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Analysis of offshore wind energy potential for power generation in three selected locations in Nigeria

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The rise in the global carbon footprint arising from fossil fuel sources has necessitated the need to explore sustainable and eco-friendly sources of energy. Wind as a source of renewable energy has been underutilized in Nigeria and this study is focused on investigating the wind energy potential in three offshore regions of Nigeria. Three statistical models namely, Weibull, Rayleigh and Exponential distribution were used to analyze the daily time series wind data for the offshore regions in Lagos (VI), Rivers (Abonemma) and Warri (Koko). This was done for a 10-year period between the year 2002–2011. The annual mean wind speeds for Lagos (VI), Rivers (Abonemma) and Warri (Koko) were determined to be 6.25, 7.32 and 7.29 m/s, respectively. The annual mean wind power densities were determined to be 171.47, 240.43 and 237.60 W/m^2, respectively. The values of the wind speed carrying the maximum energy were determined to be 7.43, 8.37 and 8.96 m/s, respectively. It was found that the wind classes of the three locations are suitable for power generation.

Keywords: capacity factors, exponential distribution, Rayleigh distribution, Weibull distribution, wind speed, wind power density

Introduction

There are various energy based mineral resources in Nigeria. These include coal and crude oil, which serve as the major sources of power generation in Nigeria. However, these sources of energy are globally identified with emission of carbon dioxide (CO_2) into the environment. Regardless of the global campaign on greenhouse gas emission, carbon dioxide emission is still a challenge due to urban and industrial wastes that are associated with carbon. With the advancement in human population and industrialization, energy needs are growing exponentially, and over-reliance on fossil fuel sources constitutes to a continuous increase in environmental pollution. Renewable energy sources are therefore alternatives to reducing greenhouse gas emission. Renewable energies are those that can be generated from wind, waves, solar, tides, geothermal and bio-fuels. Wind is one of the renewable energy sources that may be harnessed in small, medium and commercial quantities (Carta, Ramirez, and Bueno 2008).

Wind has proven to be a reliable source of renewable energy which has seen increased global investment in wind farms. However, wind energy could only be exploited in areas with high wind speeds. Wind energy is used for electricity generation in United Kingdom (Crabtree et al. 2015), China (Brennand 2001), Belgium (Ryberg et al. 2018), Germany (Ryberg et al. 2018), and United States (Hitaj 2012) to mention but a few. A survey revealed that the total global installed capacity of wind power had increased from 6,100 MW in the year 1996 to about 237,669 MW in the year 2011(Global Wind Energy Council (GWEC) 2011). African countries have not substantially invested in the wind energy technology nor its use. In north Africa, countries such as Morocco, Tunisia and Egypt have made remarkable efforts on wind energy production with total installed capacities of 291, 114 and 550 MW, respectively (GWEC 2011). South Africa also made a remarkable effort in wind power generation with a total installed capacity of 2.078 MW in 2019 (ESI Africa 2019). East Africa regions offer more wind energy potential because of the coastal nature of the region and the highlands. Ethiopia and Kenya are the only Eastern Africa countries utilizing wind for power generation with total installed capacity of 320 and 310 MW, respectively (Bishoge, Kombe, and Mvile 2020). In West Africa, Senegal is proposing to host the first ever mega windfarm while in Nigeria, wind turbines were installed in the north-western part of the country (Katsina state), but the wind turbines are not operational at the moment. A lot of work has been done aimed at characterizing the wind energy profile in different locations in the world in order to ascertain their suitability for wind power generation. Akpinar and Akpinar (2004) investigated the wind profile of Keban-Elazig area of Turkey using Weibull and Rayleigh probability distribution functions (PDFs) for a five-year period between the years 1998 and 2002. Results obtained from Goodness-of-fit showed that Weibull distribution model is best for fitting the available wind data and the area under consideration possess low wind power capacity and could only be used to generate low power for application such as water pumping and battery charging. Azad et al. (2014) statistically analyzed wind speed data from Hatiya Island in Bangladesh using Weibull distribution. The outcome of the analysis showed that more than 58% of the total hours in a year have wind speed above 6 m/s in the region under consideration. It was concluded from the study that the site has enough available wind power to drive a small wind turbine for power generation. Dahbi,

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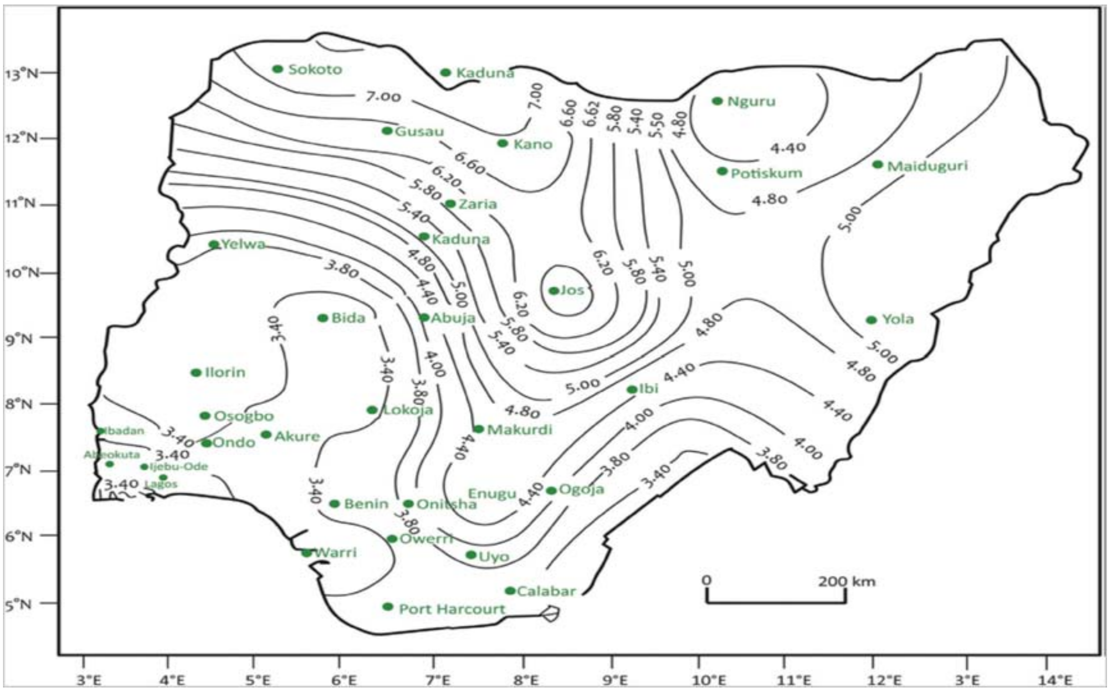

Figure 1. Wind speed in m/s determined from 40 year's measurements at 10 m height.
Source: NIMET 2009

Benatiallah, and Sellam (2013) reported on the analysis of wind energy potential in Sahara site of Algeria using Weibull distribution while a simulation model was developed to observe the characteristics of a specific wind turbine. Maximum wind power of 428 and 128 W/m^2 were evaluated for the month of July and September, respectively, while the proposed simulation model was found applicable for assessing wind power potential in the site. Sumair et al. (2020) investigated wind energy potential from eleven different sites in Pakistan using Weibull probability distribution function. Combined energy pattern and power density method was developed to evaluate the two parameters needed to define Weibull distribution while the result was compared with energy pattern factor and power density method. The outcome of the study shows that the combined method is more efficient while the energy power factor is the least efficient. Other related researches include those reported in Safari (2011), Zhou, Erdem, and Shi (2010), McQuarrie and Tsai (1998), and Dokur and Kurban (2015).

At the moment, wind energy is not extensively used for power generation in Nigeria due to over reliance on fossil fuel and hydropower. However, the supply of liquefied natural gas to thermal power plants is inadequate while the shortcoming of hydropower is associated with its dependence on water levels which vary seasonally. As such, there is the need for other sources of energy. Some areas in Nigeria are rich in wind resources such as the hilly part of the North and the offshore areas of the South-South, South-East and South-West. The variation in onshore wind characteristics in Nigeria is depicted in Figure 1. However, it may not be an easy task to locate the optimal wind farm sites in these areas due to associated factors such as very high or low wind speeds, turbulence and designing a suitable turbine to match the wind characteristics and other environmental constrains such as overhead lines, land ownership boundaries, distance from roads, proximity of communication signals amongst others within the areas.

