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Performance Evaluation and Cost of Energy from 2.0 kW (Guangmang) Wind Turbine at Danjawa Renewable Energy Model Village, Sokoto, Nigeria

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Abstract: *Power output from a wind-powered turbine generator was estimated using the method that combined the wind generator characteristic and the characteristic of wind at the selected location of operation. Danjawa village is a small community village within Usmanu Danfodiyo University, Sokoto, which is bounded by latitude of $13^o.1$ N and longitude $4^o.13$ E, with elevation of 351m. The shape and scale parameters for the location were evaluated from the twenty years (1991-2010) daily average wind speed data obtained from NIMET. The 2.0 kW (Guangmang) wind-powered generator is characterized by its cut-in wind speed, rated wind speed and furling wind speed as provided by the manufacturers. The generator power output is assumed to vary according to a third-degree polynomial with wind speed between cut-in and rated wind speeds and to be constant between rated and furling wind speeds. Similarly, the economic performance was conducted via the levelised cost of energy (LCOE) which was carried out based on the total energy output from the wind turbine and total investment on the machine. The results of the analysis indicated that the 2.0 kW (Guangmang) wind turbine generators generate 1,520.38 kWh per annum at the cost of ₦ 326 / kWh.*
Keywords: *Evaluation, Guangmang, Levelised, Polynomial and Wind speed*

I. Introduction

Energy is one of the fundamental device for economic development and a driving force for industrialization of any society [14:14]. Nigeria is endowed with both fossil fuels; nuclear and renewable sources of energy, which when effectively harnessed can be utilized for economic transformation of the country [16]. 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 [1]. 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. The wind energy market [1] 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% [17]. Renewable energy is the type that is derived from the sources that can be regenerated naturally within a relatively short time frame. For example, solar radiation, wind, hydropower, biomass, geothermal, sea wave and tide [3], yet Nigerian energy industry is probably one of the most inefficient in meeting the needs of its customers globally. This is most evident in the persistent disequilibrium in the markets for electricity and petroleum products, especially kerosene and diesel [2]. Although estimating the power output from a wind-powered turbine at a particular location is complex due to the variability of the wind speed with time and the dependence of the output power from the wind-powered turbine on the wind speed. This paper applies a method for computing expected output power from a wind-powered generator, given the observed wind speed distribution at a location and the power output characteristics of the wind-powered turbine. The output power is evaluated for the 2.0 kW Guangmang wind turbine generator installed at 18 m hub height in Danjawa renewable energy rural model village, by the Sokoto Energy Research Centre, Usmanu Danfodiyo University, Sokoto. The wind speed data used for this analysis is the 20 years daily average wind speed data for Sokoto obtained from Nigerian meteorological Agency (NIMET) due to lack of site specific wind speed data for Danjawa village. The paper also estimates the economic performance via the levelised cost of energy (LCOE) method for the 2.0 kW Guangmang wind turbine generator. The results indicated that the annual kWhs from the machine can be up to 1,520.38kWh at the cost of ₦ 326/kWh.

II. Theoretical Consideration

Since wind speed increases with height, the wind speed data used in this study were obtained at a height of 10m and the 2.0kW Guangmang hub height is 18m. The measured wind speed must be extrapolated to typical hub height of 18m. A typical extrapolation comprises a power law as below [9:11 and 18]

$$\frac{v}{v_0} = \left(\frac{h}{h_0}\right)^{\alpha} \tag{1}$$

Where, v is the wind speed at the required height h , and v_0 is the wind speed at the original height h_0 and α is the surface roughness coefficient which for the purpose of this study is assumed to be 1/7.

2.1weibull Probability Distribution Model

The Weibull probability distribution model was chosen for this study because of its wide application in wind energy studies for a long time [4: 6and 7]. The mean wind speed and standard deviation method for the estimations of Weibull parameters was found to give the best fit of the Weibull distribution model to observed wind speed data for Sokoto according to [12]. It was used to estimate the monthly and annual Weibull parameters for Sokoto in this study.

