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Original Research Article

# Performance evaluation of wind turbines for energy generation in Niger Delta, Nigeria

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ABSTRACT

This paper evaluates wind energy potentials of seven selected locations spreading across Niger-Delta region of Nigeria using wind speed data that extend over 9 to 37 years and subjected to 2-parameter Weibull distribution functions. The performance of four wind turbine models ranging from 35 to 500 kW was simulated in all the locations considered. The results show that the performance of all the wind energy conversion systems gave the least energy output values at Ikom. In addition, annual energy output ranged from 4.07 MWh at Ikom to 145.57 MWh at Ogoja with Polaris America (100 kW) and Zeus Energy (500 kW) wind turbines respectively. It was also observed that, irrespective of the site, G-3120 (35 kW) wind turbine has the highest capacity factor among the models considered. Therefore, for wind energy development, G-3120 model or wind turbine with similar rated wind speed would be most suitable in all the locations. The number of inhabitants that can be served by the energy produced using G-3120 turbine in each location was estimated.



## 1. Introduction

Energy is vital to life and development; it is an essential input for economic development. Poverty alleviation and good living standards may be impossible without access to appreciable amount of energy. Despite the environmental impact of the conventional energy (fossil fuels) resources, fossil fuels still remain the major energy sources that play crucial role in meeting world energy demand. However, continuous exploitation of these resources will thus have significant impact on cost of life as well as the deteriorating environment due to greenhouse gas emission [1]. Management and rational utilization of convectional energy resources, together with full exploitation of renewable energy resources are thus very vital [2,3]. The rapid growth of industrialization and world population that led to the increase in energy demand, depletion of finite fossil fuel resources and climate change have made renewable energy resources increasingly attractive as alternative to continued overdependence on conventional energy sources [4]. The total world consumption of marketed energy is projected to increase by 57% for the period from 2004 to 2030. However, much of the world's energy is currently produced and consumed in such a way that the level of consumption cannot be sustained at the current level of technology [5]. Presently, access to electric power in Nigeria has been generally low with the challenge being more significant in the rural areas where only about 10% of the population have access to electricity [4]. It is also reported that about 51% of the entire populace reside in remote or rural areas, that have little or no access to electricity [4]. There is therefore the need for the immediate development and full exploitation of renewable energy resources for their contribution to the total energy mix. Some of these resources found to be in vast deposit in the country include: hydropower (large and small), solar radiation, wind, biomass (fuel-wood, animal and plant wastes), etc.

In Nigeria, detailed evaluation of renewable resources is a major concern and priority in the country; hence, some of these resources are yet to be exploited while the maximum utilization of others (especially wind energy resource) is not in view. Rapid growth in energy demand above production levels has therefore always been the impact of these resources under-utilization [2]. According to Ucar and Balo [3], wind energy is called to play a crucial role in the future energy supply of the European Union and of the world. There are now many thousands of wind turbines operating across the globe with a total installed capacity of 194,390 MW out of which in Europe alone, wind power accounts for about 44% as at the end of 2010 [6]. Wind energy contribution is insignificant in

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Nigeria; the extent of her wind power development is extensively discussed in [7].

Choice of a good site and wind are two major elements to consider in installing wind energy facilities. According to Elamouri and Amar [8], the choice of site, controls wind turbine performances while a good site is determined by the rate at which wind blows at the location. Therefore, accurate and reliable wind potential analysis tools are necessary for a good assessment of the available and recoverable potential [1]. Detailed knowledge of wind characteristics and distribution are also crucial parameters that are needed to select optimum wind energy conversion system (WECS) required to optimize energy output and minimize electricity generation cost [3]. From previous work carried out so far as discussed in literatures, e.g. [7,9–12], no reference was made to research work on performance of WECS for energy generation in the coastal region of the country. In this region, there is continuous search for alternative sources of energy due primarily to environmental degradation caused primarily by oil and gas activities in the zone. The task of this work is therefore, to evaluate the performance of wind turbines ranging in size from small to medium for power generation, within the Niger Delta region of Nigeria (Fig. 1) where oil and gas activities are concentrated.

