Analysis Of Wind Energy Resource Potentials And Cost Of Wind Power Generation In Sokoto, Northern Nigeria

By

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ABSTRACT
Assessment of wind energy resource potentials for Sokoto (Latitude 13.1^0N, Longitude 5.20^0E and Altitude 531m), has been conducted based on the measured wind speed data at 10m height for a period of three years from January 2008 to December, 2010. Wind speeds data at thirty minute interval was monitored using automatic weather logging system (***Data logger model Weather Link 5.7.1*****),** provided by CBSS under the programme micro-wave propagation project (MPP). Where, five minute average wind speed data was recorded at every thirty minutes interval for three years. The results of the measurement showed that average monthly wind speed varies from 3.89m/s in the month of September to 7.89m/s in the month of February. The results of the analysis using Weibull two-parameters also showed that Sokoto has annual values of average power density and energy in the ranges between 57.53W/m^2 to 480.01W/m^2 and 503.93kWh/m^2/year to 4204.84kWh/m^2/year respectively. The economic cost analysis using LCC assessment has shown that (Endurance E-3120 (50kW) slightly perform below the Evoco 10 (10kW)) in terms of their respective capacity and cost of electric power generation, which gave estimated costs of 18.65NGN and 17.12NGN per kWh of energy produce by the turbines and capacity factor of 0.80 as against 0.74 respectively. Sokoto can therefore, be classified as suitable location for wind turbine applications where electrical energy from the wind can favorably compete with many conventional energy sources.

Keywords: Assessment, Wind energy, Resource Potentials, Weather link, Endurance, Evoco, Analysis, Monitored, Measurement, Small-Medium, Turbines, Weibull probability distribution density.

1.0 Introduction

The role of energy as a basic element of any economic development is well establishes and electric energy is an important index of a country`s economical and technological progress [1]. Therefore, energy can be said to be a fundamental devices to derive any nation from developing to developed or from stable to more stable position [2]. Energy is not only prime agent for generation of wealth but a significant factor in economic development and the driving force for industrialization of any society [3,4].The increasing global energy demand and the adverse effects of non-renewable fossil fuels on environment had motivated considerable research attention in wide range of engineering application of renewable sources such as solar, geothermal, and wind [5]. Nigeria is blessed with different energy sources from ranging from fossil fuels, nuclear and renewable sources, yet electricity generation and distribution crisis have been the main obstacle to economic development of the country [6]. 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 1011GW, which is several times more than the current global energy consumption [5,7]. The wind energy market is growing in hasty ascending manner worldwide with an installed capacity of 17.4GW in 2000 reaching up to 236GW by end of 2011 with annual average growth of 1.2% [8].

According to [9] Wind power has become an important option for electricity generation among renewable sources of energies due to the strong growth in wind installed generation capacity worldwide which could be attributable to three major reasons. First, the growing public awareness and concern about emissions, climate change and environmental issues related to other competing sources of energy. Second awareness about oil and gas reserves depletion and the predicted Global peaking of oil production. Third, the strong growth of wind power is the improvements in wind turbine technologies that have resulted in lower cost [2]. Although wind is an inexhaustible resource whose energy utilization has been increasing around the world at an accelerating pace its developmental projects continues to be hampered by the lack of reliable and accurate wind resource data in many parts of the world, especially in the developing countries such as Nigeria [10]. The ability to accurately assess renewable energy resources is an essential prerequisite to integrating renewable energy technologies into the energy supply portfolio of any community. The aim of this paper is to assess the wind energy potentials of Sokoto using primary data obtained from the field measurement at the locations and compute the unit cost of a kWh of electrical energy from the wind through the use of wind characteristics at the desired location and characteristic of the wind turbine provided by the manufacturers.

2.0 Theoretical Consideration

For wind turbines applications, the wind speed at the hub height is of interest and therefore, the wind speeds are adjusted to the wind turbine hub height using the following power law expression, [11,12,13]

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

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 and is assumed to be 0.143 (1/7) in the study.

