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Full Length Research Paper

Estimating the wind energy potential over the coastal stations of Nigeria using power law and diabatic methods

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The suitability of two coastal stations in Nigeria for wind energy generation is presented in this study. To estimate the wind speeds at the desired height 70 m for standard wind turbine, two methods; namely power law relationship and diabatic evaluation have been considered. It was found that the diabatic evaluation method performed better because certain physical conditions of farm site are included in the method. Thus when potential site data are not available diabatic method can provide a good approximation of wind speeds. Comparing the energy potential of the two coastal stations, Lagos and Calabar in this study, it was found that Lagos has stronger wind speeds than Calabar especially during peak periods. The atmospheric condition most suitable to obtain maximum wind speeds was also found to be during stable condition. Stable condition occurs mostly in the night time.

Key words: Wind potential energy, wind turbine, power law, diabatic evaluation.

INTRODUCTION

Issues of carbon emissions and climate change in relation to power generation and demand have prompted attention to renewable sources of energy generation. Recently, awareness has been turned to viability of wind powered turbines as a source of energy. World largest wind farm was completed and commissioned for use in United Kingdom. The wind farm in Thanet, located off the Kent coast is capable of generating 2 gigawatt (GW) of electricity annually. The 100 turbines, each measuring more than 300 ft, will power more than 200,000 homes. It will increase the amount of energy generated from offshore wind in the UK by a third to 1,314 MW, compared to 1,100 MW in the whole of the rest of the world (The Telegraph, 2010). Attention is now being directed toward power generation from a renewable source especially wind power.

As of September 2010, the installed capacity of wind power in the United Kingdom was over 5 GW. Wind power is the second largest source of renewable energy in the UK after biomass. Since most suitable locations for wind farm appears to be along the coast, knowledge of mean wind profile over the sea and adjacent coast is important. The study of wind profile for potential wind power is difficult to assess because only surface data at a height of about 10 m (reference height) is available. Thus there is a need to estimate the wind at sufficient heights for proper evaluation of wind power potential. According to Van et al. (1990) logarithmic relation can sufficiently describe wind profile over sea during adiabatic condition. However, when the sensible heat flux and latent heat flux are significantly different from zero, stability correction should be made. Such stability correction can be calculated using the diabatic method to account for change in temperature and moisture associated with sensible and latent heat flux. We compare potential energy generation using power law relationship and diabatic evaluation method to determine the suitability of each method for Nigerian coastal wind estimation.

In this paper we demonstrate the suitability and potential of some coastal stations in Nigeria for wind energy production. This is motivated by the fact that there is no wind farm presently in Nigeria, at least, in

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Table 1. Power law exponent p value at various stability categories.

Stability category	A	B	C	D	E	F
z_0 = 1	0.17	0.17	0.20	0.27	0.38	0.61

commercial use. Therefore there is need to evaluate the potential of some locations to determine their suitability for wind power generation.

DATA AND METHOD

Monthly wind data over some coastal stations (Lagos, Calabar) constitute the major data for this study. 18 years data between 1991 and 2008 were obtained from the archives of the Nigeria Meteorological Agency (NIMET) Oshodi Lagos. The wind speeds measured at the reference height of 10 m were used to calculate the wind speed u_z at heights between 15 and 70 m at the interval of 5 m. The power law relationship is given as;

$$U_z = U_1\left(\frac{z_2}{z_1}\right)^p \quad [1]$$

The exponent p of the power law varies with stability categories according to Irwin (1976b) as shown in Table 1; further explanation is given in Table 2 according to Turner (1994). Equation [1] was used to estimate wind speed from reference height of 10 to 70 m.