## 2. Methodology and materials

### 2.1. Wind data used in the study

Wind data spanning between 9 and 37 years were obtained for Ikom, Ogoja, Calabar, Port Harcourt, Warri, Benin-city and Asaba at a height of 10 m by a cup-generator anemometer at the respective meteorological stations of the Nigerian Meteorological Agency (NIMET) situated at each of the locations having geographical coordinates shown in Table 1. The acquired data were obtained on hourly basis, from which monthly wind speed and other wind speed parameters were determined.

**Table 1**
The geographical coordinates of the selected sites.

| Locations | Latitude (N) | Longitude (E) | Altitude (m) | Period |
|---|---|---|---|---|
| Ikom | 05.58′ N | 08.42′ E | 119.0 | 1997–2005 |
| Ogoja | 06.40′ N | 08.48′ E | 117.0 | 1978–2000 |
| Calabar | 04.58′ N | 08.21′ E | 61.9 | 1991–2007 |
| Port Harcourt | 04.51′ N | 07.01′ E | 19.5 | 1971–2005 |
| Warri | 05.31′ N | 05.44′ E | 6.1 | 1971–2001 |
| Benin | 06.19′ N | 05.06′ E | 77.8 | 1971–2007 |
| Asaba | 06.18′ N | 06.75′ E | 43 | 1997–2006 |

### 2.2. Weibull distribution

Two of the commonly used functions for fitting a measured wind speed probability distributions in a given location over a certain period of time are the Weibull and Rayleigh distribution [13]. For this study, only the Weibull distribution was considered because it produces best fit between the two statistical distributions [13]. The Weibull probability density function is given as [13]:

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

while the corresponding cumulative probability function is expressed in [7,13] as:

$$F(v) = 1 - \exp\left[-\left(\frac{v}{c}\right)^{k}\right] \quad (2)$$

where $f(v)$ = probability of observing wind speed ($v$), $k$ = dimensionless Weibull shape parameter, $c$ = the Weibull scale parameter (m/s), $F(v)$ = cumulative probability function of the observing wind speed ($v$). Several methods are used to determine the Weibull shape

