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# Reliability Analysis of the ongoing 10MW Electricity Generation from Wind in Katsina State, Nigeria

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***ABSTRACT***

*Wind potential assessment for any location is an essential and primary task in any power generation study. The amount of energy produced by a turbine depends on the characteristics of both wind speed at the site under investigation and the turbines power performance curve. Improper sitting for installation of the wind turbines results in loss of huge amount of money. This work investigates the reliability potential of the ongoing 10MW electricity generation from wind in Lambar Rimi, Katsina. The project consists of 37 wind turbines with rated power of 275kW each. Five year period (2006-2010) data for wind speed at 10m height was analysed. The average wind speed and the Weibull parameters at 10m height were extrapolated to the hub height of 55m. Seven models for the power performance curve between cut in to rated speed were compared with the manufacturer's data. The expected power output of the turbine was determined by combining wind characteristics of the location and the power output characteristics of the turbine using numerical methods. The results show that each turbine is expected to generate energy of about* $388.1 GWh/annum$ *instead of rated energy of* $2{,}409 GWh/annum$ *. Monthly capacity factor for the turbine ranges from 0.10 to 0.23. This indicates that if the 10MW project is completed, it will be reliably operating in the range of 1MW to 2.3MW power plant on average which indicates that the turbine-site matching is very low.*

***Key Words:*** *Reliability, Performance, Katsina, Wind, Project, Models.*

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## 1. INTRODUCTION

Nigeria is endowed with huge reserved of conventional energy resources (fossil fuels) and reasonable amount of renewable energy resources which includes solar, wind etc.; yet electricity generation and its distribution remains a major obstacle to its economic development [1].

Wind energy is one of the fastest growing renewable sources of energy in both developed and developing countries with total available power surrounding the earth being in the order of 1011GW, which is several times more than the current global energy consumption[1]. A study on wind energy potentials carried out by Energy Commission of Nigeria (ECN) indicated high wind speeds in Sokoto, Jos, Kano and Katsina regions[10, 12].

Although Nigerian government has been trying to encourage the exploitation of renewable energy resources in the country, not much has been achieved in the field of wind power generation. The only notable achievement is the construction of a 10MW Katsina wind farm [12, 14] and is yet to be completed.

The 10MW wind farm project is owned by the Federal Ministry of Power desired to improve electricity supply in Nigeria. The project consists of thirty seven (37) wind turbines with a rated power of 275kW each. It is located at Lambar Rimi which is about 18.6km south of the Katsina Airport. Wind speed data of the location, technical specification of the turbine used, number of the turbines used and the spacing method adopted were highlighted by[4, 14] . Both papers did not elaborate on the expected energy to be obtained based on the wind data of the location and the specification of the machine.

This work is aimed to use the wind speed data of the location and the technical details of the wind turbine to analysed the expected energy output from the project. This will be done by calculating the Weibull parameters, project their values at the hub height, come up with a suitable power curve model and determine the capacity factor of the machine.

## 2.0 METHODOLOGY

In estimation of wind energy resource potentials of any location, knowledge of the wind speed frequency distribution is of paramount importance [8]. Wind speed at a given location is continuously varying. These changes can be due to [6, 15]:

i. The season;
ii. A passing weather systems (synoptic);
iii. Changes on a daily basis (diurnal);
iv. Instantaneous changes (turbulence).

These changes make it difficult to predict the overall energy capture from a site. Hence to make meaningful estimations for long term energy capture, statistical methods are used.

### 2.1 Wind Probability Density Function

There are various probability density functions which can be utilized to fit and describe the wind speed frequency over a period of time. These include Weibull, Rayleigh, Gamma, Beta, Gaussian and Lognormal distribution[8].

In this work the two parameter Weibull probability distribution function was chosen for the analysis because of its simplicity nature and an excellent match with the measured data as reported by [1, 8, 9, 11, ] and is given by:

$$f_w(V) = \frac{k}{c}\left(\frac{V}{c}\right)^{k-1} exp\left(-\left(\frac{v}{c}\right)^k\right) \quad (1)$$

Where, $k$ the dimensionless Weibull shape parameter;
$c$ the Weibull scale parameter , and it has dimension of velocity;
$f_w(V)$ the probability of wind speed occurring.

