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ASSESSMENT OF WIND ENERGY POTENTIAL FOR ELECTRICITY GENERATION IN
KATSINA, NIGERIA

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ABSTRACT

The fear of limited availability and environmental pollution associated with conventional energy sources necessitates the need for harnessing a renewable and environmentally friendly energy source. In that regard, wind energy is certainly the alternative source because it is free, clean, non-polluting, renewable in nature and can be harnessed at an affordable cost in both large-scale and small-scale system. This paper presents an investigation of the potentiality of converting wind energy to electricity in Katsina, a city in northern Nigeria. Eleven years of wind speed records obtained from Katsina State Meteorological Inspectorate Department are used as input parameters to the wind energy model. Rayleigh probability density function is used to predict the energy that could be harvested from the wind regime. The result shows that the city has average wind speed of 4.2m/s and 5.9m/s at 10m and 50m heights respectively. The latter value is classified as class IV wind, just suitable for electricity generation. Furthermore, statistical analysis using Rayleigh probability density function based on NEG Micon 1000/60 wind turbine reveals that over 2,000 MWh of energy can be generated annually in the study area. This result implies that Katsina is a suitable site for wind power generation. It may be possible to apply this result to other cities in northern Nigeria on the same latitude and altitude.

Keywords: Wind speed; Renewable energy; Wind turbine; Rayleigh distribution.

1. INTRODUCTION

Over the years (1980 – 2010) the electric power supply in Nigeria has not been keeping pace with the social development in the country. The result is that the power is insufficient and often load shedding had to be carried out in almost all Nigerian cities every day. Correlation of a country's development with energy use has been established (World Bank, 2002). Insufficient or unreliable electric power supply retards progress and economic development. It is therefore appropriate to look for an alternative power supply system as suggested by Medugu and Malgwi (2005), which should, at least, supplement the present inadequate supply. In the light of the current trend in the world regarding environmental consciousness it is wise to look for an alternative that is viable and environmentally friendly. A study by Adegbulugbe (1991) indicates that the most promising alternatives for reducing carbon dioxide emission include the use of renewable energy sources. Considering the location of Nigeria the obvious renewable energy choices are solar, wind and hydro. The current study considers the potential of using wind as a renewable energy source for electricity generation in Katsina.

Wind is air in motion relative to the surface of the earth. It is caused by uneven heating of the earth by solar radiation. The amount of energy absorbed varies from time to time and from place to place due to non-homogenous nature of the earth. This variation results in differences in atmospheric

temperature, pressure and density which in turn develop forces that move air from one place to another. This movement of the air is called wind (Ahmed, 2011).

A wind turbine converts the kinetic energy of the wind into mechanical energy and a generator (induction or synchronous) converts the mechanical energy into electrical energy. The wind turbine is normally coupled with shaft and gearbox so as to match the low speed rotation of the turbine's rotor with the high speed rotation of the generator. The structure comprising the rotor, the generator and other relevant parts is more commonly referred to as Wind Energy Conversion System (WECS) (Johnson, 1994).

Basic components of a WECS include the tower, rotor, gearbox, generator nacelle, measuring instruments, electronic equipment and other auxiliary devices. The tower provides support to the rotor and drive train. The rotor consists of blades with aerodynamic surfaces such that when the wind blows over the blades, the rotor turns, causing the generator or alternator in the turbine to rotate and produce electricity. The gearbox matches the rotor speed to that of the generator/alternator. The nacelle is an enclosure, which protects the gearbox, generator and other components of the turbine. The measuring instruments include anemometer which measures the wind speed; a wind vane or yaw system, which aligns the turbine

with the wind, thermistor for measuring temperature, barometer for pressure measurement and pyranometer which measures solar radiation. The electronic equipment includes controls, electrical cables ground support equipment, and interconnection equipment.

Depending on the nature and type of the force, WECS can be divided into two categories, namely; aerodynamic drag WECS, and aerodynamic lift WECS. The later has higher power coefficient than the sooner, hence, more common. In fact, the modern wind turbines used for electrical power generation makes use of the aerodynamic lift principle by using their airfoils (blades) to interact with the incoming wind.

The aerodynamic lift wind turbines are further divided into two; Horizontal Axis Wind Turbines (HAWT), and Vertical Axis Wind Turbine (VAWT). Horizontal axis turbines need to be aimed directly at the wind, as such; they usually come with a tail vane that will continuously point them in the wind direction. However, the vertical axis types work whatever direction the wind is blowing, but require a lot more ground space to support their guy wires than horizontal wind turbines (Ackerman, 2005).

