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Economic assessment of water pumping systems using wind energy conversion systems in the southern part of Nigeria

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Abstract

This study assessed the wind energy potential and the economic viability of the water pumping systems supplied by various wind turbine models. The two-parameter Weibull probability density function was employed to analyze the wind speed data collected between 1971 and 2007 by the Nigerian Meteorological Agency for seven meteorological stations, in the southern part of Nigeria, namely Asaba, Calabar, Ogoja, P-Harcourt, Uyo, Benin-City, and Warri. The performance of small to medium size commercial wind turbine models of various rated powers ranging from 5.2 kW to 250 kW were investigated and economic evaluation of the wind energy in all the sites was performed using the levelised cost method. The results showed that the annual mean wind speeds range from 3.09 m/s at Warri to 4.15 m/s at Calabar, while the corresponding annual mean power densities vary from 23.17 W/m^2 to 56.22 W/m^2. Our analysis demonstrated that the wind resource in all the sites considered fall into Class 1 wind resource category, hence, they can marginally be considered for small scale standalone system for electricity generation. The cost of energy production per kWh for the selected sites varies between \$0.090 at Ogoja and \$2.118 at Uyo. Moreover, the cost of water delivered varies from \$3.33 per cubic metres in Calabar to \$54.96 per cubic metres in Uyo.

Keywords: Wind power, Wind energy conversion system, economic factors, Southern Nigeria

1. INTRODUCTION

The challenge of producing sufficient energy to meet the ever increasing global energy consumption, the rapidly depleting fossil fuel reserves, and the serious environmental problems associated with the use of fossil fuels have motivated considerable research attention on clean energy sources. Wind energy is one of the several energy sources that are both environmentally preferable and renewable. Moreover, wind energy is abundant in nature, inexhaustible, fuel-free, can generate power near load center, and thus eliminates energy losses associated with transmission network.

In the last decade, the use of wind energy to provide steady and reliable supply of electricity for both developed and developing countries are found to be on the increase (Balat, 2005). It is interesting to note that the global installed wind power capacity has increased sharply from 14 GW at the end of 1999 to reach almost 160 GW by the end of 2009, and subsequently to 197 GW in 2010, an average annual increase in cumulative capacity of 24% (GWEC, 2011). It is noteworthy that 86.4% of the global installed wind power capacity is produced by China, USA, Germany, Spain, India, Italy, France, UK, Canada, and Denmark with the rest of the world accounted for 14.6% (GWEC, 2011). In Africa, as at the end of 2010, Egypt, Morocco and Tunisia are the leading countries with installed wind capacity of 550 MW, 286 MW and 114 MW, respectively.

As in most developing countries, Nigeria whose energy demand exceeds supply from the national utility has not given wind energy utilization due preference. To date, there is no record of wind power plants connected to the national grid (Pam, 2007). Furthermore, due to fluctuations in the availability and maintenance of production sources, the current electricity production within the country is reported to be less than 4000 MW (NERC, 2011; Fagbenle *et al.*, 2011). Considering the fact that the hydropower accounts for major share of the present sources of energy available to the country, the importance of renewable energy sources like wind to provide a steady, reliable supply of electricity is desirable. According to (Gökçek and Genç, 2009), renewable energy sources are inexhaustible, clean, free, and offer many environmental and economical benefits in contrast to conventional energy sources. It is also recognized that wind energy for example, can be deployed as standalone power source; which in effect minimizes transmission losses.

In other to bring under conditions for effective use, wind energy requires detailed information of the wind characteristics and the distribution of wind speeds at the particular location or site. Prior study by (Himri *et al.*, 2008) shows that an error of 1% in wind speed measurements leads to almost 2% error in energy output. Therefore, besides wind speed and wind power, other factors that should be considered before investment in wind energy resource is made are the feasibility study of the site and the selection of appropriate turbine models (Fagbenle *et al.*, 2011). It should be remarked that the choice of wind turbine must be based on the average wind velocity at a selected wind turbine construction site (Marcius *et al.*, 2008). To date, several assessment studies on some sites in Nigeria have been performed to evaluate the wind energy potential and it viability for power generation. A more complete review of the prior studies can be found in (Ojosu *et al.*, 1990; Adekoya *et al.*, 1992; Fadare, 2010; Adaramola *et al.*, 2011; Ohunakin, 2011) and are not repeated here.