Several research investigations on wind speed characteristics and the possible potential for wind energy generation in different locations in Nigeria have been conducted. The studies were carried out considering different locations in Nigeria. For example, Ajayi and Katende (2011) analyzed twenty-one years (1987–2007) of mean wind speed data of Iseyin and Shaki in Oyo State Nigeria using the Weibull 2-parameter distribution. The data were measured using a cup generator anemometer at 10 m above ground level and the analysis of the wind characteristics showed that the average wind speeds range of 3.2–5.1 m/s for Shaki, while that of Iseyin was found to be 2.9–4.7 m/s. More recently, the wind characteristics of five more cities (Abuja, Bida, Ilorin, Jos, Lokoja, Markudi and Minna) in Nigeria were investigated (Ajayi et al. 2017) for the same twenty-one year (1987–2007). The data were analyzed using different statistical tests and were compared with the 2-parameter Weibull probability density function. Ojosu and Salawu (1990) investigated wind energy potential in Nigeria for power generation using twelve different sites while Igbokwe and Omekara (2002) carried out a stochastic simulation of hourly average wind speed in Umudike, South-East Nigeria. Chinedum, Chinekerem, and Anthony (2013) carried out logistic analysis of Nigeria offshore windfarm. Significant studies have been carried out regarding the potential for wind power generation in some other areas in Nigeria. These include the ones reported for wind potentials in Enugu, Owerri, Onitsha (Oyedepo, Adaramola, and Paul 2012) and in Plateau (Ahmed, El-Suleiman, and Nasir 2013), as well as those reported in Maiduguri (Ngala, Alkali, and Aji 2007) and in Port-Harcourt (Okechukwu, Larry, and Bode 2013).

These studies have shown the viability of wind energy for power generation in Nigeria. However, some feasibility studies need to be critically studied so as to reduce uncertainties in wind resource estimates in a particular region. In order to achieve this, several probability density distribution such as; Weibull distribution, Rayleigh distribution, Exponential distribution, Gamma distribution, Inverse Gaussian and Lognormal distribution been employed in different regions of the world (Lawan et al. 2015). The model(s) that bests fit the wind data set from the aforementioned regions have also been identified (Akgül, Senoglu, and Arslan 2016). It is therefore important to note that wind accessibility and the corresponding model is site dependent.

Among the available PDFs, the two parameter Weibull model is widely used due to its ability to give better fit for estimated monthly probability density distribution compared to other models (Justus et al. 1987). However, certain limitations such as inability to capture low wind speeds thereby causing underestimation in terms of power production (Carta, Ramirez, and Velazquez 2009; Greene and Morrissey 2011) is associated with the model, hence the need for further modification of the model into a three parameter model to better represent wind ranges with high percentages of null wind speeds to give better results (Wais 2017). In this study, the two parameter Weibull probability distribution function, Rayleigh and exponential distributions were applied to analyze wind data from Lagos (VI), Warri (Koko) and Rivers (Abonemma) located in the south-west and south-south regions of Nigeria while Goodness-of-fit of each PDFs were determined to ascertain the model that best fit the available wind data. The results of the analyses have been employed to estimate the anticipated performances of four commercial wind turbines within the stipulated regions. This study is in line with the Nigeria renewable energy masterplan which seeks to increase the supply of renewable energy from 13% of total power generation in the year 2015 to 23% in 2025 and 36% by 2030 (International Energy Agency 2013). This work may therefore serve as a source of reference for researchers as well as government, key players and investors in the wind energy sector in making decisions regarding wind power generation within the identified locations in Nigeria.

Data collection and analysis

Hourly time series wind data set for offshore areas of Lagos (VI), Rivers (Abonemma) and Koko (Warri) for a ten-year period (2002–2011) were obtained from Nigerian Meteorological Agency (NIMET), in Oshodi Lagos. The geographical coordinate of the location are as follows: Lagos marine (VI) (Latitude 06.26′N, Longitude 03.25′E, and Elevation of 2.0), Rivers (Abonemma) (Latitude 04.51′N, Longitude 07.01′E, and Elevation of 19.5) and Warri (Koko) (Latitude 05.31′N, Longitude 05.44′E, and Elevation of 6.1). Topographical maps of the three locations are shown in Figures 2–4.

The wind data were measured using a cup anemometer attached to a buoy system at 10 m above sea level. The measured wind speeds were obtained in hourly series format for 24 hours and then averaged for a day. The daily averages were used to compute average monthly wind speed. Based on the principle that all meteorological parameters have a diurnal cycle (Voiculescu et al. 2020), data gaps were identified and wind

Figure 2. Map showing Victoria Island in Lagos state, south-west Nigeria at lat. 06.26′N, long. 03.25′E.
Source: Reproduced with permission from Yusuf and Abiye (2019), copyright Elsevier, 2020

Figure 3. Abonnema in River State, south-south Nigeria at lat. 04.51′N, long. 07.01′E.
Source: Google map

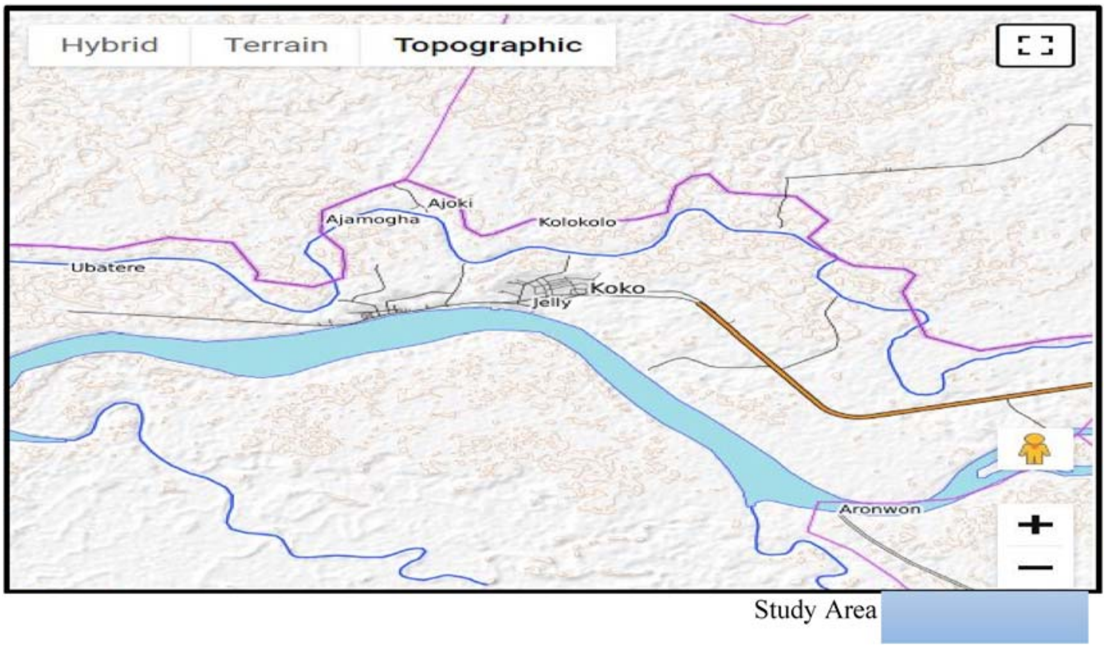

Figure 4. Warri (Koko), South-South Nigeria at lat. 05.31′N, long. 05.44′E.
Source: Google map

speed for the previous five days were averaged and used to fill the gaps. A complete year was defined as having 90% to 95% percent valid data. At 95% confidence level, the uncertainty in the mean wind speed within the three locations was determined to be ±3. The Nigerian Meteorological Agency record wind, rain, precipitations, temperature and other meteorological data every hour and publish the average every year. In accordance with the regulation of World Meteorological Agency (WMO 2017), thirty-year average weather variable is adopted by NIMET as an average baseline to evaluate climate events and provide structure of year-to-year variables.

Wind speed distributions

Weibull, Rayleigh and Exponential probability distribution models were used to analyze the collected wind data. The parameters of these probability distribution models as well as their goodness of fit were also determined. Wind power densities, wind speed carrying the maximum energy and most probable wind speed were also determined using the model that best fit the collected wind data. Four commercial wind turbine models of different configurations were selected. The result of the analysis was used to simulate their performance by determining wind power output and capacity factors; in order to test the economic viability and suitability of installing the wind turbines within the investigated locations. The theoretical analyses of the models used are outlined in the sections that follow.

Weibull distribution

The Weibull Probability Density Function (PDF) is given as (Kose 2003):

$$f(v) = (k/c)(v/c)^{(k-1)}\exp[-(v/c)^k] \qquad (1)$$

where $f(v)$ is the probability of observing wind speed; v, k and c represent the shape and scale parameters of Weibull distribution. The shape parameter is dimensionless while the scale parameter is measured in m/s.