The HAWT axis is parallel to the ground. The blades are also parallel to the wind flow. Some HAWTs operate in an upwind mode, with the blades upwind of the tower, in which case, a tail vane is usually used to keep the blades facing the wind. Other HAWT models operate in a downwind mode so that the wind passes the tower before striking the blades. Without a tail vane, the machine rotor usually tracks the wind in downwind mode. Some very large wind turbines use a motor-driven mechanism that turns the machine in

response to a wind direction sensor mounted on the tower.

The VAWT is independent of the wind direction. Because the shaft is vertical, the transmission and generator can be mounted at ground level allowing easy servicing and a low cost tower. Although vertical axis wind turbines have these advantages, they are not as efficient at collecting energy from the wind as are their horizontal counterpart. Although vertical axis wind turbines have existed for centuries, they are not as common as the horizontal types. The main reason for this is that they do not take advantage of the higher wind speed at higher elevations above the ground as well as horizontal axis turbines. The basic VAWT designs are the Darrieus (named after a French engineer who invented it in 1920s) (Ackerman, 2005), which has curved blades, the Giromill, which has straight blades, and the Savonius, which uses scoops to catch the wind.

Wind power generation started as far back as nineteenth century with the development of wind machines for charging batteries. However, large wind turbine for electricity generation began in 1980s (Boyle, 2012). The first wind turbines for electricity generation were developed at the beginning of the twentieth century. The technology was improved step by step from the early 1970s. By the end of the 1990s, wind energy has re-emerged as one of the most important sustainable energy resources (Ackerman, 2005). Thus, the research in the aviation sector in nineteenth century has not only yield an improved understanding of the forces acting on blades moving through the air, but also resulted in the development of wind turbines for electrical power generation (Bhadra and Kastha, 2011). Currently, electrical power generation from wind using wind turbines and energy system has become an established industry (Twidell and Weir, 2012).

2. WIND ENERGY MODELING

Wind is as a result of a mass of air m flowing past a given point. The wind speed v is the rate at which the air flows. The kinetic energy of the wind E is obtained from the well-known laws of motion as reported by Wagner and Mathur (2009)

$$E = \frac{1}{2} m v^2 \quad \dots \quad (1)$$

Because of air fluidity it is hard to measure the mass m , rather the mass is expressed in terms of volume of the air V , which is easier to measure. The constant that relates mass and volume is the

density given by $\rho = m/V$. Therefore replacing m with $m = \rho V$ in equation (1) gives

$$E = \frac{1}{2} \rho V v^2 \quad \dots \quad (2)$$

This energy can be harvested using wind energy conversion system (WECS). In the case of converting wind energy to electricity, the WECS is also called wind turbine as defined by Wagner and Mathur (2009) (Figure 1).

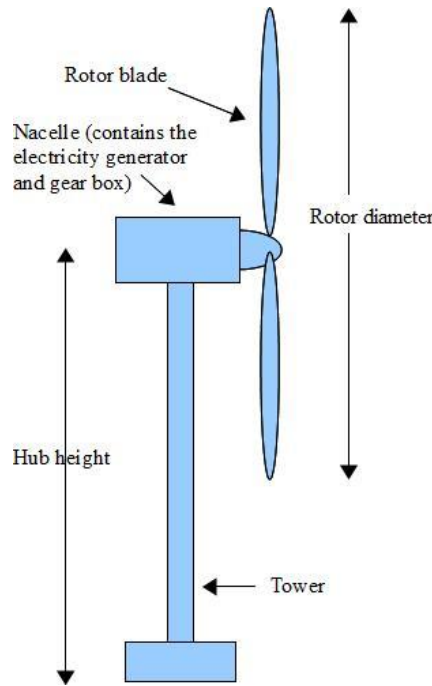


Figure 1: Side view of a horizontal axis wind turbine

In equation (2) above, V is the volume of air impinging on the wind turbine rotor blades at velocity v . If A is the total area swept by the rotor blades then the volume of air impinging on the rotor per unit time t is $V = Avt$. Substitution of this value of V into equation (2) gives

$$E = \frac{1}{2} \rho A t v^3 \quad \dots \quad (3)$$

If we now consider the fact that power is energy per unit time, the wind power density (i.e. power per unit area A) equation is given as

$$P = \frac{1}{2} \rho v^3 \quad \dots \quad (4)$$

Where: P is the wind power density in W/m^2 .