The cumulative probability, $F(V)$ is obtained by integrating the Weibul distribution function between zero and a defined wind speed (V) which gives:

$$F(V \leq b) = \int_0^b \frac{k}{c}\left(\frac{V}{c}\right)^{k-1} exp\left(-\left(\frac{v}{c}\right)^k\right) dV \quad (2)$$

Simplifying the equation gives:

$$F(V \leq b) = 1 - exp\left(-\left(\frac{v}{c}\right)^k\right) \quad (3)$$

The mean wind speed $(\bar{V})$ and standard deviation $(\sigma)$ can equally be expressed in terms of Weibull distribution function as reported by[1] Mostafaeipour *et al.*, (2014) using:

$$\bar{V} = \int_0^\infty V f_w \, dv = c\Gamma(1 + 1/k) \quad (4)$$

$$\sigma = \sqrt{c^2(\Gamma(1 + 2/k) - [\Gamma(1 + 1/k)]^2)} \quad (5)$$

#### 2.1.1 Determination of Weibull Parameters

There are various methods for the evaluations of Weibull parameters k and c [10]: Least Square Method (LSQM), Method of Moments (MOM), Standard Deviation Method (STDM), Maximum Likelihood Estimation Method (MLEM), Power Density Method (PDM) and Equivalent Energy Method (EEM).

In this study the monthly and annual values of shape and scale parameters were computed using the standard deviation method given by [1, 8, 9, 10]:

$$k = \left(\frac{\sigma}{\bar{V}}\right)^{-1.086} \quad (1 \leq k \leq 10) \quad (6)$$

$$c = \frac{V}{\Gamma(1+1/k)} \quad (7)$$

Where $\bar{V}$ , $\sigma$ and $\Gamma(x)$ are average wind speed, standard deviation and gamma function which can be expressed using the following equations[1] (Pam *et al.*, 2007; Islam *et al.*, 2011; Mostafaeipour *et al.*, 2014):

$$\bar{V} = \frac{1}{n}\sum_{i=1}^{n} V_i \quad (8)$$

$$\sigma = \left[\left(\frac{1}{n-1}\sum_{i=1}^{n}(v_i - \bar{V})^2\right)\right]^{\frac{1}{2}} \quad (9)$$

$$\Gamma(x) = \int_0^{\infty} exp(-u)u^{x-1}dx \quad (10)$$

### 2.1.2 Extrapolation of Weibull Parameters at Hub Height

Wind speed measurement at prospective wind farm site is measured for a certain period of time usually done at the standard anemometer height of 10m. Clearly, wind speed generally increase with increase in altitude. Consequently, since most modern day wind turbines have their operational hub height greater than 10m, the wind speed values measured at 10m height should be extrapolated to reflect the hub height of the turbines.

Using Weibull distribution function, adjusted shape parameter $k_h$ , scale parameter $c_h$ and wind speed $v_h$ at the desired height $h_m$ are related to the shape parameter $k_o$ and scale parameter $c_o$ at measurement height of $10m$ as $[1, 8, 9, ]$:

$$k_h = k_0/[1 - 0.088\ \ln(h_m/10)] \quad (11)$$

$$c_h = c_0(h_m/10)^{\alpha} \quad (12)$$

$$V_h = c_h\Gamma(1 + 1/k_h) \quad (13)$$

Where $\alpha$ is the power law exponent (coefficient) and is defined by (Mohammed and Mostafaeipour, 2013):

$$\alpha = [0.37 - 0.088In(c_0)] \quad (14)$$

## 2.2 Output Power of Wind Turbine

The power production of wind turbine depends upon many parameters such as wind speed, air density (a function of temperature, pressure and humidity), power coefficient (a function of turbine parameters such as blade design, tip angle etc).

The theoretical power, P captured by a wind turbine is given by[6]:

$$P = 0.5\rho A_w C_p v^3 \quad (15)$$

Where: $\rho$- air density, $A_w$- rotor area, $C_p$- power coefficient, $v$- wind speed.

Much complexity is involved in considering the effects of all the influencing parameters properly; it is therefore difficult to evaluate the output power using the theoretical equation given above.

The actual power performance of wind turbine can be described by three speed parameters: cut in speed, $V_c$ ; rated (nominal) speed, $V_r$ ; and cut out (foil) speed, $V_f$. The output power operation pattern of a pitch regulated wind turbine is as shown in Figure 1; therefore, the power delivered by the wind turbine can be expressed as[13]:

$$P_w(V) = \begin{cases} 0 & V < V_c, \\ q(v) & V_c < V < V_r \\ P_r & V_r \le V \le V_f \\ 0 & V > V_f \end{cases} \quad (16)$$