Similarly, the Weibull Cumulative Density Function (CDF) is given as (Persaud, Flynn, and Fox 1999):

$$f(v) = 1 - \exp[-(v/c)^k] \qquad (2)$$

Estimating the parameters of Weibull distribution requires a good fit of Equation (2) to the recorded discrete cumulative frequency distribution. Taking natural logarithm of both sides of Equation (2) twice gives:

$$\ln\{-\ln[1 - F(v)]\} = k\ln(v) - k\ln c \qquad (3)$$

Therefore, the plot of $\ln\{-\ln[1 - F(v)]\}$ versus $\ln v$ gives a straight line. The slope of the line is k, and the intercept with the y-axis is $-k\ln c$. Other methods applied in the determination of Weibull distribution parameters are; Method of Moment (MOM), Maximum Likelihood Method (MLM), Empirical Method (EM) and Power Factor Method (PFM).

Rayleigh distribution

The PDF of Rayleigh distribution is given as (Brano et al. 2011):

$$f(v) = 2v/c^2\exp[(-v/c)]^k \qquad (4)$$

The corresponding CDF is given as (Brano et al. 2011):

$$f(v) = 1 - \exp[-(v/c)^k] \qquad (5)$$

The shape parameter of Rayleigh distribution has a constant value of 2. The two parameters k, and c for both Rayleigh and Weibull distributions are closely related to the mean value of the wind speed as (Ulgen and Hepbasli 2002):

$$vm = c\Gamma(1 + 1/k) \qquad (6)$$

where $c\Gamma$ is the gamma function of () and v_m is the mean wind speed.

If shape and scale parameter of distribution have been calculated, wind energy estimation for the most probable wind speed and the wind speed carrying the maximum energy can be obtained. The most probable wind speed denotes the most frequent speed for a given wind probability and is expressed as (Chang 2011):

$$v_{MP} = c((k-1)/k)^{(1/k)} \qquad (7)$$

The wind speed carrying maximum energy amount of wind energy can be expressed as (Chang 2011):

$$v_{\mathrm{Max}}E = c((k+2)/k)^{(1/k)} \qquad (8)$$

Exponential distribution

For exponential distribution, the PDF is given as (Massera et al. 2012):

$$f(v) = 1/c - \exp(-v/c) \qquad (9)$$

and the corresponding CDF of Exponential distribution is given as (Massera et al. 2012):

$$f(v) = 1 - \exp(-v/c) \qquad (10)$$

Wind power density

The power of the wind that flows at speed v through a blade sweep area A increases as the cube of its velocity and is given by (Chang 2011):

$$P_v = 1/2\rho AV^3 \qquad (11)$$

where $P_v$is the aerodynamic power extracted from the airflow, ρ is the air density (typically 1.225Kg/m3). The monthly or annual wind power density per unit area of a site based on a Weibull probability density function can be expressed as follows (Celik 2003):

$$P_W = 1/2\rho c^3(1 + 3/k) \qquad (12)$$

Setting k equal to 2, the wind power density for Rayleigh density function is found to be given as (Celik 2003):

$$P_R = 3/\pi\rho v_m^3 \qquad (13)$$

The corresponding wind power density for exponential distribution in terms of the probability density and cumulative density functions is given as (Celik 2003):

$$P_E = 1/2\rho v^3 f(v) \qquad (14)$$

Evaluation of goodness of fit (GOF) of the three distribution models

In this study, three methods were employed to evaluate the goodness-of-fit of the distribution model used. These are root mean square error analysis (RMSE), Coefficient of Efficiency otherwise called chi-square (λ^2) and correlation coefficient (R^2). The expressions are as follows (Akpinar and Akpinar 2004):

$$R^2 = \sum_{i=1}^{n} (y_i - z)^2 - \sum_{i=1}^{n} (x_i - y_i)^2 / \sum_{i=1}^{n} (y_i - z)^2 \quad (15)$$

$$\lambda^2 = \sum_{i=1}^{n} (y_i - x_i)^2 / \sum_{i=1}^{n} (y_i - z)^2 \quad (16)$$

$$\mathrm{RMSE} = \left[1/N \sum_{i=1}^{n} (y_i - x_i)^{1/2} \right] \quad (17)$$

where y_i is the ith actual data, x_i is the ith predicted data with the Weibull distribution, N is the number of observations and n is the number of constants and z is the mean of actual data. Therefore, the best distribution function can be selected according to the highest value of R^2 and the lowest values of RMSE and λ^2 (Morgan et al. 2011).

Wind turbine power output and capacity factor

The capacity factor (Cf) of a wind turbine, is the ratio of the average delivered power to the rated electrical power (P_{eR}) of the wind turbine (Akpinar and Akpinar 2005; Balouktsis, Chassapis, and Karapantsios 2002). A wind energy conversion system can operate at its maximum efficiency only if it is designed for a particular site because the rated power and cut-in and cut-off wind speeds must be defined based on the site wind characteristics (Akpinar and Akpinar 2005). The performance of a wind turbine installed in a given site can be determined by the amount of average power output over a period of time (Pe,ave) and the conversion efficiency or capacity factor of the turbine. The capacity factor and mean power output of a wind turbine can be determined using the following expression based on Weibull distribution (Akpinar and Akpinar 2005):

$$CF = Pe, ave/PeR \quad (18)$$

$$Pe, ave = PeR$$

$$(e^{-(Vc/c)k} - e^{-(Vr/k)k}/(Vr/c)^k - (Vr/c)^k - e^{-(Vt/C)k}) \quad (19)$$

where V_c, V_r and V_t are the cut-in wind speed, rated wind speed and cut-off wind speed, respectively. Hence the capacity factor and the average power output are important parameters in wind energy conversion systems (WECs) (Oyedepo, Adaramola, and Paul 2012). It is therefore important to select these parameters so that the output from the WECs is maximized. The Weibull shape parameter and scale in relation to the wind turbine hub height can be determined using Equation 20 and 21 (Oyedepo, Adaramola, and Paul 2012):

$$k(h) = ko[1 - 0.088\mathrm{in}(ho/10)]/[1 - 0.088\mathrm{in}(h/10)] \quad (20)$$

$$C(h) = CO(h/ho)^n \quad (21)$$

The exponent n can be determined from Equation 22 (Ohunakin, Adaramola, and Oyewola 2011):

$$n = [0.37 - 0.088\mathrm{in}Co]/[1 - 0.088\mathrm{in}(h/10)] \quad (22)$$

Results and discussions

Evaluation of goodness of fit (GOF)

A comparison of the three models was done using Root Mean Square Error Analysis (RMSE), Coefficient of Efficiency (λ^2) and Correlation coefficient (R^2). The best performing model is the one with the highest value of (R^2) and lowest values of RMSE and λ^2 (Morgan et al. 2011). The results of GOF evaluated for each of the three locations are shown in Table 1. It can be seen from Table 1, that the highest values of R^2 and lowest value of RMSE and λ^2, was recorded for Weibull distribution. Rayleigh distribution also provides a good fit compared to exponential distribution. Hence the models with the best fit; Weibull and Rayleigh probability distribution models were used in determining the wind power densities while the wind speed carrying the maximum energy and most probable wind speed was calculated using Weibull distribution.

Mean wind speed and wind power density

The variations in the characteristics of monthly and annual wind speeds within the three locations are presented in Tables 2–4. From Table 2, the highest values of wind speeds were recorded for the month of March, April, July and August for Lagos (VI). It was also observed from Table 2 that the month of October, November and December exhibit the lowest wind speed with monthly average of; 4.80, 4.33 and 4.13 m/s, respectively. Similarly, the wind power densities show a large month to month variation. The monthly mean power densities vary between 43.036 W/m^2 in December and 383.392 W/m^2 in August. Therefore, based on Batelle-Pacific Northwest Laboratory (PNL) wind power classification scheme (Ilinca et al. 2003), mean power densities for the months of January, October, November and December fall into class 1 ($P_D < 100$). Wind power densities for the months of May and June fall into class 2 ($100 < P_D \leq 150$). For the month of September, the estimated wind power density belongs to class 3 ($150 < P_D \leq 200$), while February wind power density belong to class 4 ($200 < P_D \leq 250$). High wind power densities were obtained in the months of March, April and July with all belonging to Class 5 ($250 < P_D \leq 300$). The highest wind power density was obtained for the month of August belonging

Table 1. Evaluation of goodness of fit of the three models used.

Locations	Model type	R^2	RMSE	λ^2
Lagos	Weibull distribution	0.9939	0.0068	0.0061
	Rayleigh distribution	0.4228	0.0664	0.5772
	Exponential distribution	−0.5773	0.1098	1.5773
Port Harcourt	Weibull distribution	0.979	0.0153	0.021
	Rayleigh distribution	0.2138	0.0937	0.7862
	Exponential distribution	−0.4202	0.1259	1.4202
Warri	Weibull distribution	0.9758	0.0176	0.0242
	Rayleigh distribution	0.1939	0.1016	0.8061
	Exponential distribution	−0.3678	0.1324	1.3678

Table 2. Wind speed and mean power density in Lagos Marine (VI).