It is clear from equation (3) that the most important parameter in determining wind power density is the wind speed. It determines the amount of energy a wind turbine can convert to electricity. The equation also assumes that the wind speed v is constant, which is far from true. In reality the wind speed changes in time and space frequently and constantly. It is therefore better to work with average wind speed \bar{v} , in which case the power density is given by

$$P = \frac{1}{2} \rho \bar{v}^3 \quad \dots \quad (5)$$

However, some researchers (Kainkwa, 2000; Naci, 2003) prefer using the power density model in terms of the mean wind speed and the deviations about the mean speed. All other wind speeds are considered to be equal to the mean plus or minus ϵ , where ϵ is a fluctuation parameter, which can be negative, zero or positive. The wind speed is then expressed in terms of average speed as $v = \bar{v} + \epsilon$. Let δ be the sum of all successive deviations from the mean value \bar{v} , then

$$v = \bar{v} + \epsilon \quad \dots \quad (6)$$

Substituting $v = \bar{v} + \epsilon$ in equation (5) and considering equation (6) results in

$$P = \frac{1}{2} \rho (\bar{v} + \epsilon)^3 \quad \dots \quad (7)$$

This is the equation used by Kainkwa (2000) and Celik (2003) to estimate wind power density. In this study we would use equation (5) because of its simplicity. The power delivered by a wind turbine is calculated from equation (5) or equation (7) by multiplying P with the area swept by the turbine's rotor.

3.1 Katsina wind energy data

Katsina city is geographically located at 13° 01'N latitude and 07° 41'E longitude. The city is at an average altitude of 480 m above sea level and has a mean maximum annual temperature of 39°C. The

monthly wind speed data recorded at 10 m height for a period of 11 years (1996–2006) were obtained from the State Meteorological Inspectorate Department, Katsina Airport (Wether Report, 2007) (Table 1).

Table 1: Monthly Averages of Wind Speed, v (m/s) at 10 m Height in Katsina

Month/Year	1996	1997	1998	1999	2000	2001	2002	2003	2004	2005	2006	Average	St. Dev.
January	3.13	3.56	3.25	5.06	3.81	4.81	5.06	4.31	4.88	4.88	3.78	4.2300	0.7112
February	3.56	3.5	3.5	4.38	3.63	4.75	3.88	4.13	4.81	3.81	3.19	3.9218	0.5090
March	3.69	3.88	3.94	4.69	3.88	4.5	4.19	4.81	5.19	3.31	3.44	4.1382	0.5675
April	3.63	3.56	3.69	4.88	3.69	4.84	4.56	5.00	4.38	4.31	3.5	4.1855	0.5583
May	3.75	3.5	3.88	4.94	3.81	5.19	5.19	4.31	5.19	4.44	3.75	4.3591	0.6345
June	3.69	3.69	3.69	5.31	3.75	5.06	5.25	4.5	5.00	4.56	3.63	4.3755	0.6676
July	3.81	3.88	5.75	5.63	3.69	5.38	5.31	4.56	5.00	3.13	3.56	4.5182	0.8943
August	3.56	3.69	5.75	5.19	3.75	5.13	5.06	4.31	4.69	2.81	3.69	4.3300	0.8591
September	3.69	3.63	3.63	4.94	4.69	5.06	4.81	4.13	4.44	2.75	3.38	4.1045	0.7101
October	3.75	3.62	4.89	4.81	4.44	4.13	4.31	3.75	3.88	3.19	6.94	4.3373	0.9576
November	3.75	3.69	4.31	3.63	3.94	3.81	3.69	4.56	3.56	3.56	3.75	3.8409	0.3034
December	3.88	3.87	4.81	3.88	4.94	4.25	4.25	3.88	4.75	3.69	3.88	4.1891	0.4269

The next important parameter in equation (5) is ρ , the air density. It is usually assumed that the density of air at 15°C and at zero altitude (sea level) is 1.225 kg/m³. We need to note that the density is affected by humidity, altitude and temperature. Cold air is denser than warm air. Also, the air density and pressure are generally higher at lower altitudes than at higher altitudes. Modifications are therefore required before equation (5) (or equation 7) can be used to estimate the wind power density. The combined temperature and altitude correction for air density is given Masters (2004) as

$$\rho_c = 1.225K_T K_A \quad \dots (8)$$

Where ρ_c is the corrected air density and K_T and K_A are correction factors for temperature and altitude respectively. For the quoted mean altitude and temperature in Katsina, $K_T = 0.95$, $K_A \approx 0.943$. The corrected air density is thus $\rho_c = 1.097\text{kg/m}^3$, neglecting humidity.