2.1 Wind speed probability using Weibull parameters

The Weibull probability distribution has probability density function and cumulative distribution functions using the two-parameter being expressed as in to equation (2) and (3) respectively [14,15,16] as;

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

$$F(v) = 1 - e^{-\left(\frac{v}{c}\right)^{k}} \qquad (3)$$

Where k is dimensionless Weibull shape parameter and c is the Weibull scale parameter (m/s). Although there are various method discussed by [17,18,19] on the evaluation of Weibull parameters k and c, in this study the monthly and annual values of shape and scale parameters were computed using standard deviation methods so that the two parameters of Weibull functions k and c can be related to mean speed v_m and standard deviation σ by [6] as;

$$k = \left(\frac{\sigma}{v_m} \right)^{-1.086} \qquad (1 \le k \le 10) \quad (4)$$

$$C = \frac{v_m}{\Gamma\left(1 + \frac{1}{k}\right)} \quad (5)$$

$$\Gamma(x) = \int_0^{\alpha} t^{x-1} e^{-t} dt \quad (6)$$

Where Γ is the gamma function, however Lysen used the following approximation to find *c*, as reported by [17]

$$\frac{c}{\bar{V}} = (0.568 + 0.433/k)^{-\frac{1}{k}} \quad (7)$$

The two significant wind speeds for wind energy estimation are the most probable wind speed (v_{mp}) and the wind speed carrying maximum energy $(v_{\max E})$ which according to [10] can be expressed as:

$$v_{mp} = C\left(\frac{k-1}{k} \right)^{\frac{1}{k}} \quad (8) \text{ and}$$

$$v_{\max E} = C\left(\frac{k+2}{k} \right)^{\frac{1}{k}} \quad (9)$$

Respectively, Wind turbine system operates at its maximum efficiency at its design or rated wind speed and it would be essential the rated wind speed and the wind speed carrying maximum energy should be as close as possible.

2.2 Wind Power Density Function

The power of wind at speed (v) through a blade of sweep area (A) increases as the cube of its velocity and is given by [20,21] as:

$$P(V) = \frac{1}{2} \rho A v_m^3 \quad (10)$$

Where ρ is the mean air density at average atmospheric pressure at sea level and at room atmospheric temperature, which depends on altitude, air pressure and temperature [21] While, the expected monthly or annual wind power density per unit area of a site based on a Weibull probability density function can be expressed follows [22]

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

Where, $P(V)$ is the wind power (W), $p(V)$ is the wind power density (W/m^2), ρ is the air density at the site (considered to be 1.22kg/m^3 in this study), and A is the swept area of the rotor blades (m^2) and C is the Weibull scale parameter (m/s).

2.3 Evaluation of Wind Energy

The daily, monthly and yearly extractable mean wind energy is evaluated using the following equations [10]:

$$\bar{E}_j = 24 \times 10^{-3} \ \bar{P}_T (KWh/m2) \quad (13)$$

$$\bar{E}_{jm} = 24 \times 10^{-3} \ d\bar{P}_T (KWh/m2) \quad (14)$$

$$\bar{E}_y = \sum_{n=1}^{n=12} \bar{E}_{jm} (KWh/m2/year) \quad (15)$$

Where $\bar{p}_T = p(V)$ in (W/m^2) and d is number of days in the corresponding month considered.

2.5 Power Output of a Wind Turbine and Capacity Factor

Wind energy conversion system can operate at maximum efficiency only if it is designed for a particular site; this is because the rated power, cut-in and cut-off wind speed must be defined based on the wind characteristics [5]. Performance of a wind turbine at any given location can be evaluated by the amount of mean power output over a period of time (P_{out}) and the conversion efficiency or capacity factor of the turbine C_f can be defined as the fraction of the of the power output over a period of time to the rated electrical power (P_{eR}) of the wind turbine [5] and [10] through the following expressions based on Weibull distribution function, and for Rayleigh distribution function $k = 2$.

$$p_{out} = p_{eR} \left(\frac{e^{-\left(\frac{Vc}{C}\right)^{\kappa}} - e^{-\left(\frac{Vr}{C}\right)^{\kappa}}}{\left(\frac{Vr}{C}\right)^{\kappa} - \left(\frac{Vc}{C}\right)^{\kappa}} - e^{-\left(\frac{Vf}{C}\right)^{\kappa}} \right) \quad (16)$$