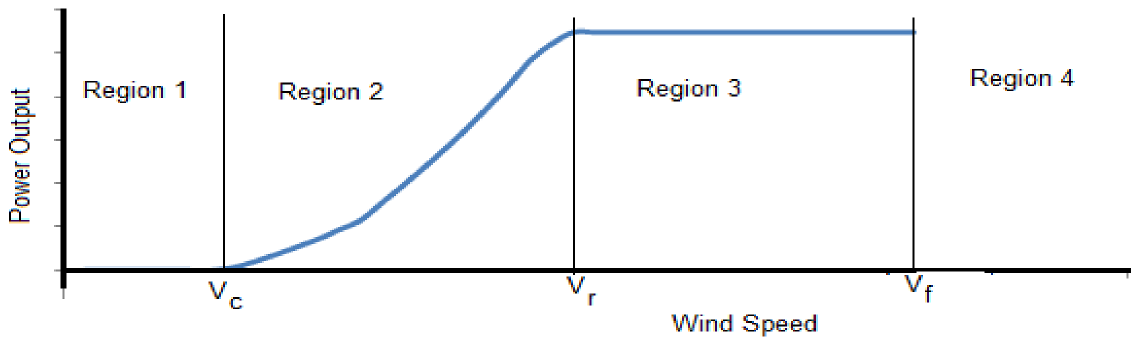


**Figure 1: A Typical Power Curve of a Pitch Regulated Wind Turbine**

In the first region, the velocity is less than the cut in velocity and the output power of the turbine is zero; while in the second region between the cut in and the rated speed there is a rapid growth of power produced. In the third region, a constant output (rated) is produced in the case of pitch regulated turbines until the cut off speed is attained; whereas stall regulated turbines have decrease power output in this region and therefore should not be modelled as a constant. . Beyond this speed (region 4), the turbine is taken out of operation to protect its components from high winds; hence it produces zero power in this region[13]. The average power produced by a wind turbine, $P_{ave}$ can be calculated by [3, 6]:

$$P_{ave} = \int_o^\infty p_w(V) f_w(V) dV \quad \text{……… (17)}$$

Where, $p_w(V)$ -is the machine power curve model; $f_w(V)$ -probability density function

Based on the power curve of figure 1, equation 17 can be written as:

$$P_{ave} = P_{C-r} + P_{r-f} = \int_{V_c}^{V_r} q(v) f_w(V) dV + \int_{V_r}^{V_f} P_r(v) f_w(V) dV$$

Where, $P_{C-r}$ is the power from cut in to rated speed (growth region)

$P_{r-f}$ is the power from rated to cut off speed (rated region)

$P_{r-f}$ can be further simplified as:

$$P_{r-f} = P_r(v) \int_{V_r}^{V_f} \frac{k}{c}\left(\frac{V}{c}\right)^{k-1} exp\left(-\left(\frac{v}{c}\right)^k\right) dV = P_r[1 - exp\left(-\left(\frac{v_f}{c}\right)^k\right)] - P_r[1 - exp\left(-\left(\frac{v_r}{c}\right)^k\right)]$$

Therefore,

$$P_{c-r} = \int_{V_c}^{V_r} q(v) \frac{k}{c}\left(\frac{V}{c}\right)^{k-1} exp\left(-\left(\frac{v}{c}\right)^k\right) dV \quad \text{……… (18)}$$

$$P_{r-f} = P_r[exp\left(-\left(\frac{v_r}{c}\right)^k\right) - exp\left(-\left(\frac{v_f}{c}\right)^k\right)] \quad \text{……… (19)}$$

$$P_{ave} = P_{C-r} + P_{r-f} \quad \text{……… (20)}$$

### 2.2.1 Power Curve Modeling

To find average power from cut in speed to rated speed (power growth region), the output power of the machine has to be determined. The best way is to measure the actual machine output performance; alternatively, manufacturers data can be used through some numerical methods (discrete modelling) or modelling the characteristics of the machine (continuous modelling).

There are many power curve modelling techniques that can be used in the power growth region. Table 1 shows some simple models whose coefficients $a_i$ and $b_i$ are determined from the two extreme conditions in the region (i.e. $q(v) = 0$ when $= V_c$ ; $q(v) = P_r$ when $V = V_r$) then solving the equations simultaneously [2].