Studies that evaluate the economic viability of the water pumping systems (WPSs) supplied by wind energy conversion systems (WECSs) have been performed by researchers (e.g., Genç, 2011). The findings clearly reveal a strong dependence of economic viability of a wind powered generation plant on the site-specific conditions such as the wind speed, direction, and power density. The summary of the discussion provided above suggests that, detailed assessment of the potential and economic viability of the development of wind powered pumping system at a typical location must be conducted prior to investment of resources. The prime objectives of this study therefore, are to assess the wind energy potential and to perform economic evaluation of the water pumping systems supplied by wind energy conversion systems at several locations in the southern part of Nigeria in order to ascertain the most promising sites for WPSs in the region. The selected locations of study are Asaba, Calabar, Ogoja, P-Harcourt, Uyo, Benin-City, and Warri.

2. MATERIALS AND METHOD

2.1. Data sources

The wind speed data for the seven sites considered in this study were obtained from the Nigerian Meteorological Agency (NIMET), Oshodi, Lagos, Nigeria. The geographical coordinates of these sites are given in Table 1. The data were acquired over a period of 36 years (1971–2007) using a cup-generator anemometer at a hub height of 10 m. The acquired data were obtained on hourly basis, from which monthly wind speed and other wind speed parameters were determined.

2.2. Mathematical analysis

There are several density functions that can be used for the wind data analyses. The two most common are the two-parameter Weibull and Rayleigh functions. However, the Weibull distribution has been found to be more versatile, accurate, and adequate in describing and predicting the characteristics of prevailing wind profile over a place (Justus *et al.*, 1978; Akpinar *et al.*, 2005; Akdag *et al.*, 2009; Akdag *et al.*, 2010). Prior studies have also shown that the Rayleigh distribution is somewhat simpler to use because it has only one parameter (Johnson, 2006). In this study, the two-parameter Weibull probability density function was employed in carrying out the analyses of

Table 1. The geographical coordinates of the selected sites.

	Latitude (°N)	Longitude (°E)	Elevation above sea level (m)
Benin-city	06.32	05.61	77.8
Warri	05.52	05.75	6.1
P-Harcourt	04.75	07.00	19.5
Uyo	05.05	07.93	64.0
Calabar	04.95	08.33	61.9
Ogoja	06.50	08.67	117.0
Asaba	06.18	06.75	43.0

wind speed potentials over the sites considered. The Weibull distribution function is given by [e.g., (Mathew *et al*., 2002 and Akpinar *et al*., 2005)]:

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

where $f(V)$ is the probability of observing wind speed V; k is the dimensionless Weibull shape parameter and c is the Weibull scale parameter in m/s. It is noteworthy that, the scale factor is related to the mean wind speed through the shape factor which determines the uniformity of the wind speed in a given site.

The corresponding Weibull cumulative distribution is given by [(e.g., Mathew *et al*., 2002 and Akpinar *et al*., 2005)]:

$$F(V) = 1 - e^{-(V/c)^{k}} \tag{2}$$

where $F(V)$ is the cumulative distribution function of observing wind speed V. The monthly and annual values of Weibull parameters were calculated using a power density method proposed by Akdag and Dinler (2009). According to these authors, the merits of power density method over other commonly used methods (e.g. graphical, maximum likelihood and moment (or standard deviation) methods) for calculating Weibull parameters are: (i) it has an easy expression, (ii) it does not require binning and solving linear least square problem or iterative procedure, (iii) if power density and mean wind speed are available it is very simple to estimate Weibull parameters, and (iv) it is more suitable to estimate power density for wind energy applications. The shape and scale factors are thus computed from equations (3) and (4) given by (Akdag *et al*., 2009):

$$k = 1 + \frac{3.69}{(E_{pf})^{2}} \tag{3}$$

$$c = \frac{V_m}{\Gamma\left(1 + \frac{1}{k}\right)} \tag{4}$$

where V_m is the mean wind speed (m/s), $\Gamma(x)$ is the gamma function which is defined as (Jowder, 2009; Ouammi *et al*. 2010):

$$\Gamma(x) = \int_0^{\infty} t^{x-1} e^{-t}\, dt \tag{5}$$

and E_{pf} is the energy pattern factor which is defined as (Mathew 2006, Akdag *et al.*, 2009):

$$E_{pf} = \frac{\frac{1}{n}\sum_{i=1}^{n} V_i^3}{\left(\frac{1}{n}\sum_{i=1}^{n} V_i\right)^3} = \frac{\overline{V^3}}{\left(\overline{V}\right)^3} \tag{6}$$

Instead of using equation (4) to determine the scale factor, the following expressions can also be used (Balouktsis *et al,* 2002):

$$C = \frac{V_m k^{2.6674}}{0.184 + 0.816 k^{2.73855}} \tag{7}$$

It should be noted that Equation (6) is used in this study to estimate the monthly and annual scale factors.