The two – parameter Weibull wind speed probability distribution, *P(V)*, is expressed by[9] as:

$$P_v = \left(\frac{k}{c}\right)\left(\frac{v}{c}\right)^{k-1} e^{-\left(\frac{v}{c}\right)^k} \tag{2}$$

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

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 [11]

$$k = \left(\frac{\sigma}{\overline{V}}\right)^{-1.086} \tag{4}$$

and $$c = \frac{\overline{V}}{\Gamma(1 + 1/k)}, \tag{5}$$

Where Γ is the gamma function is expressed (Stroud, 1995)

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

$$\Gamma(x) = \left(\sqrt{2\pi x}\right)\left(x^{x-1}\right)\left(e^{-x}\right)\left[1 + \frac{1}{12x} + \frac{1}{288x^2} - \frac{139}{51840x^3} + ...\right] \tag{7}$$

However, due complex nature in evaluating gamma function Lysen, (1983) used the following approximation method to find *c*,

$$\frac{c}{\overline{V}} = \left(0.568 + 0.433/k\right)^{-\frac{1}{k}}. \tag{8}$$

Monthly and annual Weibull parameters *c* and *k* at 18 m height were determined for Sokoto by means of equation (4) and (5), using twenty years (1991-2010) observed daily mean wind speed data obtained from the Nigerian Meteorological Agency, Federal Ministry of Aviation, Abuja, Nigeria. The monthly and annual summaries of the observed data are shown in table 2.

2.2 Estimation of Wind Power Density and Wind Energy.

[18], used the following equation to estimate wind power

$$p_{(v)} = \frac{1}{2}\rho A v_m^3 \tag{9}$$

However, wind power density can be evaluated based on the Weibull parameters as given by [18] as follows:

$$P(V)=\frac{P(v)}{A}=\frac{1}{2}\rho c^{3}\Gamma\left(1+\frac{3}{k}\right) \quad (10)$$

2.3 Power Output from 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 [1]. 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 [10] through the following expressions based on Weibull distribution function, and for Rayleigh distribution function $k = 2$.

$$P_{out} = P_{eR}\left(\frac{e^{-\left(\frac{v_c}{c}\right)^k}-e^{-\left(\frac{v_r}{c}\right)^k}}{\left(\frac{v_r}{c}\right)^k-\left(\frac{v_c}{c}\right)^k}-e^{-\left(\frac{v_f}{c}\right)^k}\right) \quad (11)$$

And (12)

$$C_f=\left(\frac{e^{-\left(\frac{v_c}{c}\right)^k}-e^{-\left(\frac{v_r}{c}\right)^k}}{\left(\frac{v_r}{c}\right)^k-\left(\frac{v_c}{c}\right)^k}-e^{-\left(\frac{v_f}{c}\right)^k}\right)$$

Capacity factor C_f can further be expressed as:

$$C_f=\frac{P_{out}}{P_{eR}} \quad (13)$$

Where v_f , 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 [1]. 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 [9] .

III. Cost Analysis

Different methods are generally used to estimate the operating cost of a unit of energy produced by the wind energy conversion system. The most commonly used method however, is the Levelised cost of Electricity (LCOE) [11]. The LCOE is a measure of the marginal cost of electricity over a period of time and it is commonly used to compare the electricity generation costs from various sources of energy, it also gives the average electricity price needed for a net present value of zero when a discounted cash flow analysis is performed [1]. The costing of unit energy involves three major steps which includes;

(i) Estimation of energy generated by the wind turbine over a given period
(ii) Estimate the total investment cost of the project and
(iii) Dividing the cost of investment by the energy produce by the system.

The unit cost of energy using LCOE method can be estimated using the following equation (Olayinka, et al, 2011)

$$LCOE=\frac{CFR}{8760P_{eR}C_f}\left(C_I+C_{om(esc)}\right)\text{Cost/kWh} \quad (14)$$

Where C_I is the total investment cost, $8760P_{eR}C_f$ is the annual energy output of wind turbine in kW/h CFR and $C_{om(esc)}$ are the capital recovery factor and present worth of the annual cost throughout the lifetime of the wind turbines expressed as;

$$CFR=\frac{(1-\varepsilon)^n\varepsilon}{(1+\varepsilon)^n-1} \quad (15)$$

$$c_{om(esc)}=\frac{C_{om}}{\varepsilon-e_{om}}\left[1-\left(\frac{1+e_{om}}{1+\varepsilon}\right)^n\right] \text{ Cost / year (14)}$$