On the other hand, to estimate wind speed using diabatic method, we start from the Monin – Obukhov (M-O) similarity theory which relates the mean gradient of wind speed, temperature and humidity to the universal function of dimensionless stability parameter z/L. The gradient functions are, as given by Large and Pond (1982);

$$\frac{kz}{u_*}\frac{\partial U}{\partial z} = \phi_m(z/L) \quad [2]$$

$$\frac{kz}{\theta_*}\frac{\partial \theta}{\partial z} = \phi_t(z/L) \quad [3]$$

$$\frac{kz}{q_*}\frac{\partial q}{\partial z} = \phi_q(z/L) \quad [4]$$

where U, θ, q are the wind speed, the absolute temperature and absolute humidity respectively. The quantities u_*, θ_* and q_* are friction velocity, temperature scale and humidity scale respectively. Absolute temperature profile is approximated by $\theta = T_{air} + 0.01z$ and L is given by;

$$L = \frac{-(u_*)^2 T_v}{kg\theta_{*v}} \quad [5]$$

where T_v the absolute virtual temperature, g is the acceleration due to gravity and θ_{*v} is the virtual temperature scale. Integration of equations 2 to 4 gives the profile function for wind speed, temperature and humidity. For wind speed, the profile function can be written as;

$$U_z = \left(\frac{u_*}{k}\right)\left(\ln\left(\frac{z}{z_0}\right) - \psi_m\left(\frac{z}{L}\right)\right) \quad [6]$$

Von Karman constant (k = 0.40), z and z_0 are the height of wind speed and roughness length respectively. The costal of Nigeria can be characterized as regularly covered with large obstacles with open spaces roughly equal to obstacle heights, sub – urban houses, village and mature forest. Following the Devenport – Wieringa roughness classification (Wieringa, 1981) z_0 has been taken as 1.0 m. In the present case, it required to calculate the wind speed U_2 at a specific height z_2, given the wind speed U_1 at the height z_1, thus equation 6 can be rewritten as;

$$U_2 = U_1\left[\ln\left(\frac{z_2}{z_0}\right) - \psi_m\left(\frac{z_2}{L}\right)\right] \Big/ \left[\ln\left(\frac{z_1}{z_0}\right) - \psi_m\left(\frac{z_1}{L}\right)\right] \quad [7]$$

Where ψ_m is the stream function given as, for unstable condition (L<0);

$$\psi_m = 2\ln\left(\frac{1+x}{2}\right) + \ln\left(\frac{1+x^2}{2}\right) - 2\tan^{-1}x + \pi/2 \quad [8]$$

Where $x = (1-16(z/L))^{1/4}$

For stable condition

$$\psi_m = -5(z/L)$$

For simplicity, L values have been carefully chosen for unstable (L<-200) and stable (L>200) (Van et al., 1990) atmospheric

Table 2. Pasquill – Gifford stability categories.

Stability category	Classification	Natural phenomena	Most likely occurrence
A	Extremely unstable	Strongly thermal instability	Late morning to mid afternoon in spring and summer
B	Moderately unstable	Transitional periods, moderate mixing	Dry time transitions, all year
C	Slightly unstable	Transitional periods, slight mixing	Day time transitions, all year
D	Neutral	Strong winds, overcast day/night transitions	Day time, cloudy; high winds; day time transitions, all year
E	Slightly stable	Transitional periods, night time, moderate winds	Night-time transition, all year
F	Moderately stable	Clear night-time skies, very limited vertical mixing, plume planning and meandering	Night, clear skies, light winds, all year

conditions and then, equation 7 was used to construct diabatic wind profile from 10 to 70 m at interval of 5 m. The wind power relation was obtained as, (Stull, 2000);

$$P = \frac{1}{2}\rho U^3 \quad [9]$$

where P, ρ and U are respectively wind power, air density and wind speed. Wind energy potential was computed by integrating estimated power using trapezoidal method.

Climate of the study area

Lagos has a tropical savanna climate (Köppen climate classification Aw) that is similar to that of the rest of southern Nigeria. There are two rainy seasons, with the heaviest rains falling from April to July and a weaker rainy season in October and November. There is a brief relatively dry spell in August and September and a longer dry season from December to March. Monthly rainfall between May and July averages over 300 mm (12 in), while in August and September it is down to 75 mm (3 inches) and in January as low as 35 mm (1.5 inches). The main dry season is accompanied by harmattan winds from the Sahara Desert, which between December and early February can be quite strong. The average temperature in January is 27℃ (79℉) and for July it is 25℃ (77° F). On average the hottest month is March; with a mean temperature of 29℃ (84℉); while July is the coole st month (BBC, 2010).