3.2 Wind speed projections

As seen in the equations (6) and (7), the energy content of the wind varies with the third power of the average wind speed. Therefore even a small change in wind speed will result in large change in

the wind power. Modest improvements in wind speed can be obtained by mounting the wind turbine on a tall tower, typically 30m, 40m, 50m, etc. Although these heights are not large enough to cause significant drop in air density, they are however enough to provide small increments in the wind speed. Meteorological stations, as a matter of convention, measure wind speed at 10m above ground level. These readings have to be used to extrapolate the wind speed at higher heights. The approximate increase of wind speed with height for different surfaces can be calculated from the following formula (Earnest and Wizelius, 2011):

$$v_2 = v_1 \left(\frac{h_2}{h_1} \right)^\alpha \quad \dots (9)$$

Where: v_1 is the known (reference wind speed) at height h_1 , v_2 is the wind speed at a projected height, h_2 , and α is an empirical constant which is determined by the roughness of the terrain under consideration. For Katsina terrain the value of $\alpha = 0.214$ is used (Weather Report, 2007).

The calculated average wind speed data in Table 1 (at height of 10 m above ground level) were used in

equation (9) to compute the projected wind speeds at 20-80 m heights as presented in Table 2.

Table 2: Projected Monthly Average Wind Speeds

	Average Wind Speed v_2 in m/s at Various Hub Heights							
	v_1 at 10m	v_2 at 20m	v_2 at 30m	v_2 at 40m	v_2 at 50m	v_2 at 60m	v_2 at 70m	v_2 at 80m
January	4.23	4.91	5.35	5.69	5.97	6.21	6.41	6.60
February	3.92	4.55	4.96	5.27	5.53	5.75	5.94	6.12
March	4.14	4.8	5.24	5.57	5.84	6.07	6.28	6.46
April	4.19	4.86	5.3	5.64	5.91	6.15	6.35	6.54
May	4.36	5.06	5.52	5.87	6.15	6.40	6.61	6.80
June	4.38	5.08	5.54	5.89	6.18	6.43	6.64	6.84
July	4.52	5.24	5.72	6.08	6.38	6.63	6.85	7.05
August	4.33	5.02	5.48	5.83	6.11	6.35	6.57	6.76
September	4.10	4.76	5.19	5.52	5.79	6.02	6.22	6.40
October	4.34	5.03	5.49	5.84	6.12	6.37	6.58	6.77
November	3.84	4.45	4.86	5.17	5.42	5.63	5.82	5.99
December	4.19	4.86	5.30	5.64	5.91	6.15	6.35	6.54

3.3 Statistical wind energy assessment

It may be noted from the Table 1 that the average wind speed does not vary much with time. The data obtained consists of readings of wind speeds taken every day for a month. These are then averaged out to produce a single average value for the month. However, in reality it is well-known that the behavior of the wind varies considerably within a month even from time to time within a single day. Sometimes it blows in gusts and at other times not. There are times that the wind speed is zero, etc. Therefore the wind regime is better analyzed statistically using probability density functions. The Rayleigh probability density function (PDF), which is a special case of the Weibull PDF (Rinne, 2009) is often used to analyze data in meteorology, life sciences and engineering. As noted by Johnson (1994) and Masters (2004), analysis of wind regime using the Rayleigh distribution is straightforward and produces acceptable results. The Rayleigh PDF is given by

$$f(v) = \frac{2v}{c^2} \exp\left[-\frac{v^2}{c^2}\right] \dots (10)$$

Where: v is the independent variable (wind speed in our case); c is a scaling parameter (estimated as $c = 2\bar{v}/\sqrt{\pi}$); \bar{v} is the average wind speed.

What is important in the analysis of wind energy potential is determination of the wind speed and its availability at a given place. These values are then compared with energy requirements and the wind turbine technology. In particular the following turbine parameters are required: rated output, cut-in speed, rated speed and cut-out speed. These pieces of information, when considered together, enable a prospector to draw conclusions regarding the wind energy potential at the place. We want to know for how long will the wind speed be equal or above a specified speed u (e.g. the cut-in speed of the wind turbine). Similarly it is important to know for how long a certain speed u m/s can be sustained, etc. This information can be obtained by using the Rayleigh cumulative distribution function (Masters, 2004; Rinne, 2009), which is obtained by integrating equation (10) over the interval 0 to u . After simplifying, this leads to

$$F(u) = 1 - \exp\left[-\frac{u^2}{c^2}\right] \dots (11)$$

Where: u is a certain specified wind speed and \bar{v} is the average speed of the wind.