2.3. Wind speed variation with height

It is a matter of common observation that the wind speed generally increases with height. In most cases, the available wind data are measured at height different from, for example, the wind turbine hub height. Since, the wind speed at the hub height is of interest for wind power application, the available wind speeds are adjusted to the wind turbine hub height using the following Power law expression (Akpinar *et al.*, 2005):

$$\frac{V}{V_o} = \left(\frac{h}{h_0}\right)^{\alpha} \tag{8}$$

where V is the wind speed at the required height h, V_o is wind speed at the original height, h_0, and α is the surface roughness coefficient and is assumed to be 0.143 (or 1/7) in most cases. The surface roughness coefficient, α can be determined from the following expression (Ucar and Balo, 2009):

$$\alpha = [0.37 - 0.088\ln(V_o)] / \left[1 - 0.088\ln\left(\frac{h_0}{10}\right)\right] \tag{9}$$

Alternatively, the Weibull probability density function can be used to obtain the extrapolated values of wind speed at different heights. Since, the boundary layer development and the effect of the ground are non-linear with respect to wind speed, parameters c and k of the Weibull distribution will change as a function of height by the following expressions (Justus *et al.*, 1978):

$$c(h) = c_o \left(\frac{h}{h_o} \right)^n \tag{10}$$

$$k(h) = k_o \left[1 - 0.088 \ln\left(\frac{h_o}{10} \right) \right] / \left[1 - 0.088 \ln\left(\frac{h}{10} \right) \right] \tag{11}$$

where c_o and k_o are, respectively, the scale and shape parameter at the measurement height h_o and h is the hub height. The exponent n is defined as:

$$n = [0.37 - 0.088 \ln(c_o)] / \left[1 - 0.088 \ln\left(\frac{h}{10} \right) \right] \tag{12}$$

2.4. Mean wind power density

The mean wind power density can be estimated by using the following equation:

$$P_D = \frac{P(V)}{A} = \frac{1}{2} \rho V_m^3 \tag{13}$$

where $P(V)$ = the wind power (W), P_D = the wind power density (W/m^2), ρ = the air density at the site (assumed to be 1.225 kg/m^3 in this study), A = the swept area of the rotor blades (m^2). Both the mean wind speed and power density are generally used to classify the wind energy resource (e.g. PNL wind power classification scheme, (Illica *et al.*, 2003)). However, the wind power density (wind power per unit area) based on the Weibull probability density function can be calculated using the following equation (Celik, 2004):

$$P_D = \frac{P(V)}{A} = \frac{1}{2} \rho c^3 \Gamma\left(1 + \frac{3}{k} \right) \tag{14}$$

where Γ( ) is the gamma function:

2.5. Wind turbine energy output

The performance of a wind turbine installed in a given site can be evaluated by the magnitude of its power output over a period of time and the conversion efficiency or its capacity factor. The electrical power output of a model wind turbine is commonly simulated using (Garcia *et al.*, 1998; Akpinar and Akpinar, 2005; Mathew 2006):

$$P_e = \begin{cases} 0 & \upsilon < \upsilon_c \\ P_{eR}\dfrac{\upsilon^k - \upsilon_c^k}{\upsilon_r^k - \upsilon_c^k} & \upsilon_c \le \upsilon \le \upsilon_r \\ P_{eR} & \upsilon_r \le \upsilon \le V_f \\ 0 & \upsilon > \upsilon_f \end{cases} \tag{15}$$

where υ_c, υ_r, and υ_f are, respectively, the cut-in wind speed, rated wind speed, and cut-off wind speed; and P_{eR} is the rated power of the wind turbine.

The average power output ($P_{e,ave}$) of a turbine, an important parameter that relates the total energy production and the total income can be computed using the following expression based on Weibull distribution function (Akpinar and Akpinar 2005):

$$P_{e,ave} = P_{eR}\left\{ \frac{e^{-\left(\frac{\upsilon_c}{c}\right)^k} - e^{-\left(\frac{\upsilon_r}{c}\right)^k}}{\left(\frac{\upsilon_r}{c}\right)^k - \left(\frac{\upsilon_c}{c}\right)^k} - e^{-\left(\frac{\upsilon_f}{c}\right)^k} \right\} \tag{16}$$

and the capacity factor, CF; a useful parameter for assessing the performance of a wind turbine is given by:

$$CF = \frac{P_{e,ave}}{P_{eR}} = \frac{E_{wt}}{TP_{eR}} \tag{17}$$

where E_{wt} is energy generated over a period of time T (usually, 1 year or 8760 hrs).