Where C_{om}, e_{om}, n and ε are the operation rate cost for the first year, escalation rate of operation and maintenance costs, useful lifetime of turbine, and discount rate, respectively. The discount rate can be corrected for inflation rate (r) and inflation escalation rate (e) using the following expression.

$$e_a = \{(1+e)(1+r)\} - 1 \tag{16}$$

Where e_a is called the apparent escalation rate. The discount rate can be determined from;

$$\varepsilon = \frac{(1+i)}{(1+e_a)} - 1 \tag{17}$$

The LCOE method of analysis was used to estimate the cost of energy per unit kWh of the Guangmang 2.0kW wind turbine based on the following assumptions:

i. The life time (n) of the turbine is 20 years
ii. The interest rate (*i*) and inflation rate (*r*) were to be 21 and 4% [5].

While the inflation escalation rate (*e*) was assumed to vary between 0 and 5%

iii. Operating and maintenance cost (C_{om}) was assumed to be 25% of the annual cost of the wind turbine (System price/Life time) and escalation rate of operation and maintenance ($C_{om(esc)}$) is assumed to vary between 0% and 10%
iv. Other initial costs civil work and other installation cost approximated to be (₦ 500,000)
v. It is also assumed the Guangmang 2.0 kW will produce same amount of energy throughout its life period.

IV. Results And Discussion

The data was analyzed basically using the Microsoft excel spread sheet (2007). The maximum monthly wind speed is computed as 7.89 m/s in the month of February and as lowest as 4.10 m/s in the month of September as shown in figure 1. Table 1 depicts the characteristics of the Guangmang 2.0kW wind turbine as provided by the manufacturers. Table 2, also shows that the Weibull shape parameter K which varies from 2.62 in the month of January, to 4.04 in the month of June this indicating that wind is more frequent in the month of January and least frequent in June, the monthly and annual power output from the Guangmang wind energy conversion system also showed variation from 7.65 W/m^2 in the month of September to 92.90 W/m^2 in the month of February, with corresponding energy output ranging from 8.52 kWh for the month of September to 62.43kWh for the month of February, this is a clear indication that the amount of power output does not only depend on the wind speed of the location but also associated to other factors such as capacity factor of the wind conversion system. However, as can be seen, the month of October is among the month with very low wind speed when compared with other months of the year such as December, January and February with very higher wind speeds due to westerly wind of harmattan period, but yet the month of October recorded highest power output from the turbine and this could be attributed to high capacity factor recorded for the month, and for same reason low power output was observed in the month of September. The monthly capacity factors for the wind conversion system was observed to be very low throughout the year which proved very low performance of the machine, this can further be reaffirmed from figure 2 which show correlation coefficient of R^2 = 0.89 for linear exponential regression coefficient. Therefore the location is not best option for optimum performance of the machine because for most times the wind machine is operating between the cut in wind speed and rated wind speed i.e. (2.5-12 m/s) the rated wind speed. Figure 3 and 4 show that monthly probability density and cumulative distributions of the time series data for the period of 20 years of the site can be seen to have a similar tendency of wind speeds for the distributions, the peak of the distribution density function frequencies of the location skewed towards the higher values of the mean wind speed which also indicated the most frequent wind velocity. It can however be observed from figure 3 that the most probable wind speed of 6m/s was found in the month of September, where a peak frequency of about 50% was obtained. Similarly, it can be observed from same figure that there is tendency of obtaining wind speed of about 8m/s in all the months, in fact other months have likelihood of wind speeds exceeding10m/s. However, the power output curve of 2.0kW Guangmang rated power wind turbine, whose characteristic properties is given in table 1, power curve is shown in figure 5. Considering the assumptions and cost of expenditure on the procurement and installation of Guangmang 2.0kW wind conversion system as indicated in table 3, the computed specific costs per kWh for the wind machine based on LCOE (present value cost/ total energy output for the turbine life time), using operation and maintenance costs of 25% of the total machine initial cost, the specific costs is computed to be 326 NGN per kWh. This proved that even though the machine was not the best option for Danjawa location, wind power technology is still a viable renewable energy source in Danjawa Renewable Energy rural model village of Sokoto State.