**Table 1: Various Models for Wind Turbine in Power Growth Region**

| Model Type | Expression | Coefficients | | Equation |
|---|---|---|---|---|
| Linear | $q(v) = a_1 + b_1 V$ | $a_1 = \frac{-P_r V_c}{V_r - V_c}$ | $b_1 = \frac{P_r}{V_r - V_c}$ | $q(v) = P_r(\frac{V - V_c}{V_r - V_c})$ |
| Quadratic | $q(v) = (a_2 + b_2 V)^2$ | $a_2 = \frac{-P_r^{\frac{1}{2}} V_c}{V_r - V_c}$ | $b_2 = \frac{P_r^{\frac{1}{2}}}{V_r - V_c}$ | $q(v) = P_r(\frac{V - V_c}{V_r - V_c})^2$ |
| Cubic 1 | $q(v) = (a_3 + b_3 V)^3$ | $a_3 = \frac{-P_r^{\frac{1}{3}} V_c}{V_r - V_c}$ | $b_3 = \frac{P_r^{\frac{1}{3}}}{V_r - V_c}$ | $q(v) = P_r(\frac{V - V_c}{V_r - V_c})^3$ |
| Cubic 2 | $q(v) = a_4 V^3 - b_4 P_r$ | $a_1 = \frac{P_r}{V_r{}^3 - V_c{}^3}$ | $b_1 = \frac{V_r}{V_r{}^3 - V_c{}^3}$ | $q(v) = P_r(\frac{V^3 - V_c{}^3}{V_r{}^3 - V_c{}^3})$ |
| Cubic 3 | $q(v) = a_5 V^3$ | $a_5 = \frac{P_r}{V_r{}^3}$ | - | $q(v) = P_r \frac{V^3}{V_r{}^3}$ |
| Weibull based | $q(v) = a_6 + b_6 V^k$ | $a_6 = \frac{-P_r V_c{}^k}{V_r{}^k - V_c{}^k}$ | $b_6 = \frac{P_r}{V_r{}^k - V_c{}^k}$ | $q(v) = P_r(\frac{V^k - V_c{}^k}{V_r{}^k - V_c{}^k})$ |

A more complex model is a polynomial of a third degree given by:

$$q(v) = av^3 + bv^2 + cv + d \quad \text{……… (21)}$$

The constants $a$, $b$, $c$ and $d$ can be determined from two different methods:

i. Least Square Error Method[16]; or
ii. Four cardinal Points Method [11].

The cardinal points are $v_c$, $v_r$ , $v_m = (v_c + v_r)/2$ and $v_x = 2(v_c + v_r)/5$.

Values of the cardinal points are substituted into parametric equations given by:

$$\left.\begin{aligned} a v_c^3 + b v_c^2 + c v_c + d &= 0 \\ a v_r^3 + b v_r^2 + c v_r + d &= P_r \\ a v_m^3 + b v_m^2 + c v_m + d &= P_r (v_m/v_r)^3 \\ a v_x^3 + b v_x^2 + c v_x + d &= P_r (v_x/v_r)^3 \end{aligned}\right\} \qquad (22)$$

The co-efficient are evaluated by solving the parametric equations simultaneously

### 2.2.2 Model Evaluation

After developing the model from the data, it is important to determine whether this model appropriately represents the behavior of the actual data for the power curve. It is done using some commonly used performance metrics as shown in Table 2.

Table 2: Statistical Parameters for Model Evaluation

| **Parameter** | **Equation** |
|---|---|
| Mean Bias Error (MBE) | $MBE = \frac{1}{n}\sum_{i=1}^{n}\left(Y_{a(i)} - Y_{m(i)}\right)$ |
| Mean Absolute Deviation (MAD) | $MAD = \frac{1}{n}\sum_{i=1}^{n}\left\|Y_{a(i)} - Y_{m(i)}\right\|$ |
| Mean Percentage Error (MPE) | $MPE = \frac{1}{n}\sum_{i=1}^{n}\left(\frac{Y_{a(i)} - Y_{m(i)}}{Y_{a(i)}} \times 100\%\right)$ |
| Root Mean Square Error (RMSE) | $RMSE = \left\{\frac{1}{n}\sum_{i=1}^{n}\left(Y_{a(i)} - Y_{m(i)}\right)^2\right\}^{1/2}$ |
| Karl Pearson's Coefficient of Correlation, R | $r = \frac{\sum Y_{a(i)}Y_{m(i)} - n\bar{Y}_{a(i)}\bar{Y}_{m(i)}}{\left(\sqrt{\sum Y_{a(i)}^2 - n\bar{Y}_{a(i)}^2}\right)\left(\sqrt{\sum Y_{m(i)}^2 - n\bar{Y}_{m(i)}^2}\right)}$ |

$n$: number of data; $Y_{a(i)}$: ith actual value, $Y_{m(i)}$:ith modeled value and $\bar{Y}$:average value

### 2.2.3 Capacity Factor

Due to wind speed variability, a wind turbine rarely operates at its rated output, therefore the capacity factor is commonly used to estimate its average energy production which in turn can be used for the economic appraisal of wind power projects and for the ranking of potential sites[3, 6].