2.6. Water pumping system using wind turbine

The wind-powered pumping systems falls into three major groups: mechanical–piston, mechanical–air lift (rotodynamic), and electrical. In general, the volume of water produced by rotodynamic and electrical pumps are considered to be more than that of piston pump at the same wind speed regime. This is because there is a better match between the rotodynamic and electrical pumps and the wind rotor than for a piston pump (Mathew and Pandey, 2003; Hau, 2006). The power required to deliver a volume of water V_w (m^3) can be expressed as:

$$P_{out} = \frac{\rho_w g V_w H}{\eta T} = \frac{\rho_w g Q_w H}{\eta} \tag{18}$$

where Q_w is the volumetric flow rate (m^3/day), ρ_w is the water density (kg/m^3), g is the acceleration due to gravity (m/s^2), H is the pump head (m), and η is the system efficiency.

The efficiency of transmission of pumping is assumed to be 0.575 (Genç, 2011). The pump head of 15 m is used for the present study. This pump head was chosen because it is within the range of the water table level of 3 to 20 m in this part of Nigeria (Adelana *et al.*, 2008). The volumetric flow rate of water was evaluated using:

$$Q_w = \frac{\eta P_{out}}{\rho_w g H} \tag{19}$$

while the annual volume of water produced by the wind energy conversion systems is determined from (Mathew, 2006; Genç, 2011):

$$V_w = \frac{\eta E_{wt}}{\rho_w g H} \times \frac{24 * 3600}{24 * 365} \text{m}^3 \text{ / year} \tag{20}$$

2.7. Cost analysis of wind energy

The evaluation of the cost of unit energy produced by WECs for either electricity generation or water pumping involves three basic steps: (i) the estimation of energy generated (or water produced) by the wind turbine over a given period (e.g. a year); (ii) the estimate of the total investment cost of the project, and (iii) the ratio of the total cost of investment to the electricity (or water) produced by the system. Several methods have been employed to estimate the operating cost of a unit energy produced by WEC_S. The most widely used method, however, is the levelised cost of electricity (LCOE) (Gökçek and Genç, 2009). The LCOE can be described as the ratio of the total annual cost of the WEC_S to the electricity produced by the system. The annualised cost of the wind energy conversion systems can be estimated using the following expression:

$$C_{wt} = CRF(C_1 + C_{om(esc)}) \tag{21}$$

where C_{wt} is the annualised cost of the wind energy conversion systems, C_I is the total investment cost which includes the cost of: the wind turbine, battery bank, civil work and installation, inverter, and miscellaneous cost; *CRF* and $C_{(om)esc}$ are, respectively, the capital recovery factor and present worth of the annual cost throughout lifetime of the wind turbines. The *CRF* and $C_{(om)esc}$ can be defined, respectively by (Equation 22) and (Equation 23) [Gökçek and Genç 2009]:

$$CRF = \frac{(1+r)^n r}{(1+r)^n - 1} \tag{22}$$

$$C_{(om)esc} = \frac{C_{om}}{r^{-e_{om}}}\left(1-\left(\frac{1+e_{om}}{1+r}\right)^{n}\right)\text{cost / year} \tag{23}$$

where C_{om}, e_{om}, n and r are the operation and maintenance cost for the first year, escalation of operation and maintenance, useful lifetime of turbine, and discount rate respectively. The levelised cost of electricity can then be calculated from:

$$C_{elec} = \frac{C_{wt}}{E_{wt}}\text{cost / kWh} \tag{24}$$

where $E_{wt} = 8760 P_{eR} C_f$ is the annual energy output of wind turbine in kWh. Similarly, cost of water can be estimated using the following expression:

$$C_{water} = \frac{C_{wt}}{V_w}\text{cost / m}^3 \tag{25}$$

3. RESULTS AND DISCUSSION

3.1. Wind speed probability distribution and mean wind speed

The annual Weibull probability density functions and the annual cumulative frequency functions calculated from the measured wind speeds for the selected locations of study are shown in Figure 1a and Figure 1b, respectively. The probability density function illustrates the fraction of time for which a given wind speed possibly prevails at a location. As expected the peak of the density function frequencies of all the sites skewed towards the higher values of mean wind speed (Fig. 1a). It should be remarked that the peak of the probability density function curve indicates the most frequent velocity. Figure 1(a) also reveals that the most frequent wind speed expected in Benin, Warri, Port-Harcourt, Uyo, Calabar, Ogoja and Asaba are approximately 3.5 m/s, 3.0 m/s, 3.5 m/s, 3.5 m/s, 4.5 m/s, 4 m/s and 3.5 m/s, respectively. The corresponding frequencies are about 46%, 48%, 37%, 55%, 36%, 34% and 46%, respectively. Moreover, Calabar and Warri have respectively, the highest and least spread of the wind speed of all the sites considered.