Table 1: Characteristic of the Guangmang Wind Turbine

Model	E-2000
Brand	Guangmang
Rated Voltage	48/120
Rated Current	41/20
Rated Power	2000
Start-Up wind speed (m/s)	2.5
Rated wind speed (m/s)	12
Security wind speed (m/s)	35
Generator type	PMG
Diameter (m)	3.2
RPM (r/m)	400
blades material	GFRP
Blades No.	3

Table 2: Monthly mean wind speeds, standard deviation, Weibull parameters Power and energy output and capacity factor.

Month	$\bar{v}_{(10)}$	$\bar{v}_{(18)}$	σ	K	C	power	Energy	C_f
Jan	6.97	7.58	3.12	2.62	3.97	83.08	61.81	0.04
Feb	7.25	7.89	2.98	2.88	4.40	92.90	62.42	0.05
Mar	6.45	7.01	2.62	2.91	3.95	60.93	45.33	0.03
Apr	5.72	6.22	2.77	2.41	3.05	40.77	29.36	0.02
May	5.51	5.99	1.96	3.37	3.67	28.48	20.51	0.01
Jun	5.72	6.22	1.72	4.04	4.17	24.68	18.36	0.01
Jul	5.48	5.96	1.76	3.76	3.87	23.34	17.37	0.01
Aug	4.69	5.10	1.98	2.79	2.79	16.57	12.33	0.01
Sep	4.05	4.40	1.73	2.76	2.39	7.65	5.51	0.00
Oct	4.33	4.71	1.97	2.58	2.43	11.45	8.52	0.01
Nov	5.83	6.34	1.99	3.52	3.98	34.01	24.49	0.02
Dec	6.60	7.18	2.98	2.60	3.73	68.89	51.26	0.03
Ave	5.72	6.22	2.30	2.95	3.523	38.12	27.83	0.02

Table 3: Energy cost produced by the Guangmang 2.0 kW per kWh based on 25% initial Cost of operation and Maintenance

Wind turbine type	Guangmang
Ave power output (W/m^2)	18.94
Annual Energy output (kWh)	14.09
Capacity factor (%)	9.00
Cost of civil works (NGN)	500,000.00
Annual cost of the Wind turbine (NGN)	60,000.00
Total investment cost (NGN)	1,275,000.0
C_{omr} (25% annual cost of energy)	15,000.00
Total Energy Output in kWh (NGN)	3,911.00
Specific Cost per kWh (NGN)	326.00

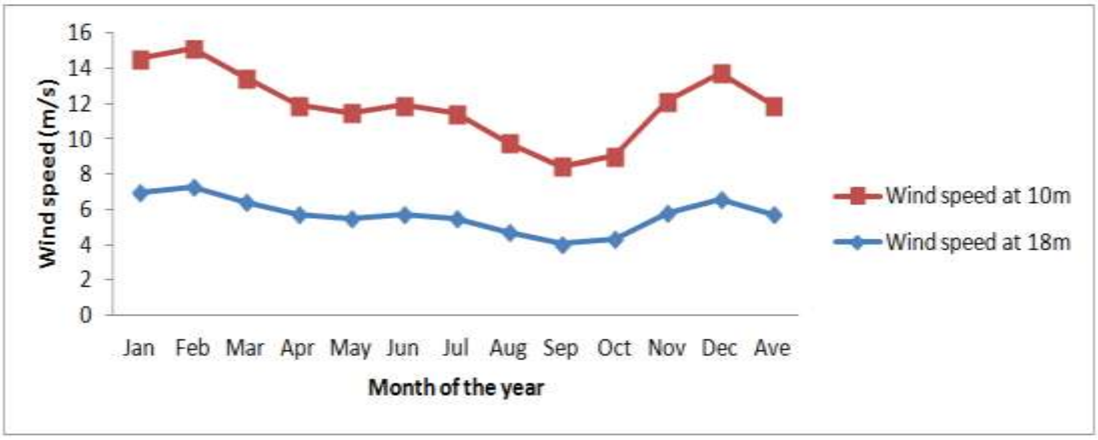

Figure1: Monthly mean wind speed variation for Sokoto (1991 – 2010)