And

$$C_f = \frac{p_{out}}{p_{eR}} \text{ Respectively} \quad (17)$$

Capacity factor C_f can further be expressed as:

$$C_f = \left(\frac{e^{-\left(\frac{Vc}{C}\right)^{\kappa}} - e^{-\left(\frac{Vr}{C}\right)^{\kappa}}}{\left(\frac{Vr}{C}\right)^{\kappa} - \left(\frac{Vc}{C}\right)^{\kappa}} - e^{-\left(\frac{Vf}{C}\right)^{\kappa}} \right) \quad (18)$$

Where V_c, V_r and V_f are the cut-in, rated and cut-off wind speed, respectively usually provided by the turbines manufacturers. However, it has been established fact that the cost effectiveness of a wind turbine can be roughly estimated by the capacity factor of the turbine. The capacity factor is hence a very useful parameter for both consumer and manufacturer of the wind turbine system [5]. It is however suggested that for the wind turbine to be cost effective for a particular location the capacity factor should be within the range of 0.25 to 0.40 [20]

2.6 Life Cycle Cost Analysis

This is one of the most comprehensive methods of evaluating the economic performance of any wind conversion system [23]. The economic analysis of the selected wind turbine models was performed using LCC method, where the cost of a kWh of energy produced by a turbine at the site was evaluated by taking into account the following information and assumptions:

1. Interest rate (r) and inflation rate (i) were taken as 23 and 5% respectively [24] while the inflation escalation rate (e) was assumed to vary between 0 - 5% (2.5%)
2. The life time (t) of the machine was anticipated to be 20 years
3. Operation, maintenance and repairs cost (Comr) is estimated to be 25% of the annual cost of the wind turbine (system price / life – time) and the escalation rate of operation and maintenance (Com(esc)) was assumed to vary between 0 - 10% (5%) as reported by [9]
4. Other initial costs included that for the land, installation cost, and grid integration which were assumed to be 30% of the wind turbine cost.
5. It was also further assumed that the wind turbine produces the same amount of energy output throughout the years of its lifetime.
6. Value of the scrap was assumed to be 10% of the turbine price and civil work.

The economic performance via the life-cycle cost analysis was conducted for the two selected wind turbine models, i.e. Endurance E-3120 (50kW) and Evoco 10 (10kW) wind turbine generators in kWh/N of electricity generated. The computation was based on the total costs involved, which can be divided into investment (or installed capital costs) and recurrent costs [17]. The investment is the cost incurred once in the lifetime of the project while, recurrent cost occurs periodically from time to time, these include operation and maintenance costs. The life-cycle costing method combines the installed capital cost, costs of operations and maintenance (O&M) and cost of major overhauls and subsystem replacement throughout the lifetime of a wind system [17,9]

Some key concepts and parameters in LCC analysis includes:

- The time value of money and the present worth factor
- Levelising and capital recovery factor
- Net present worth

2.6 (a) Time Value of Money and the Present worth Factor

Money to be spent in future has a different value from the one today, this is true even if there is no inflation, since a unit of money can be invested (e.g. in savings account) and bear interest, thus its value is increased by the interest (Wood and Omuya, 1983). It will often be important to know the present value of future sum of money which has been invested at a given rate of compound interest for a known number of periods. For example, suppose an amount with a present worth PW (also called present value) is invested at a discount (or interest) rate r, with annual compounding of interest for N years, the future amount, FA, after N years according to [26] is:

$$FA = PW(1+r)^N \quad (19)$$

The ratio of PW to FA is defined as the present worth factor PWF, and is given by:

$$PWF = PW/FA = \frac{1}{(1+r)^N} \quad (20)$$

2.6 (b) Levelising and Capital Recovery Factor

Levelising is a method of expressing cash flows that occur once or in irregular intervals as equivalent equal payments at regular intervals. Suppose a loan payment plan consists of a series of equal monthly or yearly installments. That is, a loan of present worth PW is to be repaid in equal annual payments A compounded over N years, at a discount rate r. The size of these annual payments A is given by [26]

$$A = PW\left[\frac{r(1+r)^N}{(1+r)^N - 1}\right]. \qquad (21)$$

The capital recovery factor, CRF, is defined as the ratio of A to PW, and is given by:

$$CRF = A/PW = \frac{r(1+r)^N}{(1+r)^N - 1}. \qquad (22)$$

2.6 (c) Net Present worth

The net present worth (NPW) is defined as the sum of all relevant present worth's for costs and revenues in an LCC analysis. If only cost factors are considered, then a cost version of net present worth, NPWc, may be used. From equation (20), where the present worth of a future cost, C, can be evaluated at year N as:

$$PW_c = C/(1+r)^N \qquad (23)$$

Where, PWc is the present worth of a future cost.