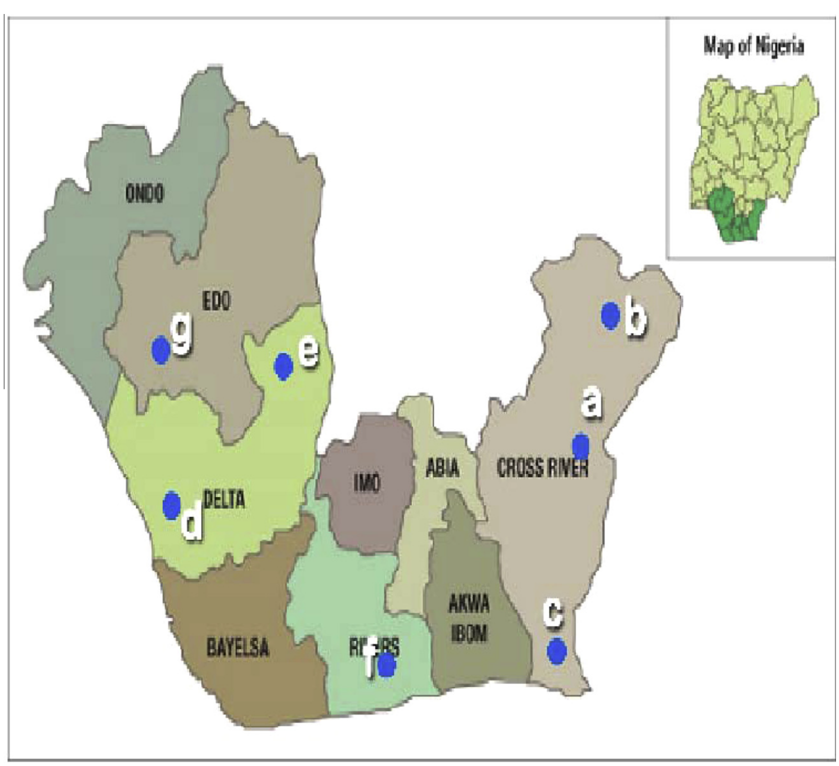


**Fig. 1.** Map of Nigeria showing states typically considered as Niger Delta region. The studied sites include: (a) Ikom (b) Ogoja (c) Calabar (d) Warri (e) Asaba (f) Port Harcourt (g) Benin. *Source:* http://ndwgnews.blogspot.com/p/national.html.

factor ($k$) and scale parameter ($c$). Two of these methods (graphical and approximated) are discussed but only the approximated approach was used in this paper because it predicts the wind speed and wind power more accurately than the other approach [14].

*2.2.1. Graphical method*

According to Akpinar and Akpinar [13], Eq. (2) can be linearized by taking double natural logarithm of both sides of the equation, to give

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

The plot of $\ln\{-\ln[1 - F(v)]\}$ against $\ln(v)$ gives a straight line. The gradient of the line is $k$ and the intercept with the $y$-axis is $-k\ln(c)$. The $c$ and $k$ factors can thus be determined by making use of the least square method through,

$$y = mx + b \tag{4}$$

where,

$$y = \ln[-\ln(1 - F(v)] \tag{5}$$

$x = \ln(v)$. Hence, from (3)–(5), values of $k$ and $c$ can be deduced as follows:

$$k = m \tag{6}$$

$$c = e^{\left(\frac{b}{-k}\right)} \tag{7}$$

*2.2.2. Approximated method*

The shape and scale parameters ($k$ and $c$) of the Weibull distribution are given in [14] as:

$$k = \left(\frac{\sigma}{v_m}\right)^{-1.086} \tag{8}$$

$$c = \frac{v_m}{\Gamma\left(1 + \frac{1}{k}\right)} \tag{9}$$

where, $\sigma$ is the standard deviation, $v_m$ is the average wind speed (m/s) and $\Gamma(x)$ is the gamma function of ($x$). These parameters are expressed as [13]:

$$v_m = \frac{1}{n}\sum_{i=1}^{n} v_i \tag{10}$$

$$\sigma^2 = \frac{1}{n-1}\sum_{i=1}^{n}(v_i - v_m)^2 \tag{11}$$

$$\Gamma(x) = \int_0^{\infty} t^{x-1}e^{-t}dt \tag{12}$$

**Table 2**
Monthly variations of wind characteristics for Ikom.

| | $v$ (m/s) | $v_{mpb}$ | $v_{maxE}$ | $k$ | $c$ (m/s) | Power density (W/m$^2$) |
|---|---|---|---|---|---|---|
| Jan | 2.32 | 2.43 | 2.66 | 5.55 | 2.52 | 8.54 |
| Feb | 3.30 | 3.45 | 3.76 | 5.71 | 3.57 | 24.37 |
| Mar | 3.89 | 4.06 | 4.25 | 7.91 | 4.14 | 37.94 |
| Apr | 3.66 | 3.82 | 4.18 | 5.60 | 3.96 | 33.25 |
| May | 3.24 | 3.37 | 3.46 | 10.75 | 3.41 | 21.43 |
| Jun | 3.17 | 3.27 | 3.31 | 14.82 | 3.28 | 19.60 |
| Jul | 2.70 | 2.82 | 2.95 | 8.09 | 2.87 | 12.66 |
| Aug | 2.83 | 2.92 | 2.99 | 11.81 | 2.95 | 14.02 |
| Sep | 3.02 | 3.15 | 3.26 | 9.17 | 3.19 | 17.53 |
| Oct | 2.71 | 2.82 | 3.17 | 4.94 | 2.96 | 13.96 |
| Nov | 1.99 | 2.04 | 2.45 | 3.88 | 2.20 | 5.94 |
| Dec | 1.66 | 1.73 | 1.87 | 6.11 | 1.78 | 3.04 |