The capacity factor (CF) of a wind turbine is the actual energy output of a wind turbine during a given time period compared to its theoretical maximum energy output. It is given by[6]:

$$CF = \frac{1}{P_r}\int p_w(V) f_w(V)\,dV = \frac{average\ power\ output\ during\ a\ period}{rated\ powwer\ output} \quad \ldots\ldots (23)$$

For a period of one year, the CF can be calculated as [3]:

$$CF = \frac{measured\ energy\ produced\ in\ the\ year\ (Wh)}{Rating\ of\ the\ turbine\ (W) \times 8760\ (h)} \quad \ldots\ldots (24)$$

Monthly average energy produced, $E_{avem}$ is given by:

$$E_{avem} = P_{ave} \times No\ of\ days\ in\ the\ month \times 24\ hours\ per\ day \quad \ldots\ldots (25)$$

## 3.0 RESULTS AND DISCUSSIONS

Wind speed data for the location was obtained from Nigerian Meteorological Agency (NIMET) archive, Abuja for a period of five years (2006-2010), measured in knot at 10m height. The data was then converted to m/s using the relation:

$$1\ knot \equiv 0.514\ m/s \quad \ldots\ldots (26)$$

The average five year period (2006-2010) for wind speed data and standard deviation for Katsina obtained from NIMET and the Weibull parameters calculated at 10m height and extrapolated at the hub height are as shown in Table 3.

**Table 3: Average wind speed and Weibull parameters of the location.**

| Month | Values at 10m Height | | | | Extrapolated Values at 55m Height | | | |
|---|---|---|---|---|---|---|---|---|
| | $v_o$ | $\sigma$ | $k_o$ | $c_o$ | α | $c_h$ | $k_h$ | $v_h$ |
| Jan | 3.43 | 2.07 | 1.73 | 3.85 | 0.25 | 5.91 | 2.04 | 5.23 |
| Feb | 4.02 | 1.89 | 2.27 | 4.54 | 0.24 | 6.80 | 2.67 | 6.04 |
| Mar | 4.27 | 1.06 | 4.54 | 4.68 | 0.23 | 6.97 | 5.34 | 6.43 |
| Apr | 4.25 | 1.06 | 4.52 | 4.66 | 0.23 | 6.95 | 5.32 | 6.40 |
| May | 3.73 | 1.00 | 4.18 | 4.10 | 0.25 | 6.24 | 4.91 | 5.72 |
| Jun | 3.75 | 0.93 | 4.55 | 4.11 | 0.25 | 6.24 | 5.35 | 5.75 |

| | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| Jul | 4.41 | 0.94 | 5.36 | 4.78 | 0.23 | 7.11 | 6.30 | 6.61 |
| Aug | 4.66 | 0.81 | 6.69 | 4.99 | 0.23 | 7.37 | 7.87 | 6.94 |
| Sep | 4.09 | 0.85 | 5.51 | 4.43 | 0.24 | 6.66 | 6.48 | 6.20 |
| Oct | 3.58 | 1.01 | 3.95 | 3.95 | 0.25 | 6.04 | 4.65 | 5.53 |
| Nov | 3.41 | 0.98 | 3.87 | 3.77 | 0.25 | 5.80 | 4.56 | 5.30 |
| Dec | 3.27 | 1.31 | 2.70 | 3.68 | 0.26 | 5.68 | 3.18 | 5.09 |

Technical Specification of the turbine is as shown in Table 4 while the wind speed is represented graphically using Weibull probability distribution function as shown in Figure 2.

**Table 4:Technical Specification of GEV MP C 275kW Wind Turbine**

| Parameter | Specification |
|---|---|
| Rated Power | 275kW |
| Output Voltage | 400V |
| Frequency | 50Hz |
| Cut in wind speed | 3.5m/s |
| Rated wind speed | 12m/s |
| Cut out wind speed | 25m/s |
| Survival wind speed | 52.5m/s |
| Hub Height | 55m |
| Rotor Diameter | 32m |
| Number of Blades | 2 |

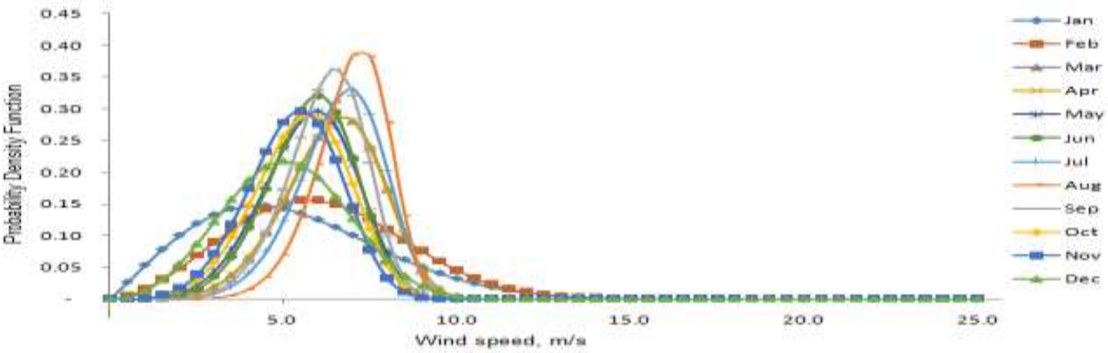


**Figure 2: Graph of Weibull probability distribution of the wind speed.**

From figure 2, the more probable speeds ranges from 4-8m/s with very few occurrence in the range of 12m/s (rated speed of the machine installed). This indicates that the machine will be operating at a capacity below its rated capacity almost all the times.