Months	V (m/s)	k	c (m/s)	Vmp	VmaxE	$Pd(W/m^2)$ Actual	$Pd(W/m^2)$ Weibull	$Pd(W/m^2)$ Rayleigh
January	5.03	3.60	5.57	5.09	6.30	78.08	99.84	141.08
February	6.96	5.38	7.53	7.25	7.99	206.08	232.96	348.19
March	7.64	5.02	8.30	7.95	8.88	272.80	313.27	466.23
April	7.42	4.45	8.14	7.69	8.85	250.66	298.44	438.83
May	6.21	4.41	6.81	6.43	7.42	146.96	175.32	257.49
June	5.97	4.22	6.55	6.14	7.18	130.33	156.50	228.49
July	7.66	4.52	8.40	7.95	9.11	274.98	328.08	483.28
August	8.55	5.09	9.31	8.91	9.93	383.39	440.50	656.19
September	6.31	4.24	6.93	6.51	7.60	153.96	185.79	271.34
October	4.80	4.14	5.28	4.94	5.81	67.62	82.38	119.85
November	4.33	4.59	4.77	4.52	5.16	49.79	59.69	88.09
December	4.13	4.17	4.50	4.21	4.94	43.04	50.94	74.20
Annual	6.25	4.49	6.84	6.47	7.43	171.47	177.17	260.79

V, mean wind speed; k, dimensionless Weibull shape parameter; c, Weibull scale parameter in m/s, Vmp, most probable wind speed; VmaxE, wind speed carrying maximum energy; Pd, wind power density.

Table 3. Wind speed characteristic speeds and mean power density in Rivers (Abonemma).

Months	V (m/s)	k	C	Vmp	VmaxE	$Pd(W/m^2)$Actual	$Pd(W/m^2)$Weibull	$Pd(W/m^2)$Rayleigh
January	7.30	6.35	8.13	7.92	8.49	238.37	291.77	437.94
February	7.22	5.81	7.87	7.62	8.28	230.68	264.98	397.20
March	7.23	6.00	7.81	7.58	8.20	231.36	258.92	388.39
April	7.26	5.71	7.92	7.66	8.35	234.77	270.13	404.70
May	7.20	6.25	7.84	7.63	8.20	228.46	261.65	392.69
June	7.34	6.38	7.98	7.64	8.33	241.86	275.72	413.85
July	7.40	6.32	8.12	7.90	8.48	247.67	290.46	435.96
August	7.41	6.35	7.99	7.78	8.35	249.08	277.15	415.99
September	7.35	6.61	8.08	7.88	8.41	243.24	286.31	429.75
October	7.33	6.55	7.93	7.73	8.26	241.57	270.74	406.40
November	7.54	6.45	8.15	7.94	8.49	262.56	293.13	440.00
December	7.29	6.95	8.34	8.15	8.65	236.89	314.45	471.81
Annual	7.32	6.31	8.01	7.80	8.37	240.43	279.25	419.13

V, mean wind speed; k, dimensionless Weibull shape parameter; c, Weibull scale parameter in m/s, Vmp, most probable wind speed; VmaxE, wind speed carrying maximum energy; Pd, wind power density.

to Class 7 ($350 < P_D \leq 400$). The wind power density calculated according Weibull and Rayleigh probability distribution model is also shown in Table 2. It can be seen that the Rayleigh distribution returns a wide variation in wind power density in comparison to the actual. This was as a result the wide discrepancy in the probability distribution representing them as inferred by Akpinar and Akpinar (2004). The corresponding values of the monthly and annual values of Weibull shape and scale parameters are also shown in the Table 2. These parameters are responsible for the variation in the PDF and CDF calculated according to Weibull and Rayleigh probability distribution models.

For Rivers (Abonemma) data as shown in Table 3, the highest value of wind speed was obtained in the month of November with a wind speed of 7.54 m/s. A comparison between the values of wind power densities from Tables 2 and 3 shows that smaller variations exist between the values of wind power densities in Rivers (Abonemma) compared to that of Lagos (VI). The monthly mean power densities vary between 228.46 W/m^2 in May and 262.56 W/m^2 in November. Therefore, based on PNL wind power classification scheme (Ilinca et al. 2003), wind power densities for the entire months falls within class 4 ($200 < P_D \leq 250$) except for the summer month of November that fall

Table 4. Characteristic speeds and mean power density in Warri (Koko).

Months	V (m/s)	k	c	Vmp	VmaxE	$Pd(W/m^2)$ Actual	$Pd(W/m^2)$ Weibull	$Pd(W/m^2)$ Rayleigh
January	7.19	6.39	7.71	7.51	8.05	227.48	248.79	373.44
February	7.29	6.60	7.81	7.62	8.13	237.19	258.58	388.13
March	7.25	6.52	7.78	7.58	8.10	233.67	254.90	382.62
April	7.33	6.53	7.86	7.66	8.18	241.04	263.01	394.79
May	7.37	6.81	7.89	7.71	8.19	245.00	266.65	400.17
June	7.40	7.29	7.89	7.73	8.32	247.76	266.63	399.73
July	7.38	7.32	8.35	8.18	8.63	246.61	316.06	473.79
August	7.35	7.23	7.95	7.78	8.22	242.91	272.46	408.54
September	7.25	6.91	8.26	8.07	8.57	233.19	305.37	458.20
October	7.18	6.67	8.36	8.16	8.70	226.70	317.16	476.04
November	7.24	6.93	8.77	8.58	9.10	232.19	366.57	550.03
December	7.30	6.63	8.61	8.40	8.96	238.30	346.31	519.81
Annual	7.29	6.82	8.10	7.93	8.41	237.60	288.62	433.12

V, mean wind speed; k, dimensionless Weibull shape parameter; c, Weibull scale parameter in m/s, Vmp, most probable wind speed; VmaxE, wind speed carrying maximum energy; Pd, wind power density.

in class 5 ($250 < P_D \leq 300$). The annual wind power density in terms of Weibull and Rayleigh distribution model are 279.25 and 419.13 W/m^2, respectively. For Warri (Koko) (Table 4), the highest value of mean wind speed was observed in the month of June with a mean speed of 7.40 m/s. The variation in wind speed within this location shows that the wind blows in regular pattern throughout the year as asserted by Akpinar and Akpinar (2004).

From Table 4, the monthly mean power densities vary between 247.76 W/m^2 in June and 226.70 W/m^2 in October. Therefore, based on PNL wind power classification scheme, all the monthly wind power densities belong to class 4 ($200 < P_D \leq 250$). From Tables 2–4, the values of k and c across the three location range between $3.6 \leq k \leq 7.32$ and $4.5 \leq c \leq 9.31$ m/s, respectively and according to (Kollu et al. 2012). The observed high values of the k and c indicates a data spread in the normal distribution and the data spread shows good consistency. According to Ajayi et al. (2014), the values of the scale parameter shows how windy a location is while the corresponding scale parameter shows how peaked is the wind distribution.

Wind speed probability distributions

The annual PDF and CDF representing the three locations estimated using Weibull distribution functions are illustrated in Figures 5–10, respectively. According to Akpinar and Akpinar (2004), Chinedum, Chinekerem, and Anthony (2013) and Fadare (2008), the probability density function is used to describe the period for which given wind speeds prevail in a location while the cumulative distribution is used for estimating the time for which wind speed is certain at a specified wind speed interval. From Figures 5–10, it can be seen that the peak of PDF and CDF curves obtained using Weibull probability density functions skewed towards higher values of mean wind speed. This is also similar to results obtained from different studies; with the curves showing similar tendencies towards wind speed distribution (Akgül, Senoglu, and Arslan 2016; Akpinar and Akpinar 2004; Amaya-Martínez, Saavedra-Montes, and Arango-