Calabar is similar to the Lagos in terms of the climate, during the winter months of November to March, which are usually referred to as the dry season in Nigeria, there could be occurrence of harmattan dust haze in Calabar but the frequency is very low. This means that winds over Calabar are predominantly south – westerly. In Summer, (wet season), the patterns of precipitation are typical of the equatorial zone (Adefolalu, 1984).

RESULTS

Wind speed – height structure

It is important to state here that the focus of this study is on the two extremes of stability category for easy comparison between the diabatic and power law methods; hence we will not duel on other stability categories that transit between the extremes (Table 2).

Wind speeds with heights were estimated using the power law relationship for extremely unstable and moderately stable conditions as presented in Figure 1.

These two conditions were estimated from average monthly wind speeds between 1991 and 2008 at reference height of 10 m, thus the wind speed converges at this height. Under the stability category F (moderately stable), estimated wind speeds over Lagos increased up to 21 m/s at height 70 m whereas in the category A (extremely unstable) wind speeds at the same height was just about 8 m/s. greater wind speeds are best achieved under the category A stability criterion, this condition is prevalent in the night time. Over Calabar, greater wind speeds estimate was also

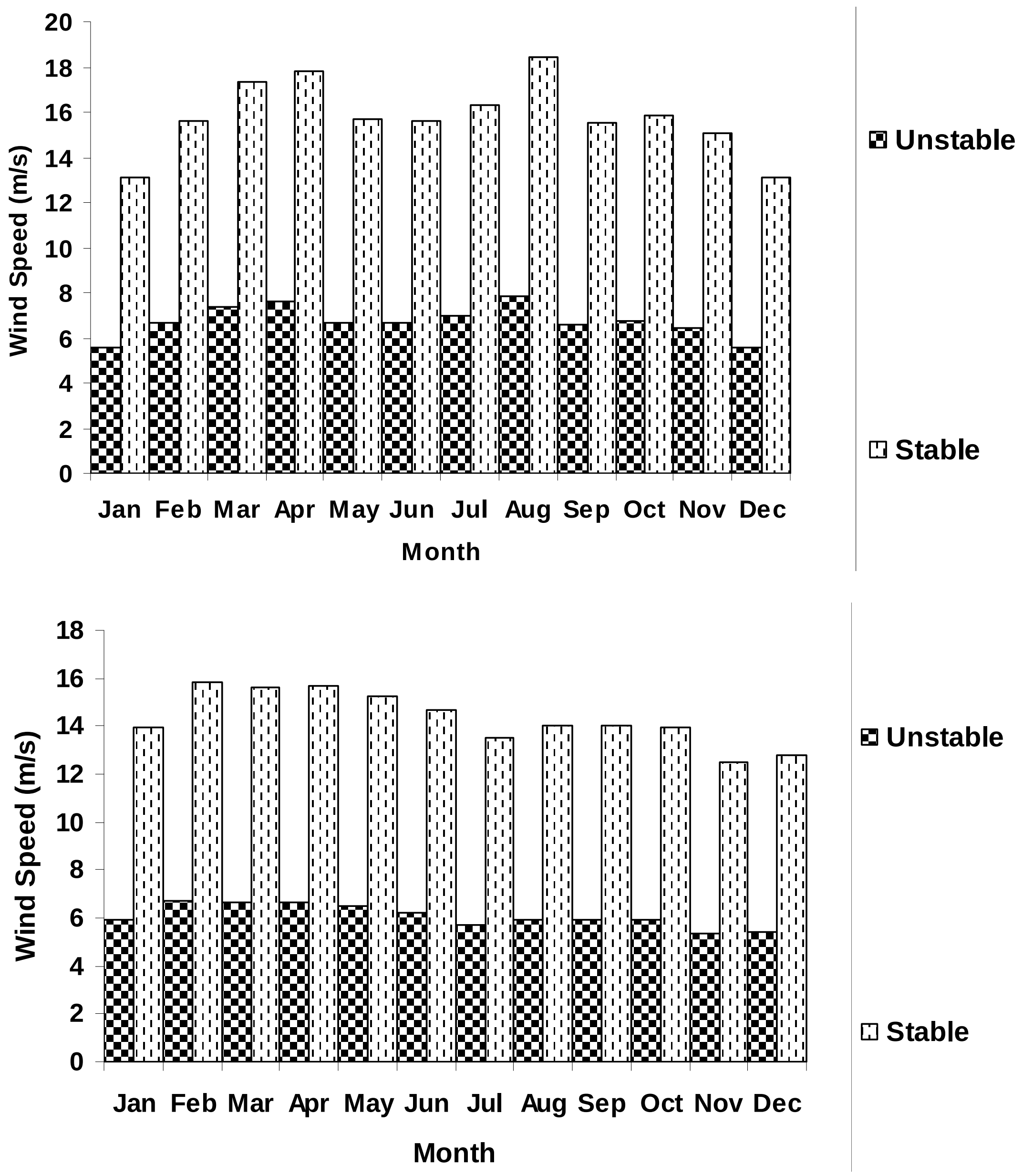

Figure 1. Variation of calculated mean monthly wind speeds in Lagos (upper panel) and Calabar (lower panel) using power law relationship.

achieved under the category F stability classification, however, the wind speeds estimated were lower than the values obtained over Lagos. Thus, Lagos is generally windier than Calabar based on the 18 years of data considered for this study.

The diabatic estimation for both stable and unstable atmospheric condition over Lagos shows that wind speeds increased with height up to 18 m/s for stable condition at height of 70 m and up to 15 m/s for unstable condition, which is similar to the wind – height structure obtained over Calabar (Figure 2), however, wind values over Calabar are lower than values over Lagos. The value for the stable condition using diabatic method is lower than the value obtained from power law. In diabatic method a number of parameters were included in the estimation of wind speeds such as the roughness length, which puts into consideration the actual features (obstacles, building) of the site that are capable of obstructing free flow of wind. Since power law does not include this consideration, the estimation from power law is unrealistically high especially in stable conditions. Thus for estimate of wind speed in stable conditions, diabatic