The cumulative probability distributions of the wind speed in all the sites (Fig. 1b) show a similar trend. It is important to note that the cumulative distribution function can be used to estimate the time for which wind speed is within a certain speed interval. For wind speeds greater or equal to 2.5 m/s cut-in wind speed, Benin, Warri, Port-Harcourt, Uyo, Calabar, Ogoja and Asaba have frequencies of about 86%, 77%, 84%, 83%, 93%, 90% and 85 %, respectively, while the same locations, respectively, have frequencies of about 52%, 32%, 53%, 34%, 73%, 67% and 47 %, for cut-in wind speed of 3.5 m/s. However, for cut-in wind speed of greater or equal to 4 m/s, only Calabar and Ogoja have

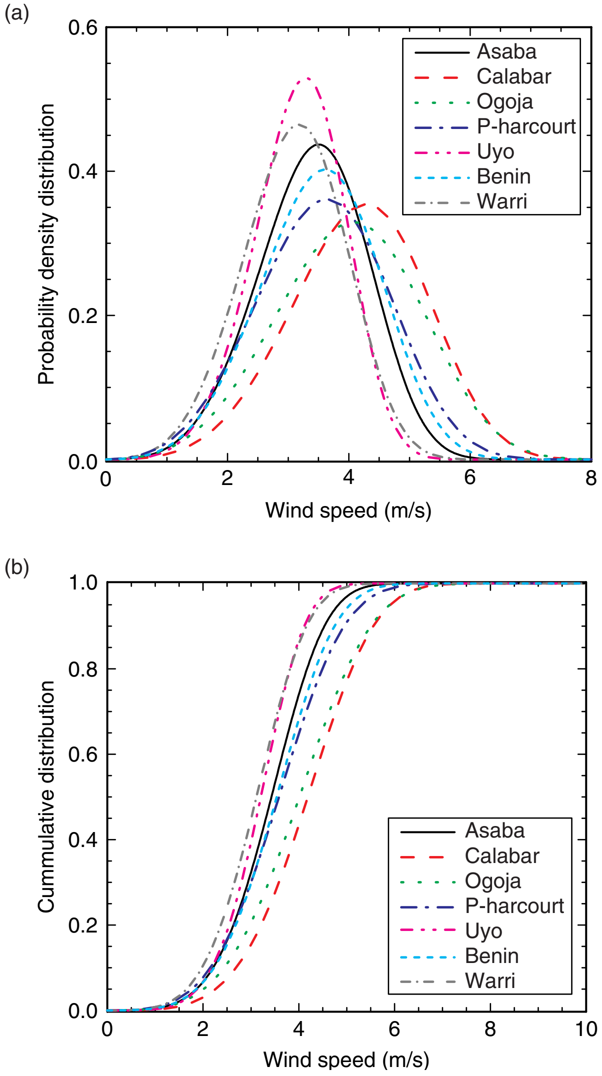

Figure 1. Plots of (a) wind speed probability density function and (b) wind speed cumulative density function.

frequency of more than 50% among all the sites. Therefore, for all the sites considered, wind turbine with cut-in wind speed between 2.0 and 2.5 m/s will be appropriate.

The site wind characteristics and Weibull parameters are presented in Table 2 for each location. The annual mean wind speeds are 3.51 m/s, 3.09 m/s, 3.56 m/s, 3.17 m/s, 4.15 m/s, 3.99 m/s and 3.39 m/s, respectively, for Benin-city, Warri, Port-Harcourt, Uyo, Calabar, Ogoja and Asaba. Furthermore, the annual mean power densities are, respectively, 34.6 W/m^2, 23.17 W/m^2, 37.06 W/m^2, 24.72 W/m^2, 56.22 W/m^2,

Table 2. Annual mean wind speed characteristics at 10 m height.

