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Wind Energy Assessment and Identification of the Appropriate Wind Energy Conversion System for Dundaye Area of Sokoto State, Nigeria

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Abstract: Automated weather station was installed at Dundaye area (13.1^0N) where ground based measurements of average hourly wind speed for a period of one calendar year (June 2016 – May, 2017) was monitored. The measured data was then compared with twenty years daily average wind speed data (1991-2010) obtained from Nigerian Meteorological Agency (NIMET). The two set of data was compared in order to validate the long term data from NIMET, where a reasonable regression coefficient (R^2) value of 0.897 was obtained. The validated long term data was then used for the wind energy analysis for power generation and identification of the most suitable Wind Energy Conversion System (WECS) for the location, using Weibull probability distribution function. Wind speed pattern, extractable wind power, wind speed carrying maximum energy and most probable wind speed for the location was computed. Similarly, expected Power output was also simulated using the characteristics of a 0.30, 0.23, 0.20 and 1.50 kW WECS from different manufacturers and Weibull parameters evaluated for the location. It was observed that the NE-2000 WECS is the most suitable system that produce optimum results for electricity generation at the location, with capacity factor of 0.36 while Bonus-3000 is the least suitable for the location with capacity factor of 0.06 among the nine WECS selected for the analysis.
Keywords: Assessment, Resource Potentials, Power, Locations, Weibull Distribution

INTRODUCTION

Energy is a key to modern life and it provides the basic necessity for sustainable economic development of any country. Rising energy prices, diminishing energy availability and security, as well as growing environmental concerns are quickly changing the global energy panorama. Similarly, population growth and increasing modernization across the globe had made the projected global energy demands to more than tripled by the end of twenty-first century. It is now apparently very clear that the global energy demand is not likely to be met by fossil fuels alone as reported by [2]. Future energy demands may have to be complemented by introducing an increasing percentage of alternative fuels technologies, such as that from solar, wind, and biomass which is already playing an increasingly important role in the new global energy economy as in [3] and [9].

Wind energy is one of the fastest growing renewable sources of energy in both developed and developing countries with total available wind power surrounding the earth being in the order of 10^{11}GW, which is several times more than the current global energy consumption [1, 14].

Wind is an inexhaustible resource whose utilization has been increasing around at an accelerating pace, while its development continues to be hampered by the lack of reliable and accurate wind speed data in many parts of the globe, especially in the developing countries like Nigeria [9]. Such data are required to enable governments, private developers, policy makers and other investors to determine the priority that should be given to wind energy utilization and to identify potential areas that might be suitable for its development [9].

While, countries like China, United States, Germany, Spain, India had gone beyond looking at the possibilities of harnessing the abundant environmentally friendly renewable energy resources and move to extend their generation capacities of expanding their generation capacities from renewable energy sources in the regions of Giga-Watt (GW) of electricity as contained in [12], the African continent represents one of the least developed in terms of installed wind power and wind electricity adoption. The North Africa region is leading the entire continent in terms of electricity generation from wind, with Egypt, Morocco on the lead followed by Tunisia, South Africa and Kenya beign in the second phase, in terms of resources assessment, installation of wind energy conversion systems as well as research on the technological advancement, as such are classified very promising countries for wind energy technology [11]. In sub-Saharan Africa, particularly the West African region, no country has yet generated grid electricity from wind despite the identified opportunities.

The Federal government of Nigeria through the Federal Ministry of Power contracted a French contractor, Vergnet S.A. to install a 10MW WECS at Lambar Rini in Katsina State, and the project is reported to be currently more than 90% completed as reported by [7]. The challenges of wind energy project development in West African countries may however be linked to inadequate measurements stations, incomplete assessmental studies and / or improper wind classification of the countries in the region as in [10]. This could partly be due to the fact that wind resources are site specific in nature. Therefore, in order to properly classify a country's wind profile, assessment of wind resource potential of the sites will be required. Nigeria's wind profile assessment has gone through various developmental stages [7]. Various policy issues have been developed by the government of Nigeria which demonstrate its intention to generate electrical energy using wind as reported in [6].

Usmanu Danfodiyo University, Sokoto in Dundaye area of Sokoto state is among the few locations in Nigeria with reasonable wind speed of monthly average of about 5.0 m/s at 10m height as reported by [13]. The aim of this research is to investigate wind speed potentials for Usmanu Danfodiyo University for the purpose of assessing wind energy resource potentials for electrical energy generation on standalone basis or on hybrid arrangement for University community as a complement to the erratic power supply being experienced by the University. Table-1 below gave details geographical location of the study area.

