri, with a variation in the shape parameter (k) from 3.24 at Gombe to 4.93 at Maiduguri. Also, a variation in the scale parameter (c) from 4.15 m/s in Gombe to 5.82 m/s at Maiduguri is observed. The most probable wind speed of the locations ranges between 3.7 m/s in Gombe to 6.24 m/s at Maiduguri. The wind speed carrying maximum energy (V_maxE) is lowest in Gombe (4.82 m/s) and highest in Maiduguri (6.24 m/s). The wind energy is classified in accordance to the National Renewable Energy Laboratory (NREL). Thewind power classification with the wind speed measured at an anemometer height of 10 m, is presented in Table 4 [17].

Table 4. Classification of wind power.

Power class	Power density at 10 m (W/m^2)
1	$0 < p \leq 100$
2	$100 < p \leq 150$
3	$150 < p \leq 200$
4	$200 < p \leq 250$
5	$250 < p \leq 300$
6	$300 < p \leq 400$
7	$400 < p \leq 1000$

Wind power class 1 is highly unsuitable for any wind power application, class 2 needs adequate considerations, a high hub-height is required for class 3 before it can be situated for wind power utilization, while class 4 and above are very suitable for grid application.

From Table 4, it is observed that the sites located in Ilorin, Makurdi and Gombe into class 1 category, signifyinga very poor wind power potential. Therefore, the sites under consideration; (Ilorin, Makurdi and Gombe) cannot be considered assuitable locations for wind power applications. The site in Maiduguri belongs to class 2, which may probably be considered for stand-alone (water pumping, battery charging and irrigation system) application.

3.2. Estimation of energy outputs of wind turbine and the associated capacity factors

Figure 7 depicts annual energy outputs for the wind turbines considered in this paper. The energy output varies from 2.891 MWh in Ilorin with WT1 model to 194 MWh in Maiduguri, annually, using WT7 model. The annual energy obtained for WT7 model is the highest as compared to the rest of the sites (Figure 8). This is mainly because it has the highest rating (850 kW). The WT1 model generated the least annual energy regardless of the sites, which again is attributed to its rating (10 kW).

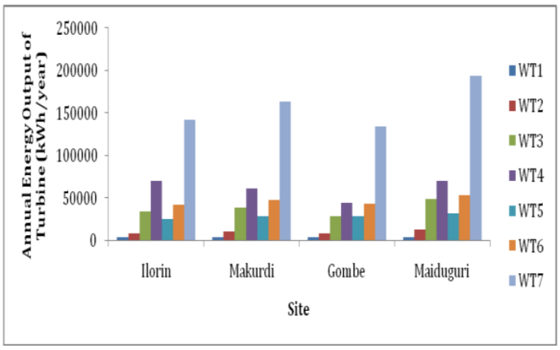


Fig. 7 Annual energy output of selected wind turbine models across sites.

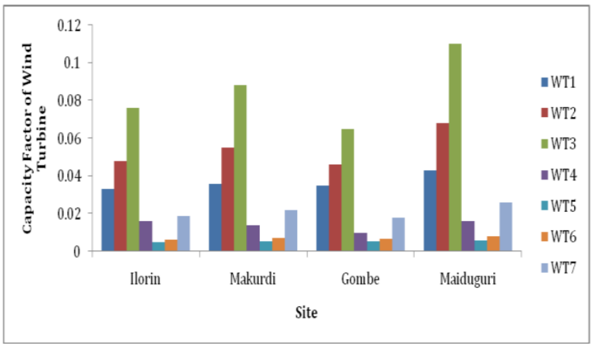
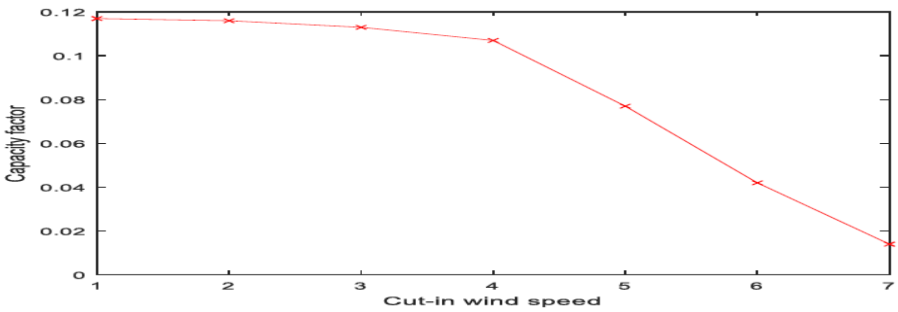
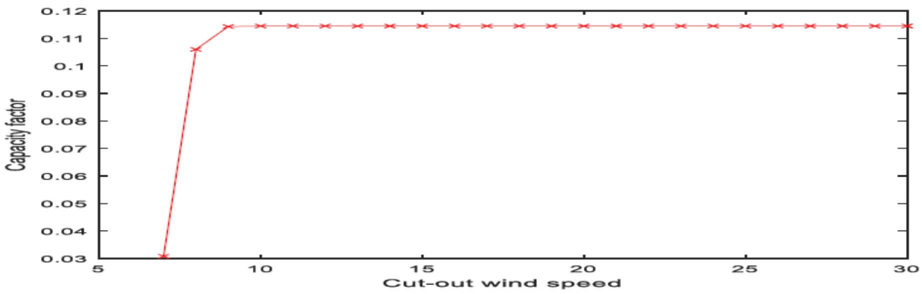