The power curve characteristic of the machine was given into 0.5m/s bins (discrete model) as shown in Table 5 [18]. From the table, it can be seen that the turbine is pitch regulated i.e. it maintain constant output from the rated to cut off speed.

**Table 5: Speed Power Characteristics of GEV MP C 275kW Wind Turbine**

| | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **Speed, m/s** | 2.5 | 3.0 | 3.5 | 4.0 | 4.5 | 5.0 | 5.5 | 6.0 | 6.5 | 7.0 | 7.5 | 8.0 |
| **Power, kW** | 0 | 0 | 0 | 3 | 10 | 18 | 27 | 36 | 47 | 58 | 78 | 98 |
| **Speed, m/s** | 8.5 | 9.0 | 9.5 | 10.0 | 10.5 | 11.0 | 11.5 | 12.0 | 12.5 | 13.0 | …. | 25.0 |
| **Power, kW** | 119 | 141 | 164 | 189 | 215 | 243 | 262 | 275 | 275 | 275 | …. | 275 |

Based on the manufacturer's speed power characteristics of the turbine in table 5, method of least square error method of the values gives: $a = -0.307$, $b = 10.08$, $c = -62.54$ and $d = 112.5$. Therefore equation 21 can be written as:

$q(v) = -0.307v^3 + 10.08v^2 - 62.54v + 112.5$ ……………………………………………………….. (27)

Also, based on the technical specification of the turbine shown in table 4, the cardinal points are: $v_c = 3.5m/s$, $v_r = 12m/s$, $v_m = (v_c + v_r)/2 = 7.75m/s$ and $v_x = 2(v_c + v_r)/5 = 6.2m/s$ Substituting the points into the parametric equations 22 and solving simultaneously gives: $a = 0.2291$, $b = -1.8153$, $c = 15.0719$ and $d = -40.3363$ . Therefore equation 21 can be written as:

$$q(v) = 0.2291v^3 - 1.8153v^2 + 15.0719v - 40.3363 \quad (28)$$

For the growth region (cut in speed to rated speed region), the output power of the turbine was evaluated based on the models shown in Table 1 and equations 27 and 28. The result obtained for the various models is as shown in Table 6. From the table, it can be seen that there are agreements between the manufacturer's value and the models value at only the rated speed and the cut in speed in most of the models. For most of the other points, the results did not match.

**Table 6: Power output of the machine in the growth region for various models.**

| Speed | Manuf. Value | Linear | Quadr. | Cubic 1 | Cubic 2 | Cubic 3 | Weibull based | 3rd Degree Poly. 1 | 3rd Degree Poly. 2 |
|---|---|---|---|---|---|---|---|---|---|
| 3.5 | 0 | 0.00 | 0.00 | 0.00 | 0.00 | 6.82 | 0.00 | 3.93 | 0.00 |
| 4.0 | 3 | 16.18 | 0.95 | 0.06 | 3.45 | 10.19 | 1.21 | 3.97 | 5.57 |
| 4.5 | 10 | 32.35 | 3.81 | 0.45 | 7.87 | 14.5 | 3.01 | 7.21 | 11.60 |
| 5.0 | 18 | 48.53 | 8.56 | 1.51 | 13.4 | 19.89 | 5.56 | 13.43 | 18.28 |
| 5.5 | 27 | 64.71 | 15.22 | 3.58 | 20.15 | 26.48 | 9.07 | 22.37 | 25.76 |
| 6.0 | 36 | 80.88 | 23.79 | 7.00 | 28.25 | 34.38 | 13.74 | 33.83 | 34.23 |
| 6.5 | 47 | 97.06 | 34.26 | 12.09 | 37.82 | 43.70 | 19.83 | 47.56 | 43.85 |
| 7.0 | 58 | 113.24 | 46.63 | 19.2 | 48.98 | 54.59 | 27.60 | 63.34 | 54.80 |
| 7.5 | 78 | 129.41 | 60.9 | 28.66 | 61.85 | 67.14 | 37.34 | 80.93 | 67.24 |
| 8.0 | 98 | 145.59 | 77.08 | 40.81 | 76.56 | 81.48 | 49.38 | 100.12 | 81.36 |
| 8.5 | 119 | 161.76 | 95.16 | 55.97 | 93.22 | 97.73 | 64.05 | 120.65 | 97.32 |
| 9.0 | 141 | 177.94 | 115.14 | 74.5 | 111.97 | 116.02 | 81.72 | 142.32 | 115.29 |
| 9.5 | 164 | 194.12 | 137.02 | 96.72 | 132.92 | 136.45 | 102.8 | 164.88 | 135.44 |
| 10.0 | 189 | 210.29 | 160.81 | 122.97 | 156.2 | 159.14 | 127.71 | 188.10 | 157.95 |
| 10.5 | 215 | 226.47 | 186.51 | 153.59 | 181.92 | 184.23 | 156.89 | 211.76 | 182.99 |
| 11.0 | 243 | 242.65 | 214.1 | 188.91 | 210.21 | 211.82 | 190.82 | 235.62 | 210.74 |
| 11.5 | 262 | 258.82 | 243.60 | 229.27 | 241.20 | 242.04 | 230.02 | 259.46 | 241.35 |
| 12.0 | 275 | 275.00 | 275.00 | 275.00 | 275.00 | 275.00 | 275.00 | 283.04 | 275.01 |