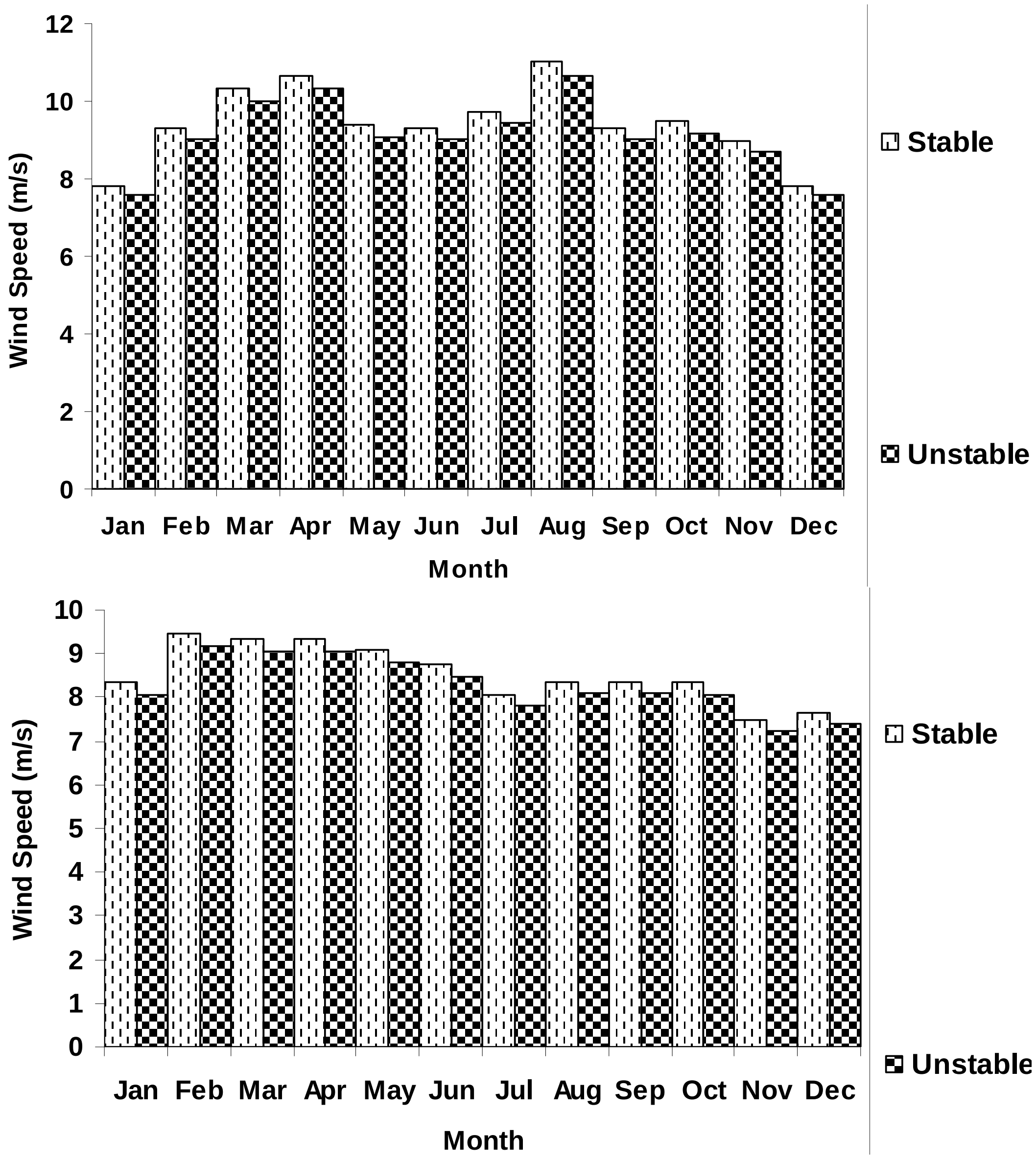

Figure 2. Variation of calculated mean monthly wind speeds in Lagos (upper panel) and Calabar (lower panel) using diabatic method.

method provides a better approximation.

Seasonal characteristics of wind speed at height 70 m

The most effective wind in terms of energy generation is the wind located at the height of the turbine blades. For this investigational purpose, the height 70 m is considered as this is the average height of turbine blade in most of commercial wind farms (ICREED, 2006), 80 m is the current industry norm which is based on wind turbines at 70 m. In Figure 3 the seasonal variation of wind at height 70 m is presented. Over Lagos, wind speeds estimated using the power law depict a wide difference between unstable and stable conditions. Wind speeds are always higher in stable condition than unstable. The observation over Calabar is similar to that obtained over Lagos. However, using the diabatic method, the difference between wind speeds estimate under the stable and unstable conditions was not much. The wide difference in the case of power law may have been due to weakness inherent in the method (for example, it does not include the effect of building and other friction – causing obstacles). Despite the shortcomings, the method has shown that there are stronger wind speeds during the stable condition than