**Table 3**
Monthly variations of wind characteristics for Ogoja.

| | $v$ (m/s) | $v_{mpb}$ | $v_{maxE}$ | $k$ | $c$ (m/s) | Power density (W/m$^2$) |
|---|---|---|---|---|---|---|
| Jan | 4.12 | 3.89 | 5.56 | 2.69 | 4.62 | 63.12 |
| Feb | 4.40 | 4.48 | 5.47 | 3.72 | 4.87 | 65.40 |
| Mar | 4.51 | 4.71 | 5.15 | 5.65 | 4.87 | 62.15 |
| Apr | 4.56 | 4.77 | 5.19 | 5.75 | 4.93 | 64.14 |
| May | 4.14 | 4.29 | 4.93 | 4.48 | 4.54 | 51.09 |
| Jun | 3.68 | 3.84 | 4.26 | 5.21 | 4.00 | 34.53 |
| Jul | 3.62 | 3.70 | 4.46 | 3.85 | 4.00 | 35.87 |
| Aug | 3.86 | 3.94 | 4.77 | 3.79 | 4.27 | 43.75 |
| Sep | 3.85 | 3.95 | 4.69 | 4.02 | 4.24 | 42.44 |
| Oct | 3.92 | 4.05 | 4.67 | 4.43 | 4.29 | 43.23 |
| Nov | 3.47 | 3.56 | 4.25 | 3.96 | 3.83 | 31.33 |
| Dec | 3.72 | 3.72 | 4.77 | 3.32 | 4.14 | 41.42 |

**Table 4**
Monthly variations of wind characteristics for Calabar.

| | $v$ (m/s) | $v_{mpb}$ | $v_{maxE}$ | $k$ | $c$ (m/s) | Power density (W/m$^2$) |
|---|---|---|---|---|---|---|
| Jan | 3.99 | 4.15 | 4.66 | 4.97 | 4.35 | 44.39 |
| Feb | 4.45 | 4.60 | 5.34 | 4.35 | 4.88 | 63.80 |
| Mar | 4.52 | 4.72 | 5.18 | 5.51 | 4.89 | 63.03 |
| Apr | 4.38 | 4.58 | 4.99 | 5.69 | 4.74 | 56.95 |
| May | 4.29 | 4.44 | 5.09 | 4.55 | 4.69 | 56.43 |
| Jun | 4.19 | 4.35 | 4.97 | 4.60 | 4.59 | 52.69 |
| Jul | 4.06 | 4.22 | 4.78 | 4.73 | 4.44 | 47.50 |
| Aug | 4.24 | 4.36 | 5.13 | 4.15 | 4.66 | 56.00 |
| Sep | 4.06 | 4.04 | 5.28 | 3.19 | 4.54 | 55.05 |
| Oct | 4.07 | 4.17 | 5.02 | 3.86 | 4.50 | 51.10 |
| Nov | 3.69 | 3.85 | 4.26 | 5.30 | 4.00 | 34.58 |
| Dec | 3.82 | 3.96 | 4.53 | 4.56 | 4.18 | 39.80 |