In order to gain insight into the accuracy and performance evaluation of the models, the statistical parameters shown in Table 2 were applied. The result is as shown in Table 7.

**Table 7: Results for Statistical Analysis of the Models in Growth Region**

| Parameter | Linear | Quadr. | Cubic 1 | Cubic 2 | Cubic 3 | Weibull based | 3rd Deg. Poly 1 | 3rd Deg. Poly 2 |
|---|---|---|---|---|---|---|---|---|
| MBE | -27.33 | 15.8 | 37.37 | 15.67 | 11.19 | 32.62 | 0.03 | 12.46 |
| MAD | 27.73 | 15.8 | 37.37 | 15.72 | 13.46 | 32.62 | 3.11 | 12.95 |
| MPE | -83.82 | 25.12 | 53.03 | 15.1 | -7.89 | 42.09 | 1.55 | 3.09 |
| RMSE | 33.5 | 18.54 | 44.25 | 19.96 | 17.61 | 39.34 | 3.77 | 18.00 |
| $R$ | 0.9796 | 0.9955 | 0.9672 | 0.9935 | 0.9935 | 0.9732 | 0.9992 | 0.9938 |
| $R^2$ | 0.9506 | 0.9911 | 0.9351 | 0.987 | 0.987 | 0.9471 | 0.9983 | 0.9876 |

For perfect correlation, values of $R$ and $R^2$ are equal to unity. From the result (Table 7), the values of the coefficients are high which indicates that in all the models as the velocity increase the power also increase i.e. high correlation between the calculated values and the manufacturer's value.

Negative value of MBE indicates average over estimation in the calculated values while positive value of MBE indicates average under estimation. The result (table 7) indicates that the linear model averagely overestimated the power while all the other models averagely under estimated the power output as compared to the manufacturer's value.

High values of MAD, MPE and RMSE indicate that there is high deviation between the average power outputs indicated by the models as compared to the manufacturer's value (ideal conditions are zero values).

Based on the statistical analysis carried out, it can be seen that only few models indicated by table 1 can adequately represent the power characteristics of the turbine. A better option is to use the manufacturer's data and predict the performance using numerical integration method.

There are many numerical integration models that can be used: Rectangle rule, Midpoint rule, Trapezoidal rule, Simpson's rule, etc. In this work, Trapezoidal rule was adopted and it is given by (Stroud and Booth, 2003):

$\int_a^b f(x)dx \approx \frac{\Delta x}{2}(y_o + 2y_1 + 2y_2 + \cdots + 2y_{n-1} + y_n)$ …………………………………………… (29)

From technical specification data sheet of the turbine as indicated in Table 4:

$v_c = 3.5m/s,\ v_r = 12m/s,\ v_f = 25m/s,\ P_r = 275kW$

To find the average power output for the month of January, from table 3, the Weibull parameters at the hub height (55m) are: $c_h = 5.91m/s,\ k_h = 2.04$.

The output power of the turbine at a given speeds $q_w(v)$ is as indicated in Table 5; the Weibull probability density function $f_w(V)$ can be calculated using equation 1; the power strip, $Y_i$ can be calculated as the product of $q_w(v)$ and $f_w(V)$. The results obtained for January is as shown in Table 8.