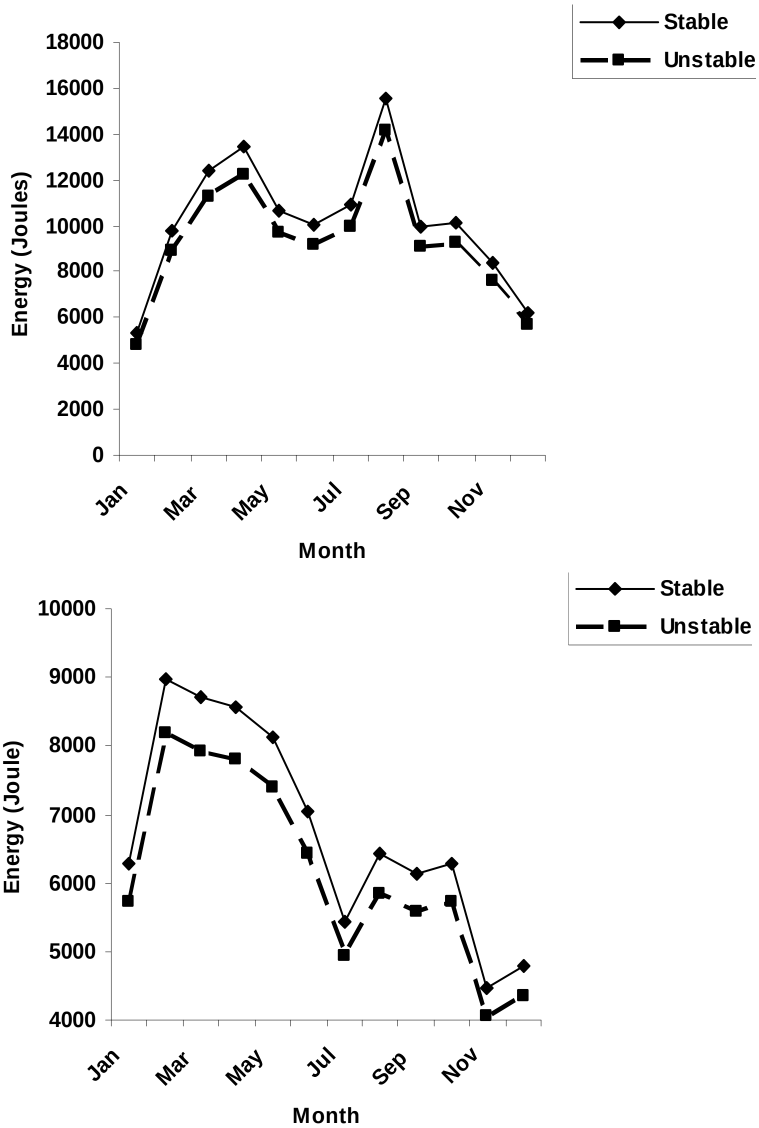

Figure 3. Variation of mean monthly energy for Lagos (upper panel) and Calabar (lower panel). Maximum energy occurs in August and March in Lagos and Calabar respectively.

unstable condition. Diabatic method also revealed similar deduction. Stronger wind speeds occur during the stable condition due to the thermal stratification of the atmosphere. A statically stable atmosphere will offer less friction and enhance wind speeds than unstable, mixed atmosphere. Since stable condition often occur in the night, it is envisaged that more power will be generated from the wind turbine during the night.

The seasonal variation of wind speed at 70 m over Lagos using both methods shows a generally increasing speed from January to April. It decreases thereafter to December except in August when there was slight increase. This pattern was followed over Calabar. The months of March and April, when wind speeds were highest are months of transition between the dry and the wet season over the coastal stations, which are usually characterised by strong winds. As soon as the wet season starts properly, weak winds take over. This explains the seasonal characteristics of the wind speeds as noted earlier. Thus power generation will peak during the months of March and April. The August slight increase in wind speed may be due to the characteristic of 'little dry season' that (usually) occurs during the month. Comparing seasonal wind estimation from both power law and diabatic methods, it is observed that power law method slightly overestimate wind speeds.

This can be understood from the fact that power law does not consider the friction effects usually offer to wind

Table 3. Power generation stations in Nigeria showing the peak and off peak supply. Note that there is no wind turbine.

Station	Turbine	Peak gen (MW)	Off peak gen (MW)
Kainji	Hydro	237	204