Table-1: Geographical locations of the study area

Location	Latitude (^{0}N)	Longitude (^{0}E)	Altitude (m)
Sokoto	13.117	5.394	296

Theoretical Consideration

Generation of power from a Wind Energy Conversion System (WECS) requires continuous flow of wind between the cut in speed and rated speed the System, which is very difficult to accomplish for most of the locations in Nigeria [9], this is because wind by its nature is not constant and does not prevail at a steady rate, but fluctuates over short periods of time. The speed of wind is also dependent on height above the ground.

In order to estimate the wind speed at any height, we employ the Hellmann exponent law [8, 13].

$$\frac{u}{u_0} = \left(\frac{H}{H_0}\right)^{\alpha} \quad (1)$$

Where u is the wind speed at the required height H, u_0 is wind speed at the original height H_0 and α is the surface roughness coefficient known as Hellmann exponent and is assumed to be 0.143 (1/7) for a flat and open area such as Northern Nigeria. The wind turbines system usually operates at its maximum efficiency at its design or rated wind speed and hence, it is essential that the rated wind speed and most probable wind speed at the location of operation should be similar according to [9]. The available power in the wind per unit area at any wind speed may be estimated using the equation 2 below as reported by [5, 8].

$$P_{(v)} = \frac{1}{2}\rho A V_m^3 \quad (2)$$

Where ρ is the air density in kg/m^3 and V_m is monthly mean wind speed i m/s. According [15], there is fundamental limit on which the efficiency by which power can be extracted from wind system. Similarly [14] also mentioned that the maximum extractable power from any wind conversion system/ machine is limited by the Betz limit which is assigns with the power coefficient *Cp* = 16/27. Making the maximum extractable power from any kind of WECS per meter becoming as:

$$P_{\max} = \frac{1}{2}\rho A C_P V_m^3 W/m^2 \quad (3)$$

Weibull Probability Distribution Function

There are many probability distributions functions that are applicable in many areas of study such as Normal, Rayleigh, Chi-Square and Weibull distributions. However, for the purpose of this studies Weibull probability distribution functions was selected for the statistical analysis because from the reports in various literatures it appears to be more appropriate for wind speed data analysis as contained in [9, 4], this is because it give a better fit for measured data than the other statistical functions.

The two – parameter Weibull wind speed probability distribution, $P_{(v)}, \ and$ cumulative distribution $F_{(v)}$ is expressed by (10, 13) as:

$$f_{(v)} = \left(\frac{k}{c}\right)\left(\frac{v}{c}\right)^{k-1} e^{-\left(\frac{v}{c}\right)^{k}} \qquad (4)$$

$$F_{(v)} = 1 - e^{-\left(\frac{v}{c}\right)^{k}} \qquad (5)$$

Where *c* is the scale parameter and *k* is the shape parameter. The scale parameter *c* has units of speed and is related to the mean wind speed. The shape parameter *k* is dimensionless and is inversely proportional to the variance of the wind speeds about the mean wind speed.

If the mean wind speed $\overline{V}$ and standard deviation σ are known, then *k* and *c* can be computed from the approximate relation [13]:

$$k = \left(\frac{\sigma}{\bar{v}}\right)^{-1.086} \qquad (6)$$

$$c = \frac{\bar{v}}{\Gamma(1 + 1/k)} \qquad (7)$$

Where Γ is the gamma function that can be expressed using the equation:

$$\Gamma(x) = \int_{0}^{\alpha} t^{x-1} e^{-t} dt \qquad (8)$$

Which can be further expressed according to Stroud, 1995 as reported by (13);

$$\Gamma(x) = \sqrt{2\pi x}\,(x)^{x-1} e^{-x}\left[1 + \frac{1}{12}x + \frac{1}{288}x^{2} - \frac{139}{51840}x^{3} + ...\right] \qquad (9)$$

Data Acquisition and Analysis

20 years daily average wind speed data (1991-2010) was obtained from NIMET, Abuja, and the data was then compared with one year average hourly wind speed from ground measurement at 3 m height, in order to validate the NIMET data. The wind speeds data was subsequently summarized to monthly average of a whole year using Microsoft excel software

Weibull Mean Wind Speed and Standard Deviation

The mean value of the wind speed V_m and standard deviation σ for the Weibull distribution estimate can be evaluated by equation 10 and 11 as reported by [11]:

$$V_m = c\Gamma\left(1+\frac{1}{k}\right) \quad (10)$$

$$\sigma = \sqrt{c^2}\left\{\Gamma\left(1+\frac{2}{k}\right)-\left[\Gamma\left(1+\frac{1}{k}\right)\right]^2\right\} \quad (11)$$

where Γ(x) is the gamma function of (x).