**Table 5**
Monthly variations of wind characteristics for Port-Harcourt.

| | $v$ (m/s) | $v_{mpb}$ | $v_{maxE}$ | $k$ | $c$ (m/s) | Power density (W/m$^2$) |
|---|---|---|---|---|---|---|
| Jan | 3.40 | 3.507 | 4.113 | 4.18 | 3.75 | 28.99 |
| Feb | 3.89 | 4.032 | 4.598 | 4.61 | 4.25 | 41.87 |
| Mar | 3.90 | 4.075 | 4.480 | 5.45 | 4.23 | 40.69 |
| Apr | 3.98 | 4.140 | 4.652 | 4.89 | 4.34 | 44.18 |
| May | 3.71 | 3.852 | 4.375 | 4.68 | 4.05 | 36.25 |
| Jun | 3.67 | 3.775 | 4.442 | 4.13 | 4.04 | 36.36 |
| Jul | 3.67 | 3.703 | 4.652 | 3.48 | 4.08 | 39.07 |
| Aug | 3.93 | 4.061 | 4.726 | 4.28 | 4.32 | 44.35 |
| Sep | 3.64 | 3.782 | 4.308 | 4.64 | 3.98 | 34.43 |
| Oct | 3.19 | 3.219 | 4.032 | 3.50 | 3.54 | 25.51 |
| Nov | 2.91 | 2.928 | 3.698 | 3.44 | 3.24 | 19.53 |
| Dec | 2.86 | 2.763 | 3.860 | 2.87 | 3.21 | 20.40 |

**Table 6**
Monthly variations of wind characteristics for Warri.

| | $v$ (m/s) | $v_{mpb}$ | $v_{maxE}$ | $k$ | $c$ (m/s) | Power density (W/m$^2$) |
|---|---|---|---|---|---|---|
| Jan | 2.66 | 2.721 | 3.284 | 3.84 | 2.94 | 14.30 |
| Feb | 2.92 | 3.011 | 4.004 | 2.75 | 3.28 | 22.24 |
| Mar | 3.00 | 2.896 | 4.052 | 2.86 | 3.37 | 23.58 |
| Apr | 3.53 | 3.677 | 4.134 | 4.89 | 3.85 | 30.99 |
| May | 3.06 | 3.192 | 3.555 | 5.09 | 3.33 | 19.96 |
| Jun | 3.30 | 3.432 | 3.528 | 9.04 | 3.47 | 22.63 |
| Jul | 3.21 | 3.342 | 3.471 | 8.69 | 3.39 | 21.01 |
| Aug | 3.29 | 3.445 | 3.745 | 5.81 | 3.56 | 24.18 |
| Sep | 3.26 | 3.399 | 3.788 | 5.09 | 3.54 | 24.13 |
| Oct | 2.92 | 2.965 | 3.667 | 3.61 | 3.24 | 19.43 |
| Nov | 2.91 | 3.048 | 3.244 | 6.75 | 3.12 | 16.29 |
| Dec | 2.94 | 3.073 | 3.375 | 5.48 | 3.19 | 17.43 |

**Table 7**
Monthly variations of wind characteristics for Benin.

| | $v$ (m/s) | $v_{mpb}$ | $v_{maxE}$ | $k$ | $c$ (m/s) | Power density (W/m$^2$) |
|---|---|---|---|---|---|---|
| Jan | 3.14 | 3.23 | 3.82 | 4.06 | 3.47 | 23.07 |
| Feb | 3.72 | 3.87 | 4.35 | 4.92 | 4.06 | 36.14 |
| Mar | 3.99 | 4.17 | 4.51 | 5.98 | 4.30 | 42.57 |
| Apr | 3.78 | 3.95 | 4.33 | 5.52 | 4.09 | 36.83 |
| May | 3.53 | 3.69 | 3.98 | 6.13 | 3.79 | 29.35 |
| Jun | 3.62 | 3.78 | 4.13 | 5.61 | 3.92 | 32.24 |
| Jul | 3.89 | 4.06 | 4.53 | 5.02 | 4.24 | 41.21 |
| Aug | 4.08 | 4.23 | 4.82 | 4.61 | 4.46 | 48.31 |
| Sep | 3.75 | 3.91 | 4.28 | 5.62 | 4.05 | 35.75 |
| Oct | 3.24 | 3.34 | 3.88 | 4.31 | 3.55 | 24.66 |
| Nov | 2.64 | 2.69 | 3.29 | 3.71 | 2.93 | 14.15 |
| Dec | 2.70 | 2.79 | 3.23 | 4.41 | 2.97 | 14.28 |