Jebba	Hydro	435	368
Shiroro	Hydro	408	-
Egbin	Steam	850	785
Trans Amadi	Gas	-	20.1
A.E.S	Gas	250	249.3
Sapele	Steam	138	144
Ibom	Gas	81.6	4.3
Okapi	Gas	425	380
Afam 1-5	Gas	59	60
Afam VI	Gas	299	302
Delta	Gas	200	205
Geregu	Gas	387	260
Omoku	Gas	40.2	12.1
Omotosho	Gas	25.2	25.2
Olorunsogo phase I	Gas	42.3	20.3
Olorunsogo phase II	Gas	-	121.6
Total		3877.4	3160.9

Source: National Mirror, 13 April, 2011.

speed by building and trees. For example, over Lagos in August, power law estimated a wind speed of about 18 m/s where in the same month, using diabatic method, the wind speed was about 11 m/s. this can be misleading especially when deciding the specification of wind turbine needed at these sites. Thus, correct estimation is better done using the diabatic method.

Monthly pattern of wind energy potential over the stations

Accurate estimation of wind speeds at the desired heights can help in forecasting the likelihood of power generation from a wind farm. Using the estimated wind speed at 70 m, expected energy output for Lagos and Calabar are shown in Figure 3. The energy outputs for both stations were calculated from the wind estimated using diabatic method only (for obvious reason). Following the monthly gradual increase in wind speeds from January to April, the energy potential of the wind speeds also increases in both stations. However, the drop in energy potential in June / July was shaper over Calabar than Lagos, suggesting that within these months energy realisation in a potential wind farm located in Lagos will be more than in Calabar. The highest peak of energy generation from wind over Lagos occurs in August at about 16000 Joules under stable condition. The peak energy reduces to about 14000 Joules under unstable condition. Over Calabar the peak energy occurs in February / March amounting to about 9000 and 8000 Joules under stable and unstable conditions respectively.