	Wind speed (m/s)	Power density (W/m^2)	k	c (m/s)
Benin-City	3.506	34.639	3.492	3.902
Warri	3.085	23.172	3.649	3.426
P-Harcourt	3.562	37.056	3.341	3.973
Uyo	3.171	24.723	3.815	3.513
Calabar	4.146	56.219	3.653	4.604
Ogoja	3.985	52.194	3.303	4.448
Asaba	3.393	30.846	3.640	3.768

52.19 W/m^2 and 30.85 W/m^2 for Benin-city, Warri, Port-Harcourt, Uyo, Calabar, Ogoja and Asaba. Based on PNL wind power classification scheme (Illica *et al*, 2003; Li and Li, 2005), the wind resource in all the sites considered fall into Class 1 wind resource category ($P_D \leq 100$). Therefore, wind resource in all the locations can marginally be considered for small scale standalone system for electricity generation. In addition, they may be adequate for non-connected electrical and mechanical applications like battery charging and water pumping. Moreover, this resource can be used for hybrid system either in combination with solar energy conversion system and/or diesel generator.

The annual Weibull shape factor in this part of Nigeria varies between 3.30 in Ogoja and 3.82 in Uyo with mean value of 3.56. Therefore, Rayleigh distribution function (in which the shape factor is assumed to be equal to 2) may not be appropriate for wind data analysis in all the locations considered in this study. The annual Weibull scale factor, which is directly related to the mean wind speed, range between 3.43 m/s in Warri and 4.60 m/s in Calabar.

3.2. Energy output and water produced by wind turbine

It is well recognized that the performance of a wind turbine is strongly dependent on its design characteristics (especially, the cut-in wind and the rated wind speeds), and the site wind speed characteristics. For optimal performance, wind turbine, in principle should be designed for specific site. However, due to economic and technical reasons, it is common to choose from available commercial wind turbine that closely matches the site wind speed conditions. The performance of five small to medium size wind turbine models with rated power range from 5.2 kW to 250 kW are simulated in all the locations considered in this study. The selected wind turbine models and their characteristic properties are given in Table 3. The annual energy outputs, capacity factors, and the amount of water produced by the selected wind turbines in each location are presented Table 4.

Table 4 clearly illustrates that the annual energy output varies from 1.19 MWh produced by using S-343 model with rated power of 5.2 kW in Warri and Uyo to 221.19 MWh produced by employing WES30 model with rated power of 250 kW in Ogoja. Based on electricity usage of 126 kWh per capital per year in Nigeria as at 2008 (UNDP, 2006), the annual energy output from S-343 model can serve electricity need of

Table 3. Technical specifications of selected commercial wind turbines[a,b].

	S-343	G-3120	E-3120	WES18	WES30
Rated Power (kW)	5.2	35	50	80	250
Hub Height (m)	36.6	42.7	42.7	39	49
Diameter (m)	6.37	19.2	19.2	18	30
Rated wind speed (m/s)	11	8	9.5	12.5	12.5
Cut-in speed wind (m/s)	4.1	3.5	3.5	2.5	3.5
Cut-off speed wind (m/s)	24	25	25	25	25
Survival speed wind (m/s)	52	52	52	60	60
Rotor	3 blades, upwind	3 blades, downwind	3 blades, downwind	2 blades, downwind	2 blades, downwind

[a] http://www.endurancewindpower.com/products.html;

[b] http://www.windenergysolutions.nl/

Table 4. Selected commercial wind turbines performance.

	S-343			G-3120			E-3120			WES18			WES30		
	E_{wt} MWh/yr	C_f (%)	V_W m^3/yr	E_{wt} WMh/yr	C_f (%)	V_W m^3/yr	E_{wt} WMh/yr	C_f (%)	V_W m^3/yr	E_{wt} WMh/yr	C_f (%)	V_W m^3/yr	E_{wt} WMh/yr	C_f (%)	V_W m^3/yr
Benincity	2.49	5.5	96	80.84	26.4	3116	59.24	13.5	2283	30.96	4.4	1193	123.70	5.7	4768
Warri	1.19	2.6	46	46.97	15.3	1810	32.30	7.4	1245	16.67	2.4	643	67.91	3.1	2617
P-Harcourt	2.98	6.5	115	88.95	29.0	3428	68.08	15.5	2624	37.47	5.3	1444	148.18	6.8	5711
Uyo	1.19	2.6	46	48.80	15.9	1881	32.55	7.4	1255	15.64	2.2	603	64.20	2.9	2474
Calabar	4.56	10.0	176	129.21	42.1	4980	102.04	23.3	3933	49.54	7.7	1909	197.93	9.0	7628
Ogoja	4.81	10.2	185	122.77	40.0	4732	101.94	23.2	3929	56.44	8.1	2175	221.19	10.1	8525
Asaba	1.92	4.2	74	68.49	22.3	2640	47.97	11.0	1849	23.99	3.4	925	96.93	4.4	3736