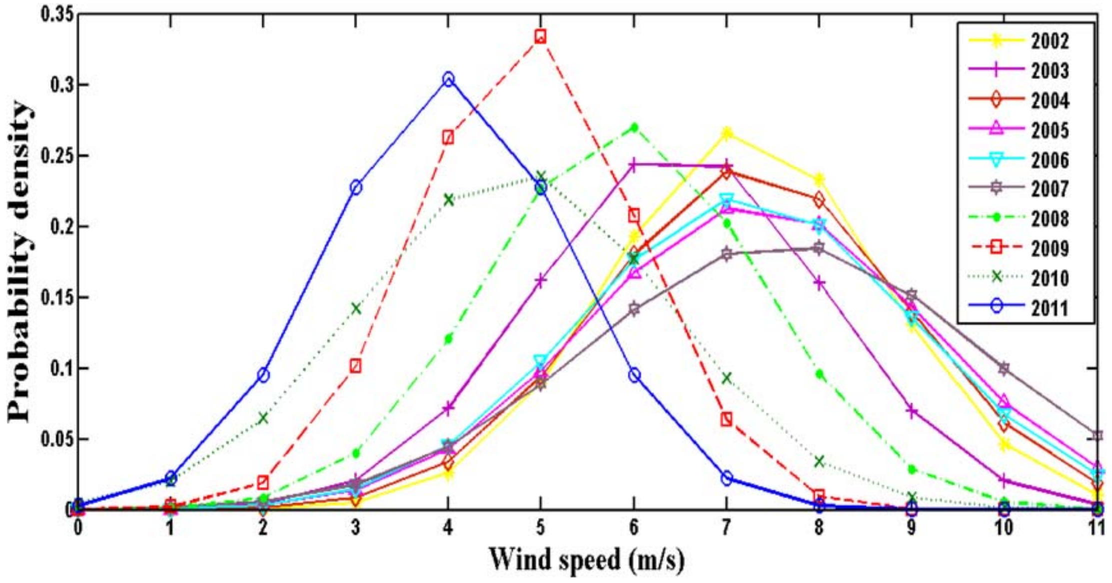

Figure 5. Yearly Weibull PDF calculated from the daily time series data for Lagos (VI).

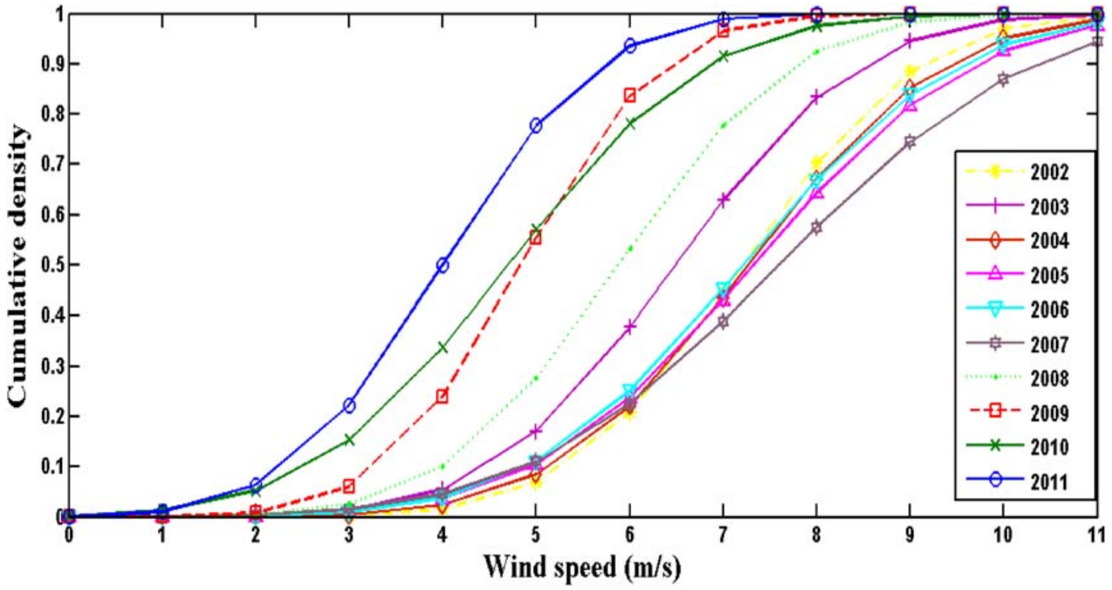

Figure 6. Yearly Weibull CDF calculated from the daily time series data for Lagos (VI).

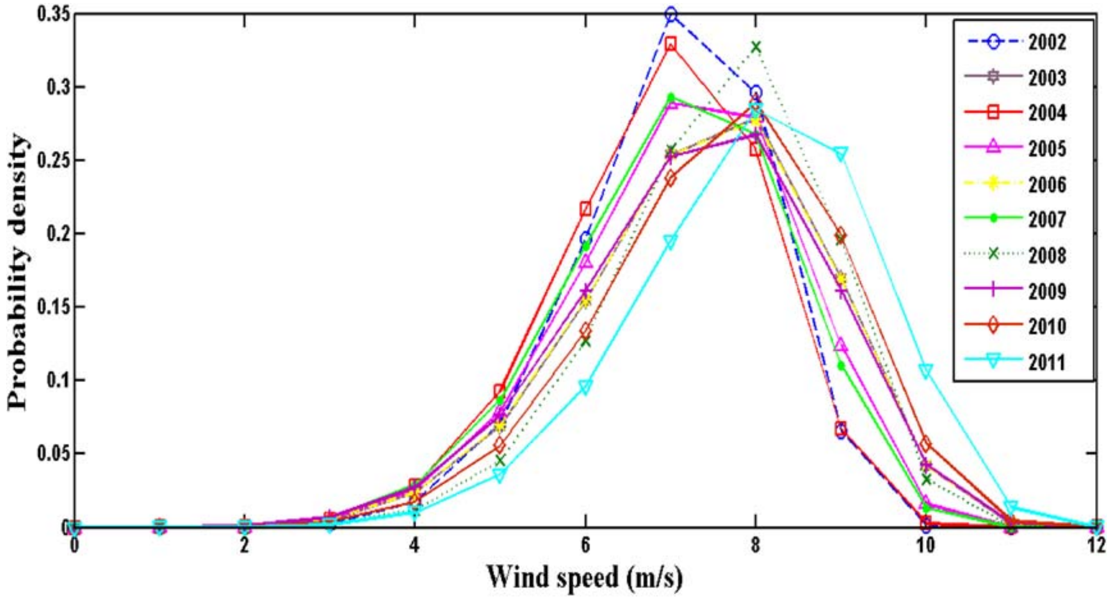

Figure 7. Yearly Weibull PDF calculated from the daily time series data for Rivers (Abonemma).

Zuluaga 2014; Dokur and Kurban 2015; Ojosu and Salawu 1990). The peak of the probability density functions curve depicts the most probable wind speeds as presented in Tables 2–4 with 8.91, 8.15 and 8.58 m/s for Lagos (VI), Rivers (Abonemma) and Warri (Koko), respectively.

The plots representing the probability density distributions estimated for the three locations using Rayleigh and Exponential distributions are presented in Figures 11–16. From the Weibull PDF and CDF representing Lagos (VI), it can be seen that about 89.9% of the data ranges between 4.17 m/s to 7.35 m/s hence the predominant wind speeds are obtainable within this spectrum while for Rivers (Abonemma), 94.95% of the wind data range between 7.04 and 7.88 m/s. In the case of Warri (Koko), 80% of the wind data range between 6.95 and 7.78 m/s.

Seasonal variation of the wind speed was estimated for the three locations. This was accomplished by dividing the twelve months in the year into rainy and dry seasons, i.e., April–October (rainy season) and November–March (dry season). This was done to ascertain the season with the highest possible wind speed and output power density. The results of the seasonal variation in wind speed and power density of the three stations are shown in the Table 5. The rainy season produced better average wind speed and wind power density profiles than dry season for all the three stations. These findings are also similar to a study reported in Ajayi et al. (2014).

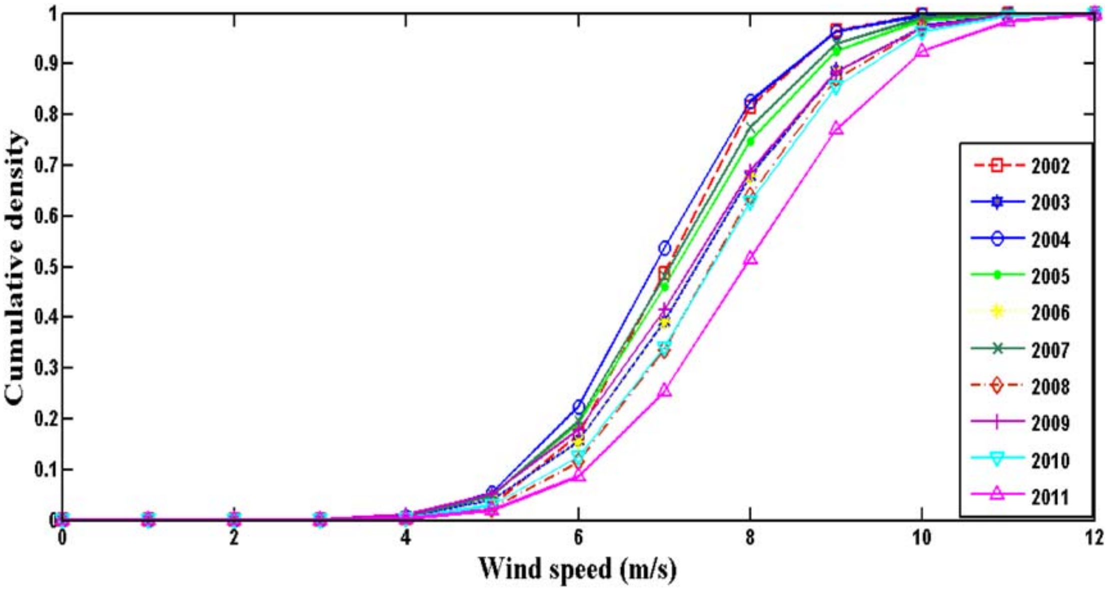

Figure 8. Yearly Weibull CDF calculated from daily time series data for Rivers (Abonemma).