Similarly, from equation (21), the PWc of a recurrent cost, C, to be paid each year for N years is (Wood and Omuya, 1983):

$$PW_c = \left(\frac{(1+r)^N - 1}{r(1+r)^N}\right)C \qquad (24)$$

The total 'life-cycle cost' of any project is obtained by adding the investment cost, the present worth of the recurrent costs and present worth of costs of any subsystem replacements. This is the net present worth of all costs. Thus,

$$NPW_c = C_c + \left(\frac{(1+r)^L - 1}{r(1+r)^L}\right)(O\&M) + \left(\frac{1}{1+r}\right)^n R_c, \qquad (25)$$

Where, Cc is installed capital cost, L is lifetime of system, Rc is replacement costs and n is year of replacement.

2.7 Levelised Cost of Energy

In its most basic form, the levelised cost of energy (COEL), in Nigerian Naira per kilowatt hour (N/kWh), is given by the sum of annual levelised cost of energy for a wind electric system divided by the annual energy production (Pam, *et al.*, 2008) [17]. Thus,

$$COE_L = \frac{\sum(Levelised\ annual\ costs)}{Annual\ energy\ production} \qquad (26)$$

Hence,

$$COE_L = \frac{(NPW_c)(CRF)}{Annual\ energy\ production} \qquad (27)$$

Since, the COEL is in N/kWh, the unit of (NPWc)(CRF) is in N/year and annual energy production is in kWh/year.

3.0 Data Acquisition and Analysis

The thirty minute interval wind speed data used in this study was monitored from weather stations installed at the locations, (Latitude 13.1^{0}N, Longitude 5.20^{0}E and Altitude 531m), Nigeria, for the period of three years (2008-2010). The measurement was by used of cup-anemometer placed at a height of 10m; where five minute average wind speed is recorded in every thirty minute and stored in a data logger. The data is then downloaded periodically by end of each month throughout the period under study using RS-232 serial cable to computer. The thirty minute wind speed data was tabulated in to daily and monthly mean relative table using Mat-lab and Microsoft excel programme.

4.0 Result and Discussion

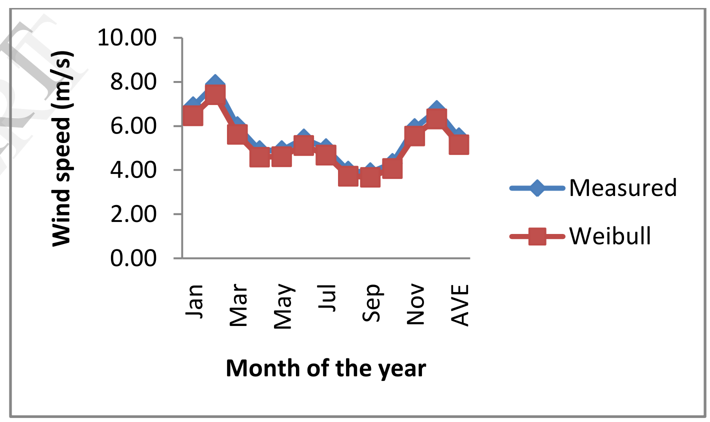

Figure 1: Comparison of monthly mean wind speeds obtained from measurement and Weibull probability distributions function for Sokoto.