Most Probable and Maximum Energy Carrying Wind Speeds

The most probable wind speed (V_{mp}) and wind speed carrying maximum energy ($V_{E\max}$) can be expressed as:

$$V_{mp} = c\left(\frac{k-1}{k}\right)^{1/k} \quad (12)$$

$$V_{E\max} = c\left(\frac{k+2}{k}\right)^{1/k} \quad (13)$$

Weibull Wind Power Density

The Weibull wind power density per unit area can be obtained from:

$$\frac{p_{(v)}}{A} = \frac{1}{2}\rho C^3\left(1+\frac{3}{k}\right) \quad (14)$$

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

Simulating Electrical Power Output from a Turbine Model

To evaluate the electrical power output from a particular wind turbine model using simulation the following equation can be used. The actual wind frequency distribution at the selected site can be marched with a suitable model of the WECS, in order to evaluate the total power output of the system [11]. Hence, a wind energy conversion system can operate at maximum efficiency only if it is designed for the particular site, since the rated power, cut-in and cut-off wind speeds must be defined based on the site wind characteristics [9]. These parameters can be chosen so as to maximize the delivered energy for a given amount of available wind energy. The mean power output $P_{e,ave}$ and capacity factor C_f are important performance parameters of WECS. While $P_{e,ave}$ determines the total energy production, C_f represents the fraction of the mean power output over a period of time to the rated electrical power P_{eR}. The mean power output $P_{e,ave}$ and capacity factor C_f of a wind turbine can be calculated using the following expressions [9, 11]

$$P_{e,ave} = P_{eR}\left\{\frac{e^{-\left(\frac{V_C}{C}\right)^K} - e^{-\left(\frac{V_r}{C}\right)^K}}{\left(\frac{V_r}{C}\right)^K - \left(\frac{V_C}{C}\right)^K} - e^{-\left(\frac{V_f}{C}\right)^K}\right\} \quad (15)$$

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

Where $V_{c,} V_r$ *and* are the cut-in wind speed, rated wind speed and cut-off wind speed respectively. However, for an investment in wind energy generation to be cost effective, the capacity factor should be within the range of 0.25 and 0.40; for capacity factor $C_f \geq 0.40$ indicate strong interaction between the wind turbine system and the environment [9, 11].

Table-2: Technical parameters of the selected wind turbines models used in the analysis

Wind Machine	v_c	v_r	v_f	P_{rt}	Hub- height (m)	Rotor diameter (m)
Bonus 300/33.4	3.0	15.0	25.0	0.3	30	33.4
Bonus 2300/82.4	3.0	15.0	25.0	2.3	60	82.4
Bonus 2000/76	4.0	15.0	25.0	2.0	60	76
ANERN	3.0	9.0	30.0	2.0	24	12
NE-2000	3.0	11.0	45.0	2.0	24	12
NE-2000	3.0	8.0	50.0	2.0	18	12
FD-2000	3.0	12.0	45.0	2.0	18	12
GE 1.5sle	3.5	14.0	25.0	1.5	65/80	77
GE 1.5xle	3.0	11.5	20.0	1.5	80	82.5

Table-2 above present the details specification of the selected wind energy conversion systems ranging from 1.5 to 2.3 kW of different cut in, rated and foiled wind speeds obtained from different manufacturers website. The turbines has rotor diameters and hub height ranging from 12 to 82.5m and 18 to 80 m respectively.