4. RESULTS AND DISCUSSION

We can now consider the wind power density in Katsina. For analysis usually hub height of 50 m was used. From Table 2, the average wind speed at this height is 5.9422 m/s. For the purpose of this

study, specifications for NEG Micon wind turbine were extracted from Masters (2004) and are listed in the first two columns of Table 3. The NEG Micon wind turbine has a rated output of 1000 kW,

60 m rotor diameter, cut-in speed of 4 m/s, rated speed of 14 m/s and cut-out speed of 26 m/s. The generator starts to produce output power at the cut-in speed. It produces its rated power at the rated

speed. The wind turbine does not produce any output at the cut-out speed, as can be seen from the last row of Table 3.

Table 3: Annual output of NEG Micon 1000/60 wind turbine at 50 m hub height

Speed u (m/s)	Power Output P at Speed u (kW)	$F(u)$	Time t at Speed u (hr)	Turbine Output (kWh/yr)
0	0	0.00000	.00	.00
1	0	0.04354	381.40	.00
2	0	0.08145	713.53	.00
3	0	0.10931	957.56	.00
4	33	0.12472	1,092.54	36,053.66
5	86	0.12760	1,117.74	96,125.60
6	150	0.11986	1,049.98	157,497.57
7	248	0.10470	917.18	227,461.24
8	385	0.08569	750.65	289,001.64
9	537	0.06603	578.43	310,616.06
10	670	0.04806	421.05	282,101.25
11	780	0.03313	290.21	226,363.39
12	864	0.02166	189.74	163,933.67
13	924	0.01345	117.82	108,870.04
14	964	0.00794	69.57	67,063.09
15	989	0.00446	39.09	38,656.02
16	1000	0.00239	20.91	20,910.59
17	998	0.00122	10.66	10,636.72
18	987	0.00059	5.18	5,110.53
19	968	0.00027	2.40	2,321.77
20	944	0.00012	1.06	1,000.39
21	917	0.00005	.45	409.64
22	889	0.00002	.18	159.75
23	863	0.00001	.07	59.54
24	840	0.00000	.03	21.24
25	822	0.00000	.01	7.28
26	0	0.00000	.00	.00
Total =		1	8,727.43	2,044,380.68

5. CONCLUSION

From the wind energy data and the statistical analysis, the following points could be drawn: The average wind speed at 10 m height in Katsina is 4.2 m/s, the wind energy potential in Katsina is therefore quite promising. As shown in Table 3, the wind power densities at the height of 50 m indicate that Katsina has good wind energy potential and wind turbines can be installed to harvest the wind energy. The hub height of 50 m was used in this study to explore the potential of electricity generation. The mean wind speed at this height was found to be 5.94 m/s, which can be classified as class IV wind, just suitable for electricity generation. The analysis based on Rayleigh PDF show that as much as 2,044.38 MWh can be generated per year using NEG Micon 1000/60 wind turbine. Wind turbines can be installed at heights greater than 50 m, giving the possibility of harvesting more wind energy.

The important factors that need to be considered when establishing a wind farm are the wind resource, site and all its implications, power economics, electric power engineering, and the wind turbine technology. In this study our main concern is the wind resource because it is most important factor in wind energy utilization. To

create a wind farm large wind turbines are required, i.e. turbines rated at higher than 100 kW. The wind resource should be such that the average wind speed is above the turbine's cut-in speed. The technology of wind turbines is so advance now that most large turbines cut-in, that is the speed at which it starts producing output, begin from 4 m/s, some even as low as 3.5 m/s. According to the data collected, the annual average wind speed is higher than the cut-in speeds of many modern wind turbines even at 10 m hub height. Thus there is a fairly good potential for establishing wind farms in Katsina. The result in the current assessment conforms to the findings reported by Adekoya and Adewale (1992) who studied 30 sites in Nigeria and concluded that the wind energy potential is such that it can be used for generation of electricity and water pumping in rural areas.

However, it should be noted that the accuracy of the instrument used to record the wind speed data used in the current study was not taken into account nor were variations that could be caused by the harmattan wind and humidity. These, plus the other factors stated earlier in this paper, need to be considered before a viable wind energy farm can be established.

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