The monthly mean wind speed at 10m height for the location is presented in figure 1, where the wind speed was observed to vary between 3.89 m/s in the month of September to 7.89 m/s in the month of February for the average of three years. This observed 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 being experienced across the state during dry seasons as a result of the North-East trade wind blowing across the whole area from Sahara and resulting in significant low temperature during this period. The Weibull monthly average wind speeds is closely describing the measured wind speed for the three years average as can be seen in figure 1. The monthly mean wind speeds Evaluated Properties for Sokoto, Nigeria, which includes monthly mean wind speed and standard deviation, monthly and annual values of Weibull parameters (k and C), most probable wind speeds and wind speed carrying maximum energy were presented in table 1. The k and c were computed using equation (4) and equation (5) at 10m height at Sokoto. It can be observed from the values of Weibull shape parameter K that ranged from 2.08 in the month of September to 3.32 for February and March respectively, that wind speed is least uniform in the month of September and most uniform in the month of February and March. The monthly scale parameter c has the lowest value of 4.39m/s in the month of September and has its highest value of 8.79m/s in the month of February. Similarly, the average annual shape parameter K and scale parameters C were found to be 2.79 and 6.15m/s for the three annual average, the monthly average scale parameter is closely related to monthly mean wind speed for the location which is in absolute agreement with the results obtained by (Pam, et al., 2008). The most probable wind speed and wind speed carry maximum energy were computed using equation (7) and equation (8) respectively, it can be observed from same table 1 that, the monthly most probable wind speed for each month of the year is very closely related to the monthly mean wind for the period under consideration. The maximum energy carrying wind speed for the locations were found to vary between 5.49m/s in August to 10.38m/s in February, similarly the highest maximum energy carrying wind speeds were observed to be between the months of December to the month of February. Figure 2 present the correlation curve for the location, where both power curve and linear curve fit methods were explored to find the correlation coefficient between the average power density and mean wind speeds for the location. It can be seen from the figure that both methods displayed a very strong correlation coefficient with values of R^2 of 0.958 and 0.996 for linear and power curves respectively.

Table 1: Monthly mean wind speeds Evaluated Properties for Sokoto, Nigeria.

	V_m	σ	k	c	V_{mp}	$V_{\max E}$
Jan	6.88	2.35	3.21	7.68	6.93	9.17
Feb	7.89	2.61	3.32	8.79	8.00	10.38
Mar	5.98	1.98	3.32	6.66	6.06	7.87
Apr	4.89	1.62	3.32	5.45	4.95	6.44
May	4.89	2.12	2.48	5.51	4.61	7.31
Jun	5.42	2.53	2.29	6.12	4.95	8.46
Jul	4.98	1.87	2.90	5.58	4.92	6.91
Aug	3.96	1.48	2.91	4.44	3.92	5.49
Sep	3.89	1.98	2.08	4.39	3.38	6.42
Oct	4.31	2.06	2.23	4.87	3.89	6.82
Nov	5.89	2.36	2.70	6.62	5.71	8.44
Dec	6.71	2.61	2.79	7.54	6.57	9.47
AVE	**5.47**	**2.13**	**2.79**	**6.15**	**5.36**	**7.73**

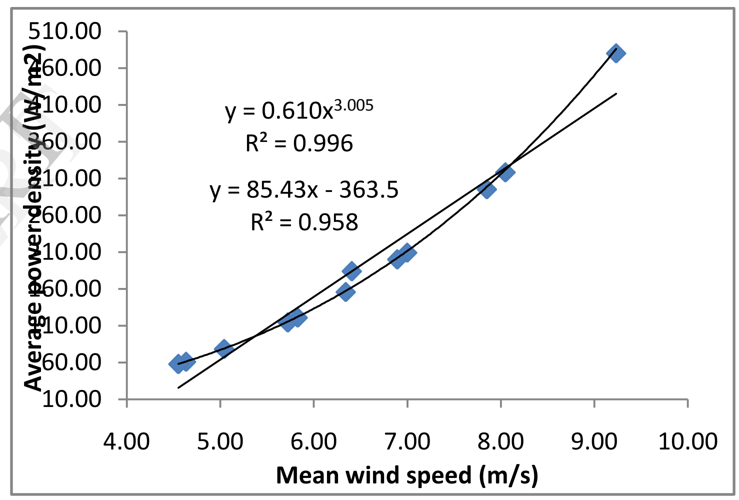

Figure 2: Linear and power curve plot of monthly average power density against monthly mean wind speed for Jos