**Table 8**
Monthly variations of wind characteristics for Asaba.

| | $v$ (m/s) | $v_{mpb}$ | $v_{maxE}$ | $k$ | $c$ (m/s) | Power density (W/m$^2$) |
|---|---|---|---|---|---|---|
| Jan | 3.48 | 3.57 | 4.24 | 4.02 | 3.84 | 31.40 |
| Feb | 3.77 | 3.94 | 4.33 | 5.39 | 4.09 | 36.77 |
| Mar | 3.96 | 4.13 | 4.57 | 5.26 | 4.30 | 42.85 |
| Apr | 4.21 | 4.40 | 4.66 | 7.07 | 4.99 | 48.80 |
| May | 3.34 | 3.49 | 3.76 | 6.26 | 3.59 | 24.84 |
| Jun | 2.95 | 3.07 | 3.17 | 9.48 | 3.11 | 16.26 |
| Jul | 2.99 | 2.99 | 3.83 | 3.35 | 3.33 | 21.46 |
| Aug | 3.05 | 3.09 | 3.83 | 3.59 | 3.39 | 22.10 |
| Sep | 2.89 | 3.02 | 3.29 | 5.72 | 3.13 | 16.36 |
| Oct | 3.10 | 3.23 | 3.58 | 5.22 | 3.37 | 20.59 |
| Nov | 3.48 | 3.62 | 4.07 | 4.87 | 3.79 | 29.64 |
| Dec | 3.49 | 3.64 | 4.05 | 5.09 | 3.80 | 29.55 |

**Table 9**
Annual wind characteristics for the seven sites for the period.

| Locations | Mean wind speed (m/s) | Average power density (W/m$^2$) | Average energy (kWh/m$^2$/year) | Class |
|---|---|---|---|---|
| Ikom | 2.87 | 17.69 | 154.33 | 1 |
| Ogoja | 3.99 | 48.21 | 421.53 | 1 |
| Calabar | 4.15 | 51.78 | 452.89 | 1 |
| Port Harcourt | 3.56 | 34.30 | 300.00 | 1 |
| Warri | 3.08 | 21.35 | 186.73 | 1 |
| Benin | 3.51 | 31.55 | 276.19 | 1 |
| Asaba | 3.39 | 28.39 | 248.10 | 1 |

From (9), $k$ and $c$ are related according to Akpinar and Akpinar [13] by:

$$v_m = c\Gamma\left(1+\frac{1}{k}\right) \tag{13}$$

### 2.3. Evaluation of most probable wind speed and maximum wind speed

Two meaningful wind speeds for energy estimation that will also be got from the scale and shape factors are the most probable wind speed ($v_{mpb}$) and the wind speed carrying the maximum energy ($v_{MaxE}$) expressed in (14) and (15) as indicated in [13]:

$$v_{mpb} = c\left(\frac{k-1}{k}\right)^{\frac{1}{k}} \tag{14}$$

$$v_{MaxE} = c\left(\frac{k+2}{k}\right)^{\frac{1}{k}} \tag{15}$$

### 2.4. Estimation of wind power density

Wind power density is a useful way of evaluating wind resource available at a potential height; it indicates the quantity of energy available for conversion by a wind turbine [15]. The available power in the wind flowing at mean speed $v_m$ through a wind rotor blade with sweep area, $A$ (m$^2$), at any given site can be estimated as:

$$P(v) = \frac{1}{2}\rho A v_m^3 \tag{16}$$

While the power of the wind per unit area is given as:

$$p(v) = \frac{1}{2}\rho v_m^3 \tag{17}$$

The wind power density (wind power per unit area) based on the Weibull probability density function can be calculated using expression given in [11] as:

$$p(v) = \frac{P(v)}{A} = \frac{1}{2}\rho c^3\Gamma\left(1+\frac{3}{k}\right) \tag{18}$$

where $P(v)$ = wind power (W), $p(v)$ = wind power density (W/m$^2$), $\rho$ = air density at the site (1.21 kg/m$^3$), $A$ is the sweep area of the rotor blades (m$^2$) and $\Gamma(x)$ is the gamma function of ($x$).