DISCUSSION

The nation's power generation hit 4,000 mega watts (MW) at the beginning of 2011 according to the data released by the Power Holding Company of Nigeria (PHCN) in the first quarter of the year, power generation increased from 3,800 MW to 4,000 MW. The improvement according to the data was achieved as a result of increased water level of hydro-electric power stations located at Kainji, Jebba and Shiroro (National Mirror, 2011). The commencement of operation by the Independent Power Plant (IPP) stations over some new locations contributed to the improvement recorded during the period (National Mirror, 2011). Despite this improvement, power supply in Nigeria remains epileptic as there are no 24 h uninterrupted power supply, even to industrial areas. It is noted from Table 3 that there is yet no wind power harnessed for the purpose of generating electricity in Nigeria. A unit turbine will produce at least 191.11 kW of electricity per hour, in the coastal stations of Lagos and Calabar, the average wind speed is about 9.0 m/s at 70 m, which translate to 478 kW of electricity at 100 % efficiency, if power is cube of wind speed. Assume the wind turbine is operating at 40% efficiency; a wind farm of 5,000 units will generate about 995 MW. Having at least five wind farms will increase the supply by at least 4,775 MW, which is more than what all existing sources in Nigeria are generating (Table 3).

It is important to consider another source of power generation to meet the demand for electricity supply. Wind energy, which remains hitherto untapped, appears promising in solving the problem of electricity shortage. Apparently, wind energy potential is exploitable in Nigeria, along the costal towns where stronger wind speeds are sufficiently available throughout the year.

Analysis presented in this study showed that night time stable condition produces stronger wind speeds. At night time, or when the atmosphere becomes stable, wind speed close to the ground usually subsides whereas at turbine hub altitude it does not decrease that much or may even increase. As a result the wind speed is higher and a turbine will produce more power than expected from the 1/7th power law: doubling the altitude may increase wind speed by 20 to 60%. A stable atmosphere is caused by radiative cooling of the surface and is common in a temperate climate: it usually occurs when there is a (partly) clear sky at night. When the (high altitude) wind is strong (a 10 m (33 ft) wind speed higher than approximately 6 to 7 m/s (20 to 23 ft/s)) the stable atmosphere is disrupted because of friction turbulence and the atmosphere will turn neutral. A daytime atmosphere is either neutral (no net radiation; usually with strong winds and/or heavy clouding) or unstable (rising air because of ground heating — by the sun). Here again the 1/7th power law applies or is at least a good approximation of the wind profile. Indiana (USA) had been rated as having a wind capacity of 30,000 MW, but by raising the expected turbine height from 50 m to 70 m, the wind capacity estimate was raised to 40,000 MW, and could be double that at 100 m.

Conclusion

Two methods (power law relationship and diabatic) have been used to determine the wind energy potential of two stations located along the coast of Nigeria. The coastal areas are usually windy and they provide suitable location for wind farm. Comparing the two methods, wind speeds estimated from diabatic method for both stable and unstable atmospheric conditions appear to be more accurate due to certain physical condition built into the method. For example, diabatic method which considered the effects of building and obstacles that offer resistance to wind is more realistic than power law which makes no assumption about physical appearance of potential wind farm locations. Furthermore, power law relationship shows a wider deviation from reality under unstable atmospheric condition. These unavoidable weaknesses in power law may lead to erroneous energy calculations. Thus, diabatic method of wind speed estimation is suitable when *in situ* measurements are not available at the desired heights.

Analysis in this study has shown that Nigerian coastal stations are good potential areas for wind farms. The coastal stations have an average wind speed of 9 m/s are capable of generating about 995 MW of electricity in a single farm of 5,000 unit of wind turbine. Five such farms will produce as much as the present power generation in Nigeria with all source put together. This alone puts wind potential energy in a good position in solving the problem of inadequate supply of electricity currently facing the country.

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