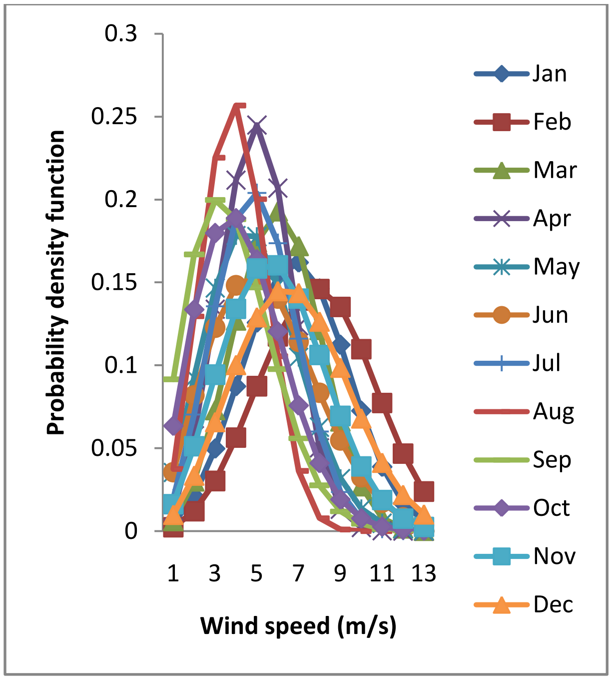

Figure 3: Monthly Wind speed Probability density distribution for three years average for Sokoto

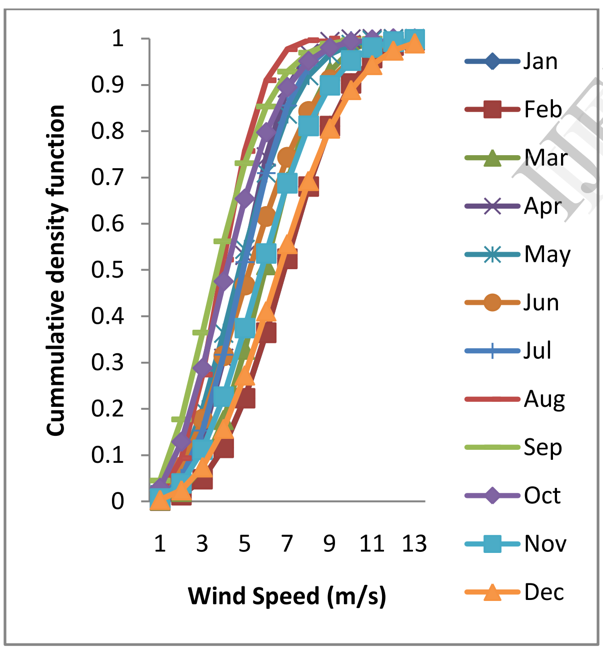

Figure 4: Monthly Cumulative probability distributions of wind speed for three years average for Sokoto