about 10 people in Warri and Uyo, while annual energy produced by WES30 model can serve about 1750 people in Ogoja. It is also noted that the annual energy generated by each wind turbine model vary from one location to another. The annual capacity factors vary from 2.2% by employing WES18 model at Uyo and 42.1% by using G-3120 at Calabar. Irrespective of the site, G-3120 (35 kW) turbine model has the highest value of capacity factor among the models considered. This might be due to its low rated wind speed of 8 m/s, being the lowest among the selected wind turbines. Detailed information about the annual energy output and capacity factor for each wind turbine models at each sites considered are also shown in Tables 4.

It should be remarked that most of the people living in the rural areas scattered around the sites considered in this study have limited access to portable and quality water. The minimum average of annual volume of water produced with water pumping systems (WPSs) using wind turbine model S-343 is 46 m^3 at Warri and Uyo, while the maximum water produced is 8525 m^3 by using WES30 wind turbine model at Ogoja (see Table 4).

According to UNDP (2006), the water usage in Nigeria as at 2006 was 36 litres per capital per day while the minimum recommended water usage per capital per day is 50 litres. Therefore, based on 50 litres per capital per day, the water delivered by the WPSs can serve from 3 to 470 inhabitants depending on the wind turbine model and the location. More information about the amount of water delivered by the WPS by each wind turbine models at each sites are also shown in Table 4. It should be noted that the annual energy and water delivered by each wind turbine can be improved upon if multiple wind turbines are used instead of single wind turbine.

3.3. Economic analysis

The economic analysis of the selected wind turbine models was performed using LCOE method. The specific cost of any wind turbine in terms of rated power was taken as the average value of the range of specific cost of the turbine (see Table 5). The cost analysis per unit kWh of energy and water produced by each wind turbine model was estimated based on the following assumptions:

i. The lifetime (η) of each wind turbine used in this study taken as 20 year.
ii. The discount rate is assumed to be 12%.
iii. Operating and maintenance cost (C_{om}) was assumed to be 25% of the annual cost of the wind turbine (system price/lifetime) and the escalation rate of operation and maintenance ($C_{(om)esc}$) is assumed to be 0%.
iv. Other initial costs including that for land, installation, and grid integration are assumed to be 30% of the wind turbine cost.
v. It is further assumed that the wind turbine produces the same amount of energy and water in each year during its useful lifetime.

3.3.1. Cost of energy output

In the addition to the quantity of water delivered by the WPSs using wind energy conversion systems, the cost of energy and water produced by the WECs is another important parameter to be evaluated (Genç, 2011). In Nigeria, the cost of electricity is regulated by the NERC. The price of electricity largely depends on how consumers are categorized (i.e., residential, commercial, industrial, etc.) and the level of consumption of electricity. For example, the current retail tariff (effective from July 2011) schedule released by the NERC (2011) shows that the unit cost of electricity varies from N2.2 ($0.014) per kWh to N15.6 ($0.100) per kWh

Table 5. Range of specific cost of wind turbines based on the rated power (Adaramola *et al.,* 2011).

Wind turbine size kW	Specific cost $/kW	Average specific cost $/kW
<20	2200–3000	2600
20–200	1250–2300	1775
> 200	700–1600	1150

Table 6. Cost of energy output and water delivered by WPS using the selected wind turbines.

	S-343		G-3120		E-3120		WES18		WES30	
	$/kWh	$/m^3	$/kWh	$/m^3	$/kWh	$/m^3	$/kWh	$/m^3	$/kWh	$/m^3
Benin-city	1.014	26.299	0.143	5.314	0.279	7.251	0.856	22.199	0.434	11.249
Warri	2.114	54.845	0.247	9.145	0.513	13.299	1.589	41.23	0.790	20.491
P-Harcourt	0.847	21.974	0.130	4.829	0.243	6.309	0.707	18.344	0.362	9.391
Uyo	2.118	54.956	0.237	8.802	0.509	13.196	1.694	43.948	0.835	21.676
Calabar	0.553	14.344	0.090	3.325	0.162	4.210	0.535	13.874	0.271	7.031
Ogoja	0.665	17.250	0.120	4.437	0.206	5.343	0.595	15.442	0.307	7.978
Asaba	2.022	52.472	0.260	9.634	0.530	13.755	1.696	44.009	0.850	22.053

($1 ≈ N156, (www.xe.com)). Since, fixed base and meter charges are also added to the total cost of electricity consumed, the actual average cost of electricity is significantly higher than values quoted above.