**Table 8: Machine output for the month of January**

| Wind Speed, m/s | Power output, kW | Weibull pdf, $f_w(V)$ | Power strip, $Y_i$ |
|---|---|---|---|
| 3.5 | 0 | 0.0376 | - |
| 4.0 | 3 | 0.0653 | 0.1960 |
| 4.5 | 10 | 0.1041 | 1.0414 |
| 5.0 | 18 | 0.1529 | 2.7529 |
| 5.5 | 27 | 0.2067 | 5.5799 |
| 6.0 | 36 | 0.2551 | 9.1846 |
| 6.5 | 47 | 0.2842 | 13.3560 |
| 7.0 | 58 | 0.2806 | 16.2728 |
| 7.5 | 78 | 0.2400 | 18.7164 |
| 8.0 | 98 | 0.1728 | 16.9318 |
| 8.5 | 119 | 0.1012 | 12.0423 |
| 9.0 | 141 | 0.0463 | 6.5285 |
| 9.5 | 164 | 0.0158 | 2.5892 |
| 10.0 | 189 | 0.0038 | 0.7183 |
| 10.5 | 215 | 0.0006 | 0.1306 |
| 11.0 | 243 | 0.0001 | 0.0146 |
| 11.5 | 262 | $3.4 \times 10^{-6}$ | $8.9 \times 10^{-4}$ |
| 12.0 | 275 | $1.01 \times 10^{-7}$ | $2.8 \times 10^{-5}$ |

The average power component from cut in to rated speed was calculated by substituting the values in equation 29 with strip width $\Delta x = 0.5$ as:

$$P_{c-r} = \int_a^b q_w f_w dv \approx \frac{0.5}{2}(0.0 + 2(0.1960 + 1.0414 + \cdots + 8.9 \times 10^{-4}) + 2.8 \times 10^{-5})$$

Therefore, $P_{c-r} \approx 40.02kW$

The average power component from rated to cut out speed $(P_{r-f})$, average power $(P_{ave})$, capacity factor $(CF)$ and monthly average energy $(E_{avem})$ were calculated using equations 19, 20, 24 and 25 respectively. The same procedure was followed for the other months and the results obtained are as shown in Table 9.

**Table 9: Monthly Average Machine Performance Parameters**

| Month | $P_{c-r}$ | $P_{r-f}$ | $Ave. Power$ $P_{ave}, kW$ | $CF = \frac{P_{ave}}{P_r}$ | $Ave. Energy$ $kWh/month$ |
|---|---|---|---|---|---|
| Jan | 40.02 | $3.96 \times 10^0$ | 43.98 | 0.16 | 32,721.12 |
| Feb | 54.44 | $2.89 \times 10^0$ | 57.33 | 0.21 | 38,525.76 |
| Mar | 53.03 | $3.4 \times 10^{-6}$ | 53.03 | 0.19 | 39,454.32 |
| Apr | 52.51 | $3.2 \times 10^{-6}$ | 52.51 | 0.19 | 37,807.20 |
| May | 36.00 | $4.7 \times 10^{-9}$ | 36.00 | 0.13 | 26,784.00 |

| | | | | | |
|---|---|---|---|---|---|
| Jun | 35.69 | $1.2 \times 10^{-12}$ | 35.69 | 0.13 | 25,696.80 |
| Jul | 56.43 | $5.0 \times 10^{-10}$ | 56.43 | 0.21 | 41,983.92 |
| Aug | 64.00 | $2.0 \times 10^{-18}$ | 64.00 | 0.23 | 47,616.00 |
| Sep | 44.74 | $5.3 \times 10^{-18}$ | 44.74 | 0.16 | 32,212.80 |
| Oct | 32.16 | $7.4 \times 10^{-9}$ | 32.16 | 0.12 | 23,927.04 |
| Nov | 27.70 | $3.0 \times 10^{-10}$ | 27.70 | 0.10 | 19,944.00 |
| Dec | 28.77 | $5.7 \times 10^{-3}$ | 28.78 | 0.10 | 21,409.10 |
| Annual | | | | | 388,082.06 |

Each turbine is rated $275kW$. Therefore rated energy of each turbine at full capacity factor is determined as:
$E_{rated} = 275kW \times 365\, days/year \times 24\, hours/day = 2{,}409{,}000\, kWh/annum$
Energy output of each turbine $388{,}082.06\, kWh/annum$.
Annual capacity factor, $CF = \frac{388{,}082.06}{2{,}409{,}000} = 0.161\, or\, 16.1\%$

## 4.0 CONCLUSION

This work investigated the reliability potential of the ongoing 10MW electricity generation from wind in Katsina State, Nigeria. The method used combines the power output characteristics of the turbine and the wind characteristics of the location. The results indicate that each turbine is expected to generate $388.1GWh/annum$ instead of rated energy of $2{,}409GWh/annum$. The annual average capacity factor was determined to be 16.1%. The monthly capacity factor ranges from 0.10 to 0.23 which means that if the $10MW$ project was completed, then it will be operating in the range of $1.0MW\ to\ 2.3MW$. This indicates that the turbine-site matching is very low. Turbines with lower cut in and lower rated speed would have yielded better result. Therefore, it is very important to analyse wind data of any region in which wind turbine is to be installed and the characteristics of the machine before the procurement.

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