### 2.5. Wind energy computation

The extractible mean daily energy, mean monthly energy, and the annual energy are defined by the relationships in Eqs. (19)–(21) respectively [16].

$$\bar{E}_j = 24\times 10^{-3}\bar{P}_T\ (\mathrm{kWh/m^2}) \tag{19}$$

$$\bar{E}_{jm} = 24\times 10^{-3} d\bar{P}_T\ (\mathrm{kWh/m^2}) \tag{20}$$

$$\bar{E}_a = \sum_{n=1}^{12}\bar{E}_{jm}\ (\mathrm{kWh/m^2}) \tag{21}$$

**Table 10**
Seasonal variations of wind characteristics for the seven sites at 10 m height for the respective period under study.

| | Rainy | | | | Dry | | | |
|---|---|---|---|---|---|---|---|---|
| | $v$ | $v_{mpb}$ | $v_{maxE}$ | Power density (W/m$^2$) | $v$ | $v_{mpb}$ | $v_{maxE}$ | Power density (W/m$^2$) |
| Ikom | 3.02 | 3.14 | 3.34 | 19.59 | 2.43 | 2.54 | 2.77 | 11.98 |
| Ogoja | 3.96 | 4.09 | 4.71 | 45.39 | 4.08 | 4.03 | 5.27 | 56.65 |
| Calabar | 4.17 | 4.30 | 4.97 | 52.59 | 4.09 | 4.24 | 4.84 | 49.33 |
| Port Harcourt | 3.62 | 3.73 | 4.37 | 35.59 | 3.38 | 3.43 | 4.19 | 30.42 |
| Warri | 3.16 | 3.27 | 3.69 | 22.47 | 2.84 | 2.94 | 3.55 | 17.99 |
| Benin | 3.61 | 3.76 | 4.19 | 33.90 | 3.19 | 3.30 | 3.80 | 24.50 |
| Asaba | 3.33 | 3.45 | 3.86 | 26.99 | 3.58 | 3.72 | 4.21 | 32.57 |