RESULT AND DISCUSSION

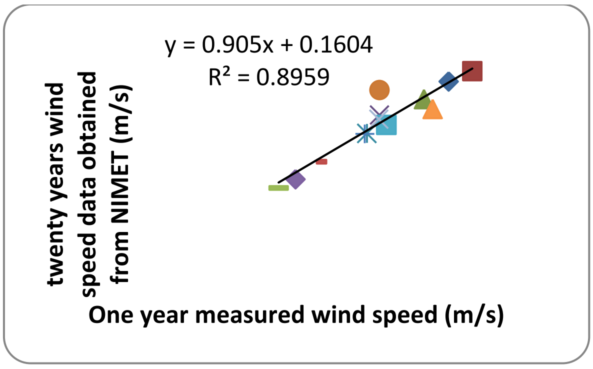

Fig-3.1: Comparism between measured data at the location and NIMET wind speed data

Figure 3.1 shows comparism between the short terms measured data and long term data obtained from NIMET, which gave a very good correlation coefficient of R^2 (0.897) between the two sets of data, this validated the long term data as such can be used for the location.

Table 3.1: Monthly average wind speed characteristic of the location

Month	$\bar{v}_{NIMET}$	σ	$\bar{v}_m$	σ	k	c	V_{mp}	$V_{max\ E}$
Jan	6.31	2.12	5.89	1.93	3.27	7.04	6.38	8.35
Feb	6.67	2.65	6.13	2.67	2.72	7.50	6.49	9.52
Mar	5.93	2.14	5.48	2.00	3.03	6.64	5.92	8.09
Apr	5.26	2.18	5.11	1.86	2.60	5.92	5.05	7.67
May	5.07	1.87	4.68	2.13	2.95	5.68	5.03	6.98
Jun	5.26	1.92	5.69	1.88	2.99	5.89	5.23	7.21
Jul	5.04	1.76	4.67	1.65	3.13	5.63	5.06	6.78
Aug	4.31	2.06	4.02	1.87	2.23	4.86	3.88	6.82
Sep	3.73	2.28	3.41	2.14	1.70	4.18	2.74	7.05
Oct	3.98	1.99	3.61	1.67	2.12	4.50	3.50	6.49
Nov	5.36	2.07	4.88	1.88	2.81	6.02	5.26	7.54
Dec	6.07	2.16	5.25	1.98	3.07	6.79	6.07	8.23
Ave	**5.25**	**2.10**	**4.90**	**1.97**	**2.72**	**5.89**	**5.05**	**7.56**

As can be seen from table 3.1 above, the monthly mean wind speed vary between 3.73 m/s in the month of September to 6.67 m/s in the month of February at 10m height for the location for the adjusted 20 years daily average. The trend in the monthly mean wind speed is related to the fact that Sokoto locations is characterized by two seasons (rainy and dry), the seasonal duration is usually between June to September and October to May for rainy and dry seasons respectively [9].

The topography is characterized by undulating land, with sand dunes of various sizes spanning across the locations with savannah vegetation and a semi-arid climate. Harmattan is experienced across the state during dry seasons as a result of the North-east trade wind blowing across the whole area from Sahara and results in significant low wind speed during this period.

The Weibull parameters (k and c), most probable wind speeds and wind speed carrying maximum energy can be observed to vary from the values of Weibull shape parameter k that ranged from 2.12 in the month of October to 3.27 for the month of January, this implies that wind speed is least uniform in the month of October and most uniform in the month of January. Similarly, the monthly scale parameter c has its lowest value of 4.18 m/s in the month of September and highest value of 7.50 m/s in the month of February, this indicated month of February as most windy, while the month of September as least windy. It can also be observed that the monthly average scale parameter for each month of the year is closely related to monthly mean wind speed for the period which is impliedly in agreement with what was presented by [13].

The most probable wind speed and wind speed carrying maximum energy can be observed from same table 3.1: that monthly most probable wind speed for each month of the year is very close to the monthly mean wind speed. The most probable wind speed and wind speed carrying maximum energy varies from 2.74 and 6.49 m/s in the month of September and October to 6.49 and 9.52 m/s in the month of February respectively. This shows that for maximum efficiency the most probable wind speed, wind speed carrying maximum energy, average wind speed of the location must be as close as possible.

Figure 3.1 shows comparism between the short terms measured data and long term data obtained from NIMET, which gave a very good correlation coefficient of R^2 (0.897) between the two sets of data, this validated the long term data as such can be used for the location.