The results of the LCOE in all the sites for selected wind turbines are illustrated in Table 6. The minimum cost of electricity is $0.090 at Ogoja using G-3120 wind turbine model, while the maximum cost is $2.118 at Uyo by employing S-343 wind turbine model. It is noted that irrespective of the site, G-3120 (35 kW) turbine model has the least cost of electricity. This observation is attributed to its high capacity factors as previously shown. Based on the assumptions used in this analysis, the wind turbine models G-3120 and E-3120 can be considered to be most economically viable options in all the sites, while other wind turbine models can be considered as marginally economically viable at the selected locations. Prior studies have shown that the cost of electricity can be reduced by increasing the number of wind turbines and their hub heights, that invariably will lead to higher energy output (Genc, 2011). Since, increasing the number of wind turbines and their hub heights can lead to higher initial cost of electricity, the option is not considered in the present study.

3.3.2. Cost of water delivered by WPSs

In Nigeria, access to reliable and quality water for domestic use is a major challenge for both the urban and rural dwellers. According to National Water Supply and Sanitation Policy (NWSSP, 2000), only about 42% of those living in the urban areas (i.e., with population of more 20,000) and semi-urban areas (i.e., with population between 5,000 and 20,000), and 29% of rural areas (i.e., with population of less than 5,000) have access to potable water supply. Therefore, most people in urban and semi-urban areas rely on private and commercial boreholes water and bottled water. While bottled water is generally used for drinking, borehole water is commonly used for all domestic activities (including drinking). The retail cost of water from commercial borehole water is about $2.668 per cubic metres (Onyenechere, 2011). The boreholes are either operated using electricity from the national grid or diesel generators. However, the electricity power outage and price of diesel oil can have significant impact on the cost of water delivered.

The cost analysis of the water delivered by WPSs using the selected wind turbines are also shown in Table 6. The cost of water delivered is found to vary from \$3.33 per cubic metres in Calabar by using G-3120 wind turbine model to \$54.96 per cubic metres in Uyo by using S-343 wind turbine model. Detailed information about the cost of water delivered by WPS using each of the selected wind turbine models at each sites considered are illustrated in Table 6. In general, based on the assumptions used in this analysis, the WPSs with G-3120 and E-3120 are most economically viable options in all the sites (especially in Calabar and Ogoja). If the cost of bottled water and impact of electricity outage as well as price of diesel oil during fuel scarcity are incorporated into the cost of water delivered, the WPSs using each of the selected wind turbines in all the sites can be considered viable in this part of the country especially in rural areas (where extension of national grid is either not practical or expensive).

4. CONCLUSIONS

This study investigates the wind power potential, the economic analysis of several wind turbine models of various rated powers ranging from 5.2 kW to 250 kW, and the cost of water delivered using these turbine models for seven meteorological sites, located in the southern part of Nigeria, namely Asaba, Calabar, Ogoja, P-Harcourt, Uyo, Benin-City, and Warri. The hourly wind speed data obtained from the Nigerian Meteorological Agency for these sites were analysed using the two-parameter Weibull probability density function and the cost analysis by levelised cost method. The results of the analyses yield the following conclusions:

- The annual mean wind speeds are 3.51 m/s, 3.09 m/s, 3.56 m/s, 3.17 m/s, 4.15 m/s, 3.99 m/s and 3.39 m/s, respectively, for Benin-city, Warri, Port-Harcourt, Uyo, Calabar, Ogoja and Asaba, while the corresponding annual mean power densities are, respectively, 34.6 W/m^2, 23.17 W/m^2, 37.06 W/m^2, 24.72 W/m^2, 56.22 W/m^2, 52.19 W/m^2 and 30.85 W/m^2. Hence, the wind resource in all the sites considered fall into Class 1 wind resource category ($P_D \leq 100$). Therefore, wind resource in all the locations can marginally be considered for small scale standalone system for electricity generation.
- Wind turbine with design cut-in wind speed between 2.0 and 2.5 m/s and moderate rated wind speed of about 8–10 m/s will be appropriate for all the sites.
- Based on the economic analysis, the wind turbine models G-3120 and E-3120 are found to be most economically viable options in all the sites to be used for electricity generation and water pumping systems.

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