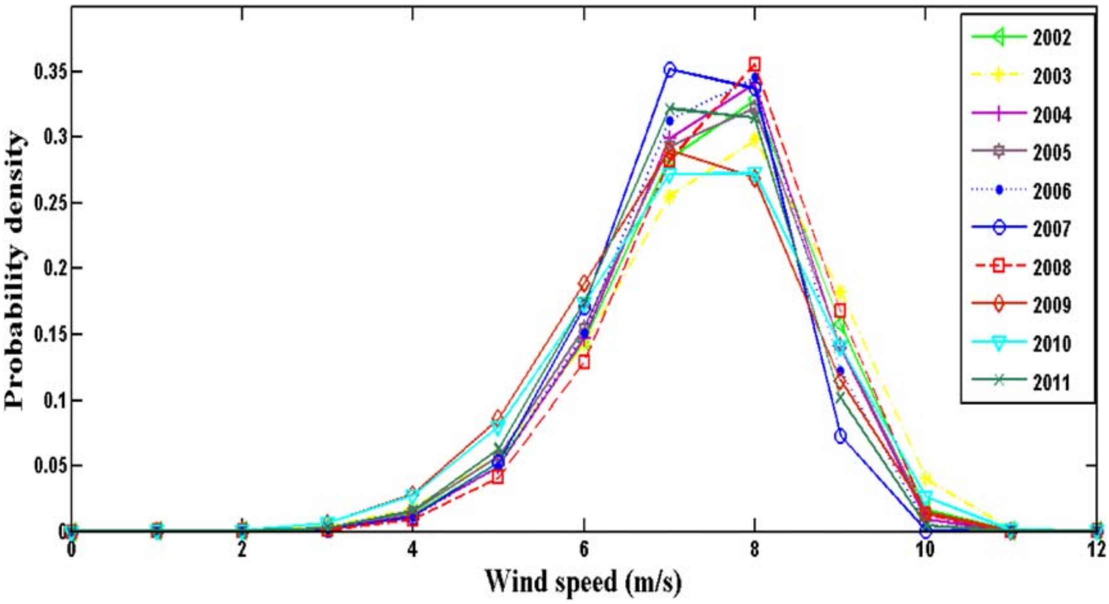

Figure 9. Yearly Weibull PDF calculated from daily time series data for Warri (Koko).

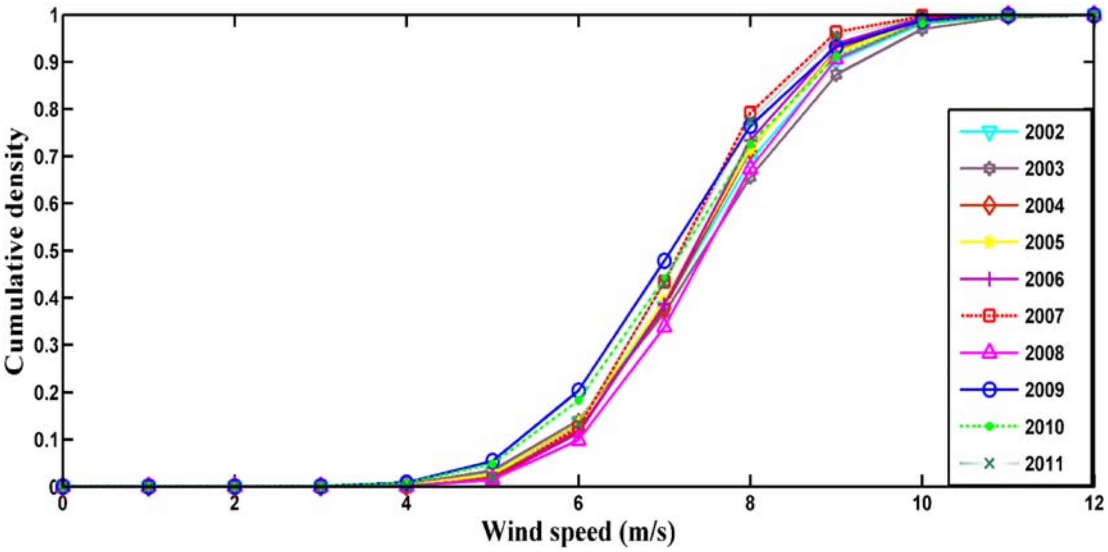

Figure 10. Yearly Weibull PDF calculated from the daily time series data for Warri (Koko).

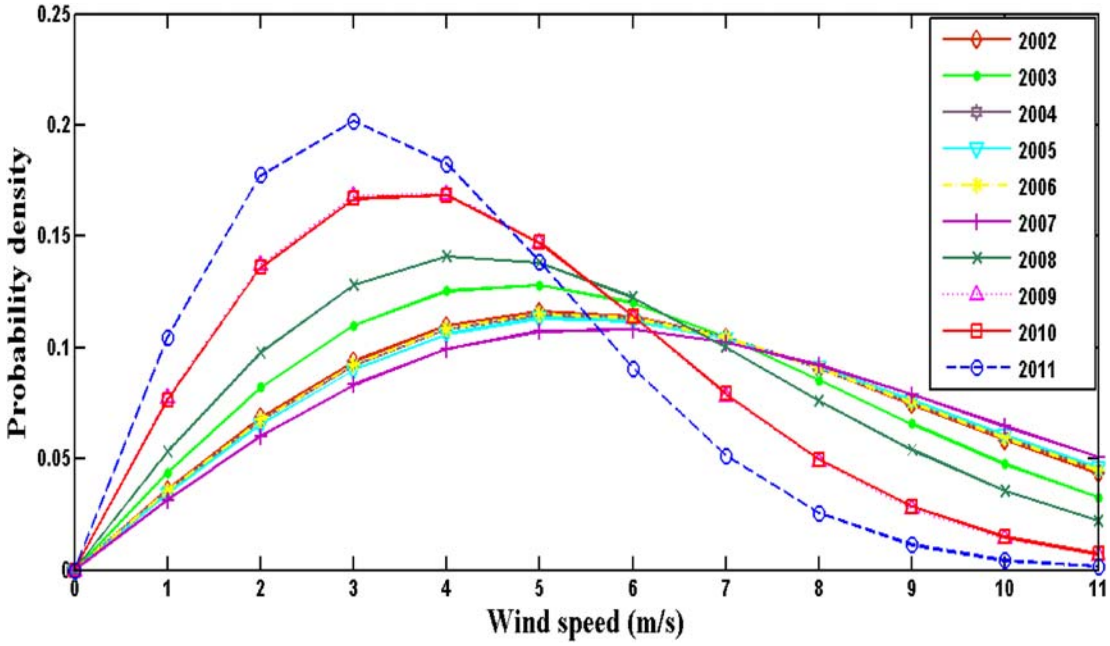

Figure 11. Yearly Rayleigh PDF calculated from the daily time series data for Lagos (VI).

Performance of selected turbines

Four medium-to-large size commercial wind turbine models, namely, Polaris 62-100, Suzlon S66, DeWind D6 and D48, with rated power from 600 to 1250 kW were selected and matched to the wind profiles of the three locations that were investigated. This was to determine the obtainable power output assuming the turbines are installed within the locations. The wind profile presented in this paper is at 10 m hub height above sea level and since the turbine hub heights are above 10 m, Equations 20 and 21 were used to obtain the value of k and c corresponding to the turbine hub height. The technical characteristics of the selected turbines are shown in Table 6.