Table-3.2: Average Power Output (Pe,ave) from the Selected Wind Energy Conversion Systems

Month	Bonus-300	Bonus-2300	Bonus-2000	ARERN-2000	NE-2000	NE-2000	FD-2000	GE-1500	GE-1500
Jan	238.90	183.16	145.86	766.94	436.71	989.38	331.03	144.55	284.69
Feb	422.12	323.62	258.95	931.36	624.97	1111.7	507.62	245.76	422.43
Mar	234.68	179.92	139.54	688.67	400.53	889.94	308.90	138.07	263.32
Apr	228.64	175.29	128.25	565.11	345.52	724.50	275.14	127.29	230.79
May	147.71	113.24	81.30	448.12	249.03	611.87	191.83	83.62	163.46
Jun	162.26	124.40	91.24	495.74	276.14	671.11	212.25	92.94	181.08
Jul	121.93	93.48	66.95	407.22	217.02	572.30	164.61	69.87	141.32
Aug	178.47	136.82	89.91	384.44	243.68	492.98	199.11	92.19	164.85
Sep	205.23	157.34	99.77	345.63	241.52	420.96	205.90	100.42	166.98
Oct	157.18	120.50	75.52	325.82	208.74	417.73	171.79	78.86	141.71
Nov	202.35	155.13	114.74	557.25	326.01	730.27	254.79	114.88	215.66
Dec	244.11	187.15	146.45	721.92	420.90	928.11	324.02	144.59	276.50
Ave	**211.96**	**162.51**	**119.87**	**553.18**	**332.57**	**713.40**	**262.25**	**119.42**	**221.07**

Table-3.3: Capacity factor (c_f) from the Selected Wind Energy Conversion Systems

Month	Bonus-300	Bonus-2300	Bonus-2000	ARERN-2000	NE-2000	NE-2000	FD-2000	GE-1500	GE-1500
Jan	0.08	0.08	0.07	0.38	0.22	0.49	0.17	0.10	0.19
Feb	0.14	0.14	0.13	0.47	0.31	0.56	0.25	0.16	0.28
Mar	0.08	0.08	0.07	0.34	0.20	0.44	0.15	0.09	0.18
Apr	0.08	0.08	0.06	0.28	0.17	0.36	0.14	0.08	0.15
May	0.05	0.05	0.04	0.22	0.12	0.31	0.10	0.06	0.11
Jun	0.05	0.05	0.05	0.25	0.14	0.34	0.11	0.06	0.12
Jul	0.04	0.04	0.03	0.20	0.11	0.29	0.08	0.05	0.09
Aug	0.06	0.06	0.04	0.19	0.12	0.25	0.10	0.06	0.11
Sep	0.07	0.07	0.05	0.17	0.12	0.21	0.10	0.07	0.11
Oct	0.05	0.05	0.04	0.16	0.10	0.21	0.09	0.05	0.09
Nov	0.07	0.07	0.06	0.28	0.16	0.37	0.13	0.08	0.14
Dec	0.08	0.08	0.07	0.36	0.21	0.46	0.16	0.10	0.18
Ave	**0.07**	**0.07**	**0.06**	**0.28**	**0.17**	**0.36**	**0.13**	**0.08**	**0.15**

The average power out from the selected WECS considered for the location has shown that the month of February produced the highest power output and month of July produces the least energy for all the machines except in the case of ARERN-2000 and NE- 2000 where the lowest average power output was observed in the month of October as shown in table 3.2, this could be as a results of lowest wind speed carrying maximum energy as can be seen in table 3.1. The performance of the WECS depends largely on the wind energy characteristics of the location, the most efficient WECS will have it capacity factor in the range of 0.25 to 0.40 [9]. The NE-2000 will be the most efficient WECS at the location with annual energy output of 713.14 kWh followed by ARERN-2000 with 553.18kWh and capacity factors of 0.36 and 0.28 respectively table 3.2. Similarly, the Bonus-2000, Bonus 2300 and Bonus 3000 are the least effective with very low efficiencies at the desired location of Dundaye, with capacity factors of 0.06, 0.07 and 0.07 respectively.