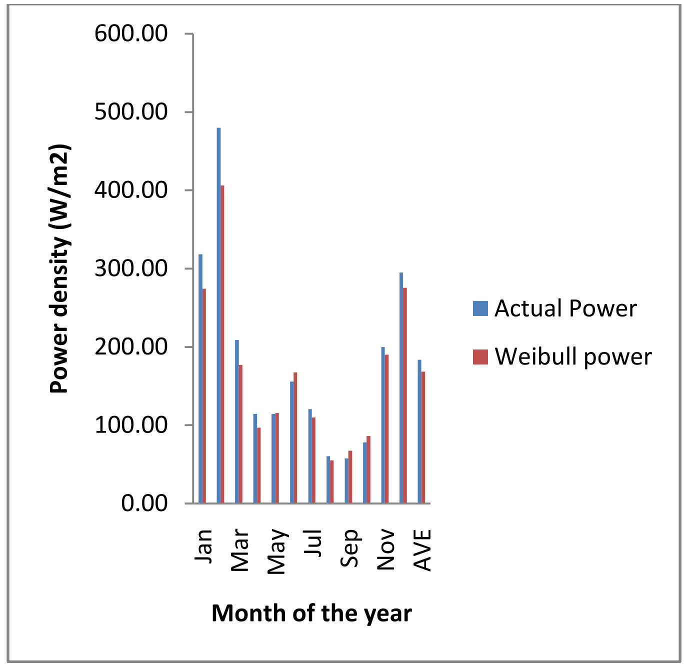

Figure 5: Monthly Power density for three years average data for Sokoto at 30m

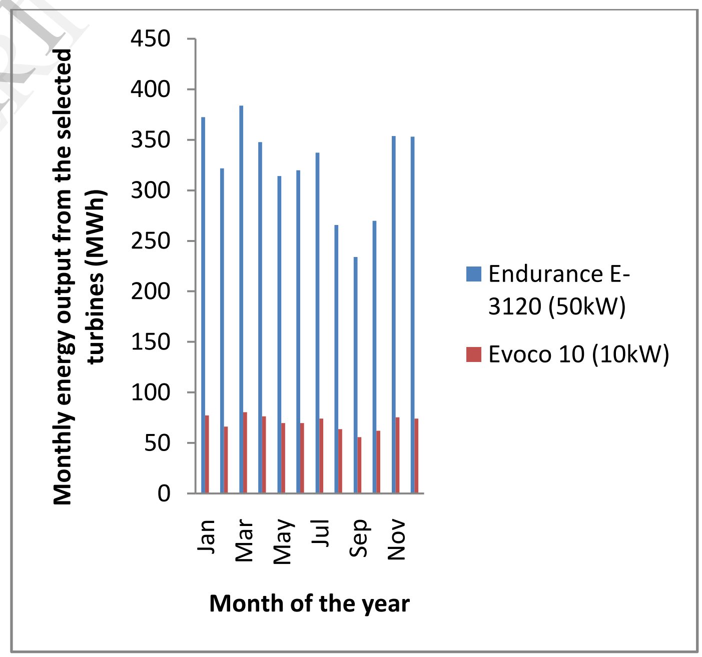

Figure 6: Monthly power output of the selected wind turbines.

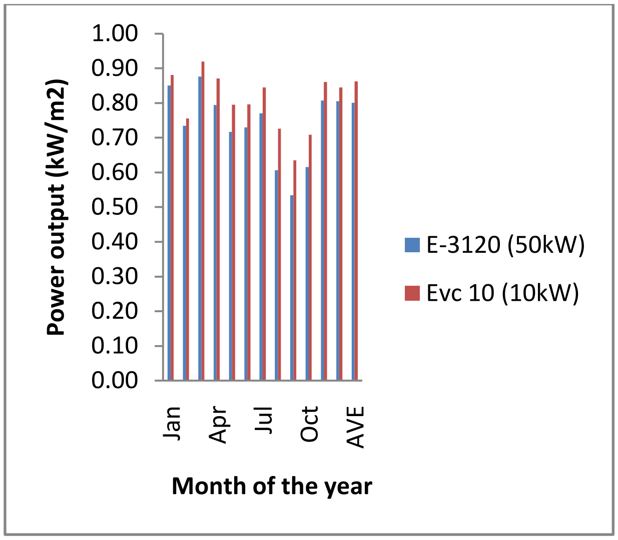

Figure 7: Monthly capacity factors of the selected wind turbines.

This indicated that power curve is a better correlation method than the linear method in wind speed data analysis. The exponent of the power curve fit was evaluated to be 3.005 (approximately 3), which is in agreement with the cubic wind speed relationship of the power density. Hence, the average power density (W/m^2) for Sokoto as a function of the mean wind speed (m/s) can be expressed in form of power law as: $\frac{p}{A} = 0.610V^{3.005}$

The monthly Weibull probability density and cumulative distributions of the three years average wind speed data for Sokoto is shown in figure 3 and figure 4 respectively. It can be seen from the figures that both curves exhibit similar tendency of wind speeds for the two distributions. The peak of the density function frequencies for the location skewed towards higher values of the mean wind speed, which also indicated the most probable wind speed [9]. As can be seen from the figure 3 the highest most frequent wind speed of about 8m/s was observed for the month of February with a peak frequency of approximately 17%, whereas, the least most probable wind speed of about 3m/s was observed in September with peak frequency of approximately 20%. Furthermore, it can be seen from same figure that there is a tendency of obtaining wind speeds of ≥ 9m/s in all the months for the whole year, while December, January and February months of the year have the likelihood of having wind speeds exceeding 12m/s.