The value of k and c obtained were used to determine the turbine performance by estimating their average power output and capacity factor. The results are presented in Table 7. The annual power output for Lagos ranges from 1735 MWh/Year to 4797 MWh/year with the DeWind D6 turbine. The highest power output was observed for DeWind D6 turbine (4797 MWh/year), followed by Polaris P62-1000 (3705 MWh/year) and Suzlon S66 while DeWind 48 produced the least power output (1753 MWh/year). These observed trends in the value of the power output were as a result of the differences in turbine hub heights and rotor diameters which are both lowest for DeWind D48 model (Table 6). The rated wind speed was highest for Suzlon S66 model

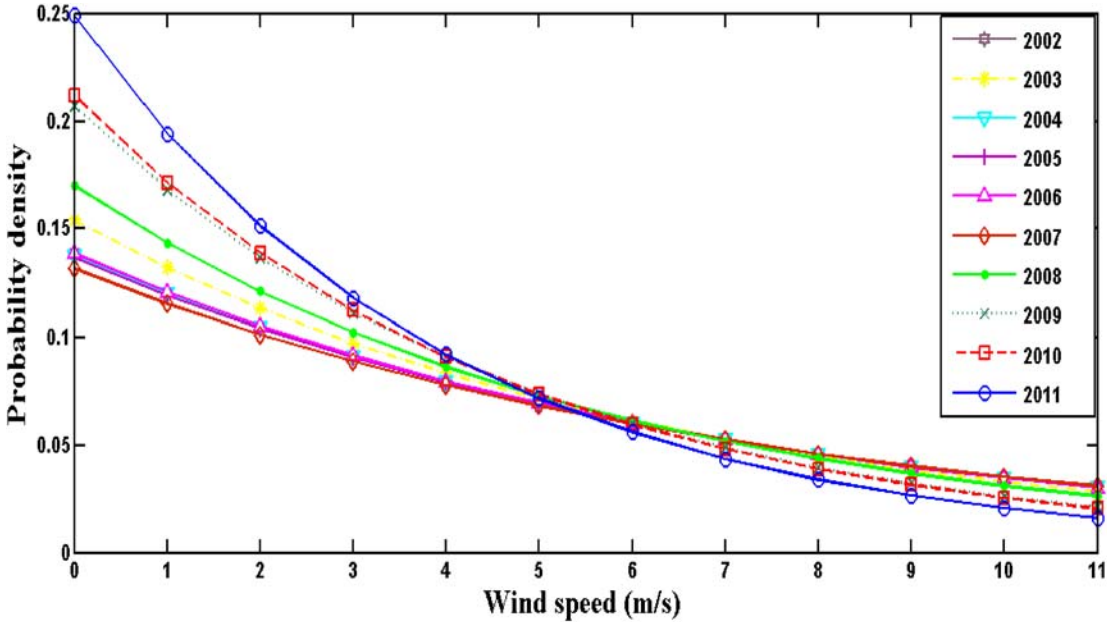

Figure 12. Yearly Exponential PDF calculated from the daily time series data for Lagos (VI).

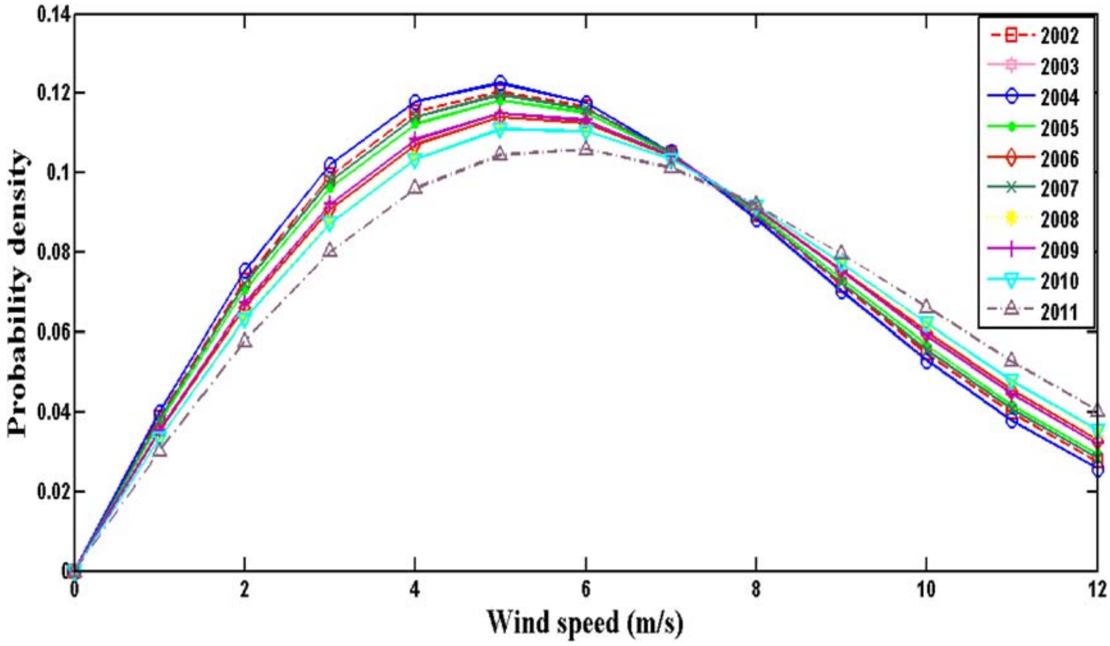

Figure 13. Yearly Rayleigh PDF calculated from the daily time series data for Rivers (Abonemma).

which is 14m/s, and the cut in wind speed was highest for Suzlon S66model, 3 m/s (Akpinar and Akpinar 2005; Oyedepo, Adaramola, and Paul 2012). However, despite the higher hub height of Suzlon S66 model, DeWind D6 and Polaris 62-1000, produced more power output in the three locations. This could be due to the lower cut-in wind speed and rated wind speed of DeWind D6 and Polaris 62-1000 models (Oyedepo, Adaramola, and Paul 2012). DeWind D48, Polaris p62-1000, DeWind D6 and Suzlon S66 produced the highest power output (2671, 5536, 6512 and 4227 MWh/Year) using data from Warri (Koko). This could be attributed to the location (Warri) having the highest value of the most probable wind speed and wind speed carrying the maximum energy compared to the other two locations.

In order to determine the cost effectiveness of these wind turbines, the capacity factors were determined for each of the locations. According to Celik (2003) the cost effectiveness of a wind turbine can be roughly estimated by the capacity factor. A minimum recommended capacity factor of 25% is required for an investment in wind turbine installation to be economically feasible (Oyedepo, Adaramola, and Paul 2012). From Table 7, it can be seen that Polaris P62-1000 has higher capacity factor values of 62.1% and 63.5% particularly for Port-Harcourt and Warri, respectively. Generally, the capacity factors as shown in Table 7 are greater than the suggested

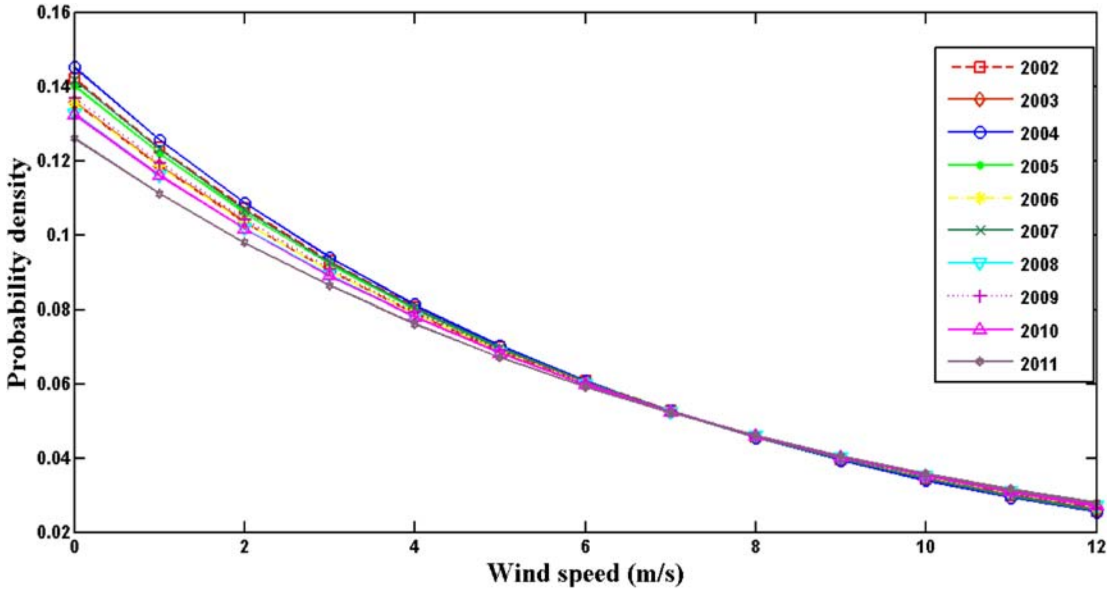

Figure 14. Yearly Exponential PDF calculated from the daily time series data for Rivers (Abonemma).