Fig. 8. Capacity factor of selected wind turbine models across sites.

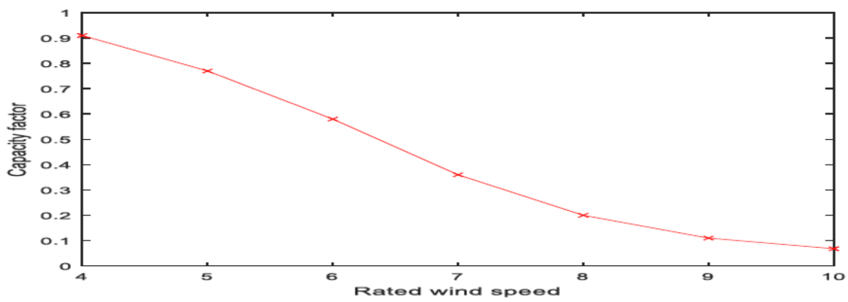
Furthermore, Figures 9(a-c) show how the cut-in wind speed (V_ci,), cut-out wind speed (V_co) and rated wind speed of turbine affects capacity factor of a wind turbine.



(a)



(b)



(c)

Fig. 9. (a) Effect of variation of V_{ci} on CF (b)Effect of variation of V_{co} on CF (c) Effect of variation of V_r on CF.

The Figure 9(a-c) illustrate that the CF is mainly influenced by rated wind speed and cut-in wind speed of the turbine, while the effect of cut-out wind speed is negligible.

4. CONCLUSIONS

This paper has investigated the potential of wind power associated with some selected locations in the North-central (Ilorin and Makurdi) and North-eastern (Gombe and Maiduguri) parts of Nigeria. Furthermore, the identification of suitable wind turbine was also examined. Based on the results obtained, it is shown that the whole year mean wind speeds are 3.72 m/s, 4.50 m/s, 4.77 m/s and 5.34 m/s for Gombe, Ilorin, Makurdi and Maiduguri respectively and their associated wind power densities obtained are 40.87 W/m^2, 67.74 W/m^2, 79.52 W/m^2 and 1097.4 W/m^2 respectively. Also, it is observed from the results obtained that the CF varies from 0.076 in Ilorin to 0.11 in Maiduguri, while the annual energy output of the turbine varies from 2.891 MWh in Ilorin with WT1 to 193.596 MWh in Maiduguri with WT7. Meanwhile, out of the four sites considered, Maiduguri is the best in terms of wind energy potential, while of the seven turbines considered, WT3 model with a V_{ci} of 2.7 m/s, V_{co} of 25 m/s, V_r of 9 m/s with a power rating of 50 kW is the most suitable choice for the sites. Furthermore, it is observed that in selecting wind turbine for generation of electrical power, two important characteristics that require critical consideration are the cut-in wind speed and rated wind speed. The cut-in wind speed value should be relatively small while the rated wind speed should match, i.e. close to the local wind regime such that an optimal utilization of energy in a moving mass of air is maintained.

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