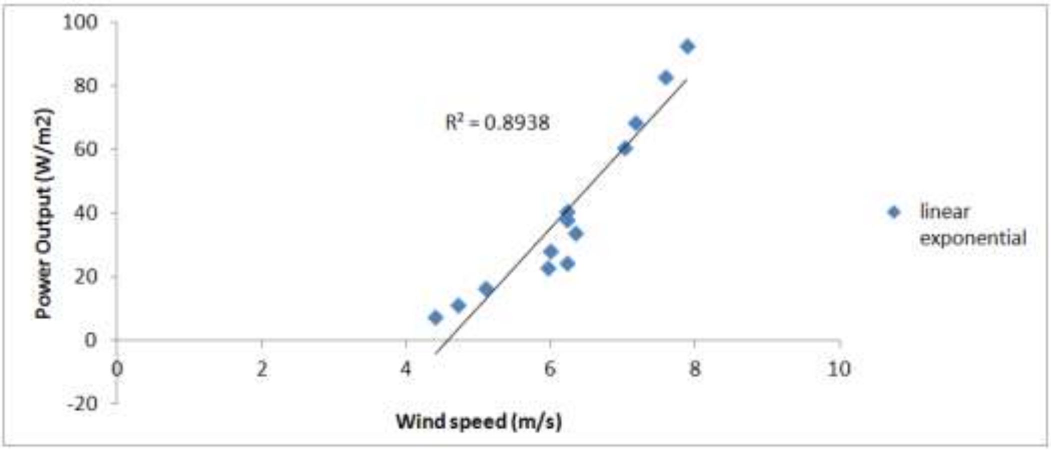

Figure 2: Linear and Exponential of monthly Power output of the Guangmang wind turbine against monthly mean wind speed of the Danjawa