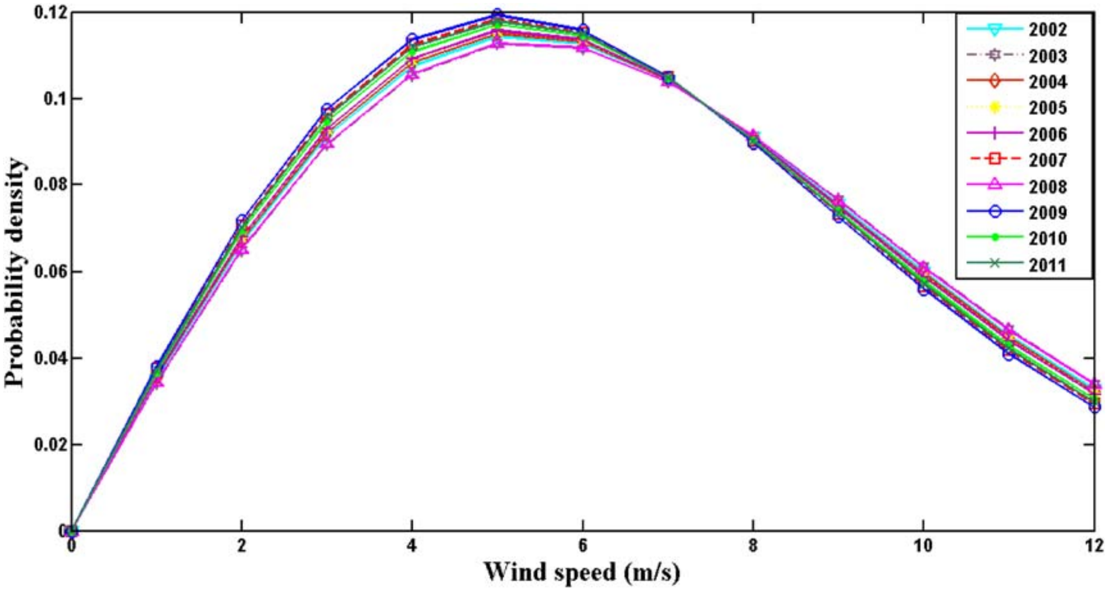

Figure 15. Yearly Rayleigh PDF calculated from the daily time series data for Warri (Koko).

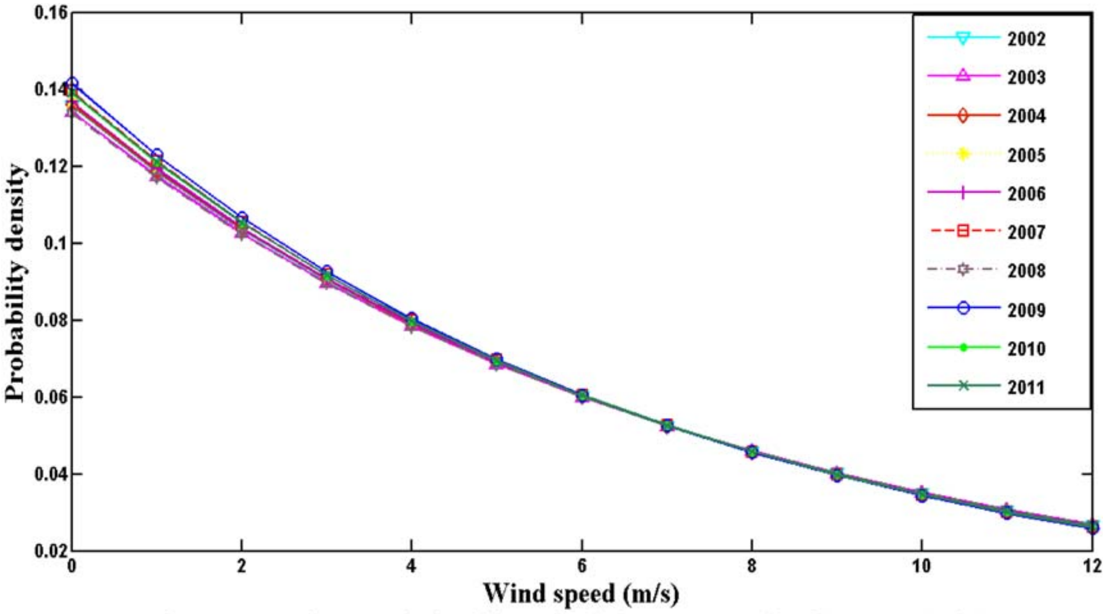

Figure 16. Yearly Exponential PDF calculated from the daily time series data for Warri (Koko).

recommended value of 25% before an investment can be considered viable. It has been asserted that the cost of generating electricity using wind turbine is inversely proportional to the capacity factor, hence the higher the capacity factor, the lower the cost of electricity generated (Diyoke 2019). The observed high-capacity factor of some of the wind turbines above is as a result of the high value of the wind speed values. Based on the annual energy output and capacity factor, Polaris 62-1000 and DeWind D6 model or wind turbine with

Table 5. Seasonal wind characteristics for Lagos (VI), Rivers (Abonemma) and Warri (Koko).

Locations	Season	V_m (m/s)	k	c (m/s)	$P_D (w/m^2)$
LAGOS	Rainy season	6.704	4.438	6.704	184.543
	Dry season	5.617	4.553	5.617	108.526
P H	Rainy season	7.327	6.31	7.982	240.887
	Dry season	7.315	6.313	8.06	239.785
WARRI	Rainy season	7.332	6.966	8.071	240.458
	Dry season	7.253	6.614	8.137	233.765

Table 6. Characteristics of some selected wind turbines.

	DeWind 48	Polaris p62-1000	DeWind D6	Suzlon S66
Rated power (kw)	600	1000	1250	1250
Hub height (m)	40	60	65	72
Rotor diameter (m)	48	62	62.3	66
Cut-in wind speed (m/s)	2.5	2.5	2.8	3
Rated wind speed (m/s)	11.5	12	12.5	14
Cut-out wind speed (m/s)	25	25	25	22

Table 7. Performance of the four selected commercial wind turbines.

Locations	Parameters	DeWind 48	Polaris p62-1000	DeWind D6	Suzlon S66
Lagos	P(e,ave) MwH/yr	1753	3705	4797	2946
	Cf (%)	33.3	42.3	43.8	26.9
Port Harcourt	P(e,ave) MwH/yr	2313	5528	6306	4251
	Cf (%)	44.0	62.1	59.9	38.8
Warri	P(e,ave) MwH/yr	2671	5536	6512	4227
	Cf (%)	50.8	63.5	59.5	40.4

similar design characteristics appear appropriate for electricity generation in the three locations. By redesigning Suzlon S66 to operate at lower cut-in wind speed and lower rated wind speed, both the capacity factor and annual power output would significantly improve and make them more economically feasible for wind power generation within the three locations.

In the case of DeWind 48, an increased hub height may improve its power output and corresponding capacity factor, but may increase the overall capital cost of manufacturing the wind turbine. This could, however, be compensated for by increase in capacity factor and annual power output.

Conclusions

The potential for offshore wind power generation in Lagos (VI), Warri (Koko) and Port Harcourt (Abonemma) using Weibull, Rayleigh and Exponential probability distribution models was investigated. Based on the considered models, it may be concluded that there is good potential for wind power generation within the three locations considered. The following conclusions can be drawn;

1. The three locations analyzed present good wind characteristics. This is shown by the monthly and yearly mean wind speed and the power density values for the whole year.
2. Weibull distribution appears better in fitting the collected wind data compared to Rayleigh and Exponential distribution based on the results obtained from Root Mean Square Error analysis (RMSE), Coefficient of Efficiency (R^2) and chi-square (λ^2).
3. The annual wind power densities for Lagos, Port Harcourt and Warri are 171.47, 240.43 and 238.29 W/m^2, respectively. It has been ascertained that of the three sites, the offshore area of Port Harcourt exhibits the most potential for wind power.
4. The wind power density of the three locations under consideration gave wind power that belongs to class 4. In accordance with the Batelle-Pacific Northwest Laboratory (PNL) wind power classification scheme, this class of wind power density is suitable for commercial wind power generation.
5. Based on the capacity factor and annual power output, DeWind D6 and Polaris 62-1000 model or wind turbine with similar design characteristics are recommended as the suitable turbines for wind power generation in the three locations.
6. It is recommended that up-to-date data should be adopted in future analysis as the analysis carried out in this study was based on currently available wind data.

Disclosure statement

No potential conflict of interest was reported by the author (s).

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