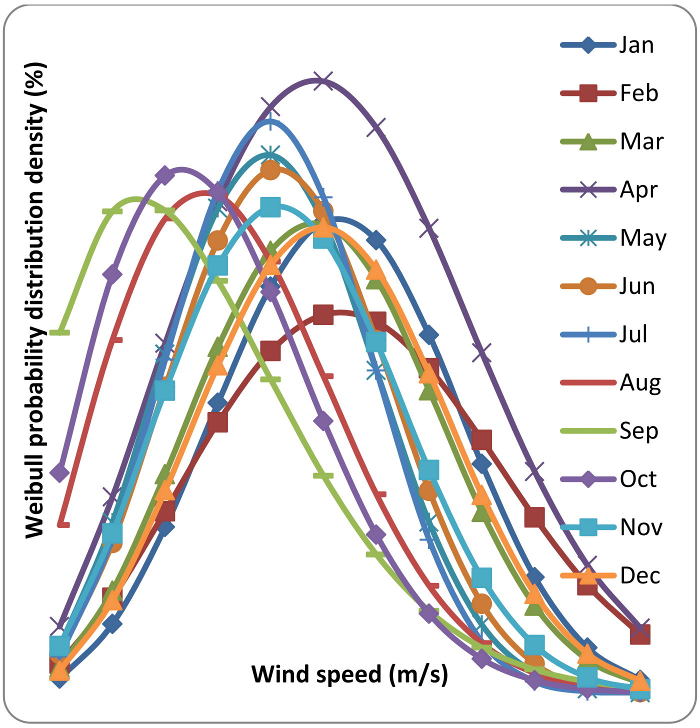

Fig-1: Monthly Weibull probability distribution density for the location

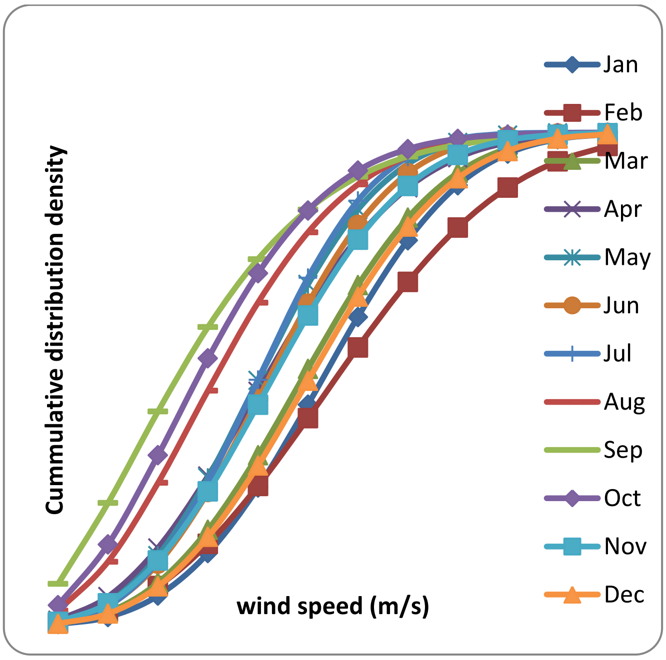

Fig-2: Cumulative Probability distribution density for the location

The plots of the Probability Distribution Density (PDD) and Cumulative Distribution Density (CDD) for the location as seen in Figure 1&2, demonstrates that the monthly most probable wind speed at the locations values that ranged from about 23% of 6m/s in the month of September to about 14% of 7 m/s in the month of February. However, the cumulative distribution density in Figure-2 has shown that the location' wind profiles follow the same cumulative distribution patterns.

CONCLUSIONS

The study assessed the monthly wind power potentials and analysed the monthly average wind power generation from selected WECS in the study area of Dundaye of Sokoto state, Nigeria. The purpose of the study was to examine the location wind profile and characteristics for electric power generation.

The outcome proved that the site wind profiles and characteristics are suitable for wind power generation, with prevalent monthly average wind speeds of 5.25 ± 2.10 m/s.

The most probable wind speed was observed to be in the ranged between 2.74 and 6.49 m/s, while wind speed carrying maximum energy ranged between 6.49 and 9.52 m/s between the months of September to February and October to February respectively. The area can be said to have possessed very high potentials for harvesting wind power. Similarly, among the nine WECS considered for the location NE- 2000 (2kW) wind turbine machines with cut_{-in} speed of 3m/s, rated speed of 8 m/s and furled wind speed of 50 m/s has proved to be the most appropriate for the sites. While, the Bonus-3000, Bonus-2300 and Bonus-2000 are the least appropriates for the site, with monthly capacity factors of 0.36 and 0.06, 0.06 and 0.07 for NE-2000 (2kW), Bonus-3000 (3kW), Bonus-2300 (2.3kW) and Bonus-2000 (2kW) respectively.

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