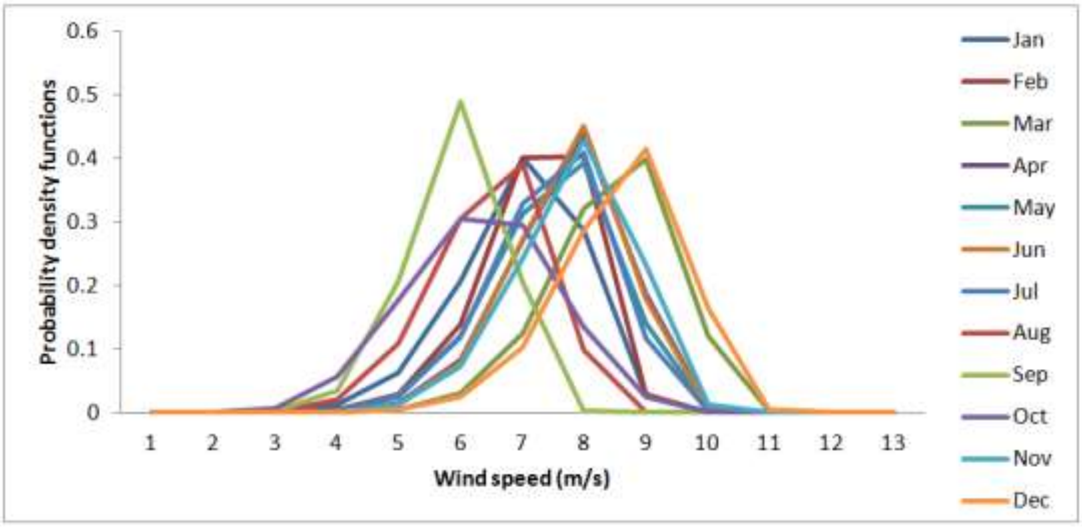

Figure 3: Monthly wind speed probability density for Danjawa, Sokoto State

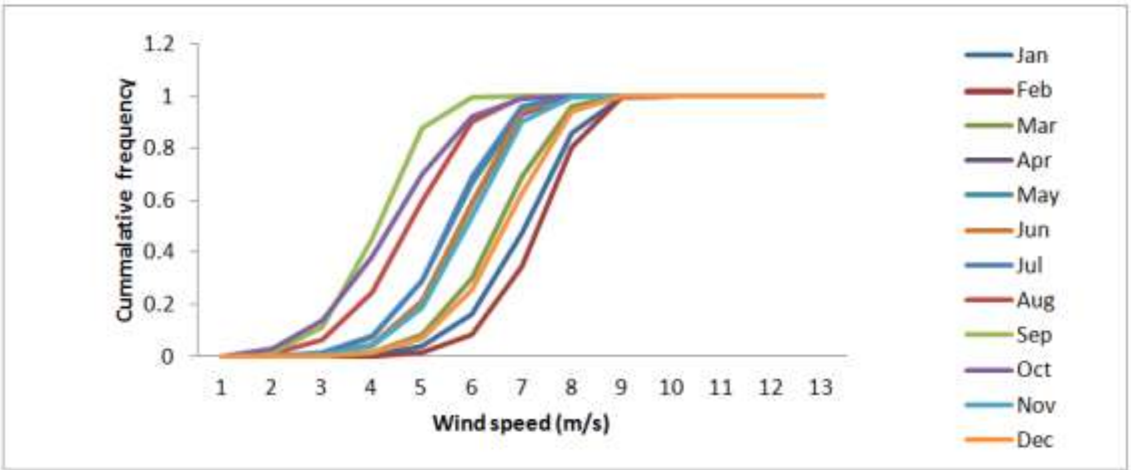

Figure 4: Monthly wind speed Cumulative frequency distribution for Danjawa, Sokoto state

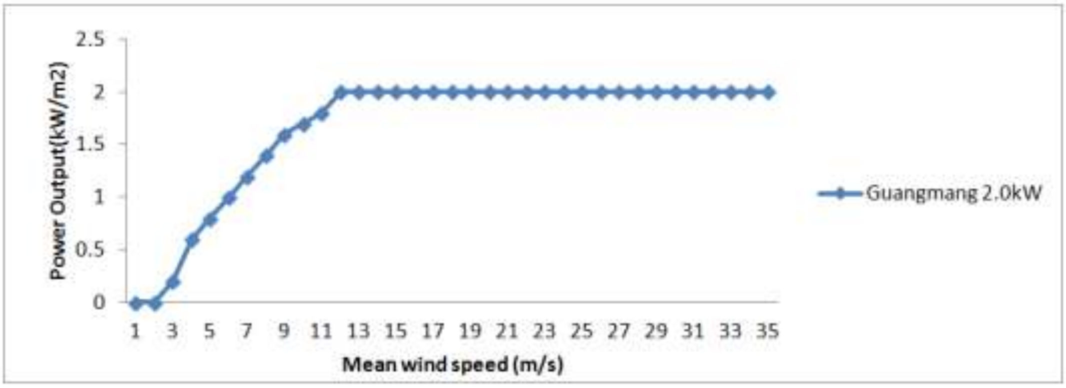

Figure 5: Power output curve of a Guangmang 2.0kW wind turbine generator

V. Conclusion

The wind energy potentials of Danjawa model rural village, in Sokoto has been studied using measurement data of twenty one year's obtained from Nigerian meteorological Agency (NIMET), and Weibull probability distribution model to evaluate the performance of 2.0kW Guangmang wind energy conversion system. Based on the analysis the following conclusion can be made.

1. Danjawa is a good location for wind energy application, if appropriate wind turbine (one with rated speed close to annual average wind speed of the location) is used it can favorably compute with all kind of energy sources be it from renewable or conventional sources.
2. The monthly mean wind speeds ranges between 4.40m/s in the month of September to 7.89m/s in the month of February, with annual average of 6.22m/s at 18m height.
3. The monthly average power and energy output from 2.0kW Guangmang wind turbine are computed to be between 7.65 W/m^2 in the month of September to 92.90W/m^2 in the month of October with energy between 5.51kWh/m^2 in the month of September to 62.42kWh/m^2 in the month of February respectively, with annual capacity factor of just 0.02%
4. The specific cost per kWh from 2.0kW Guangmang rated machine at 25% operational and maintenance cost of the total initial cost of the machine was computed to be ₦ 326

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