Economic Cost Analysis

Table 3: Characteristics properties of the selected wind turbines:

Characteristics	Endurance E-3120 (50kW)	Evoco 10 (10kW)
Rotor-diameter (m)	19.2	9.7
Hub Height (m)	22, 36	12,15
Connection	Three phase Direct grid Connect	Single/ Dual/Three phase Inverter Connect
Typical Installed cost(€)	259,000	51,000
Annual maintenance Cost (€)	2,500	450
Expected number of operational years	20	20
Warranty in years	5	5
Survival speed (m/s)	52	59
Cut-in speed (m/s)	3.5	3
Rated wind speed (m/s)	9.5	9.5
Furled wind speed (m/s)	25	25

Table 4: Total investment, O&M costs, Replacement Cost and their present worth costs.

	Endurance E-3120 (50kW)	Evoco 10 (10kW)
Installed Capital Cost	€ 259,000 (NGN60,865,000)	€51,500 (NGN12,102,500)
Annual O&M Costs (2%)	1,217,300	242,050
Present worth of the Annual O&M Costs, PWO&MC	4,604,349.40	920,867.88
Net Present Worth of all costs	80,639,598.40	16,039,845.88
Capital Recovery Factor (CRF)	0.080243	0.080243
Levelised cost of energy/year	6,470,037.54	1,287,085.35
Annual Total energy from the Turbine (GWh)	3.87	0.84
Specific cost per kWh (NGN)	18.65	17.12

The economic cost analysis using LCC method was conducted on two selected small-medium size wind turbines model namely Endurance E-3120 (50kW) and Evoco 10 (10kW) in order to compare their performance at the location. The characteristics properties of the selected wind turbines is given in table 3, while considering the assumption made earlier and cost of each of the selected wind turbines, the respective computed present worth values, Capital recovery factor, Annual levelised cost of energy, Annual total energy from each of the selected wind turbine and specific cost per kWh in Nigerian naira was also presented in table 4. The specific costs per kWh for each of the selected wind turbines are evaluated from present worth values costs / total energy output for turbine life time. The monthly energy output from the selected wind turbines is presented in figure 6, where the energy output was observed to vary from 234MWh in the month of September to 383.88MWh in the month of March and 55.589MWh in the month of September to 80.556MWh in the month of March for the Endurance E-3120 (50kW) and Evoco 10 (10kW) respectively, this could be as a result of the variation of the wind speeds recorded in the various month. Similarly, it can be clearly observed from figure 7 that Evoco 10 (10kw) wind turbine performed fairly better in each month of the year than the Endurance E-3120 (50kW) as can be seen from the value of capacity factor that vary from 0.53 to 0.88 and 0.63 to 0.92 for Endurance E-3120 (50kW) and Evoco 10 (10kW) respectively.

Conclusions

Wind energy resource potentials for Sokoto location in Northern, Nigeria was evaluated using Weibull statistical model and the performance of small to medium commercial wind turbines was also assessed using LCC analysis. Based on these the following conclusions were drawn:

1) That Sokoto is a very good location for wind energy development, with monthly wind speed variation ranged between 3.89m/s September to 7.89m/s February, at 10m height throughout the year.
2) The monthly mean power density and energy is in the ranged of 57.53W/m^2 to 480.01W/m^2 and 67.30kWh/m^2 to 406.46kWh/m^2 respectively, with monthly average power of 183.62W/m^2 and annual energy of 19.303 MWh /year, hence Sokoto falls under class 3 of the international system of wind energy classification..
3) Weibull statistical model is a very good probability distribution model in wind speed analysis from the comparisons of measured values with Weibull approximation values obtained from the model.
4) The monthly energy output from the selected wind turbines varied from 234.08MWh/month in the month of September to 283.88MWh/month in the month of March and 55.589MWh/month in the month of September to 80.556MWh/for the month of March for Endurance E-3120 (50kW) and Evoco 10 (10kW) respectively.
5) The performance of Evoco 10kW is slightly better than the Endurance E-3120 (50kW) from the specific cost per kWh obtained for Evoco 10 (10kW) as 17.12 NGN, as against 18.65NGN for Endurance E-3120 (50kW) and higher monthly average capacity factor obtained for Evoco 10kW (0.80) that is greater than that obtained for Endurance E-3120 (50kW) (0.74).

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