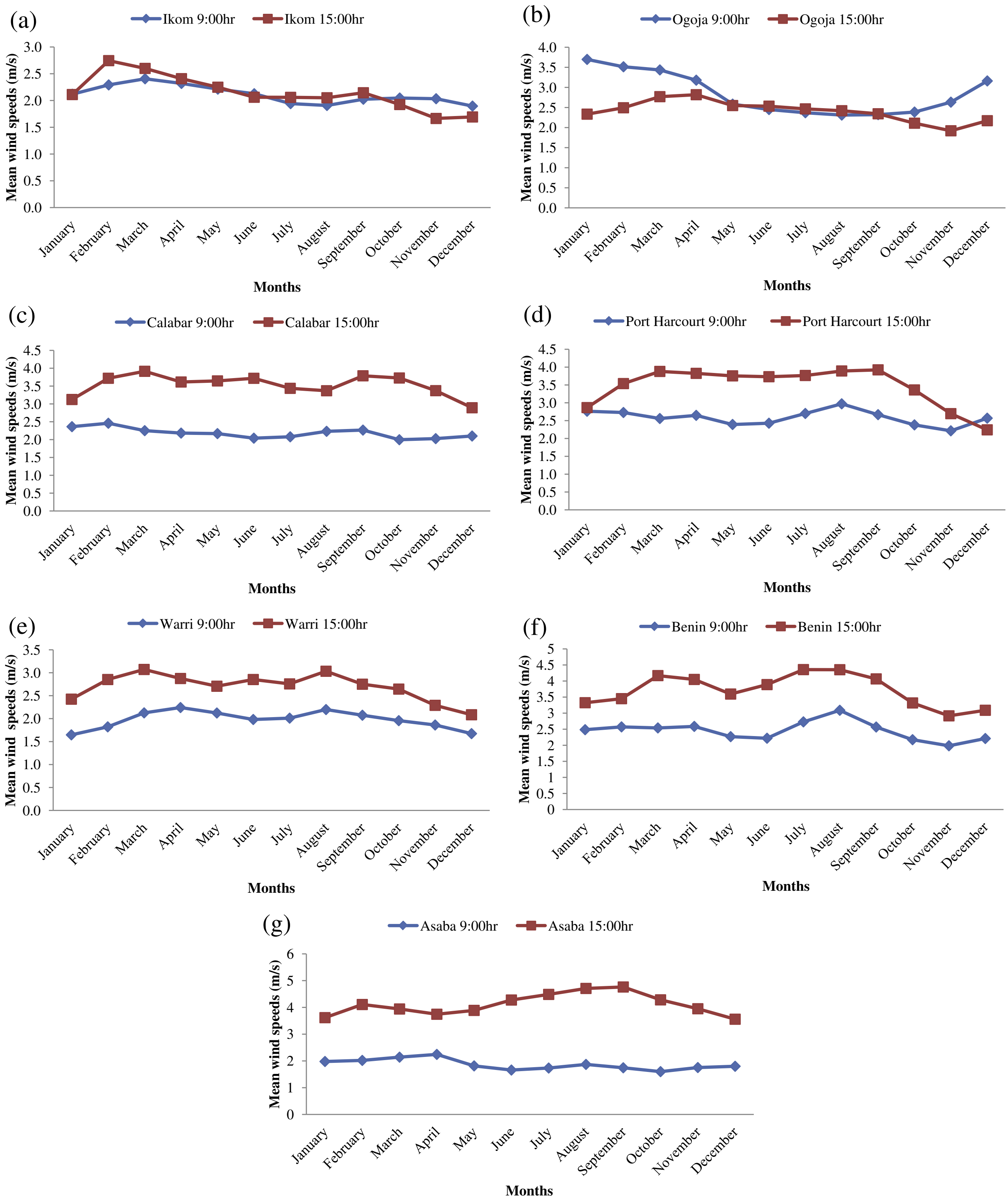


**Fig. 2.** Monthly variations of wind speeds at two synoptical hours of 9:00 and 15:00 for (a) Ikom (b) Ogoja (c) Calabar (d) Port Harcourt (e) Warri (f) Benin and (g) Asaba for the whole year.

where $\overline{P}_T = p(v)$ in (W/m$^2$) and $d$ is the number of days in the month considered.

### 2.6. Extrapolation of wind speed at different heights

The variability of wind speed depends on the distance from the ground and roughness of the terrain. Due to this fact, an equation is needed to predict wind speed at one height in terms of the measured speed at another height. The expression usually adopted to describe wind speed variation with different hub heights is the Power law given in [7] as:

$$\frac{v}{v0} = \left(\frac{h}{h0}\right)^n \tag{22}$$

where '$v$' is the wind speed at the required height '$h$', '$v_0$' is wind speed at the original height '$h_0$', and '$n$' is the surface roughness coefficient which lies in the range 0.05–0.5. Due to the nature of the vegetation zone (which is predominantly dense mangrove forests) in this region, a surface roughness coefficient value of 0.3 is assumed in this paper for extrapolation at various heights.

### 2.7. Power output of wind turbine and capacity factor

The average power output $P_{e,ave}$ and capacity factor $C_f$ are important performance parameters of WECS. $P_{e,ave}$ determines the total energy production and total income [13] while $C_f$ is the ratio of the average power output over a period, to the rated electrical power ($P_{eR}$) of the generator [11]. The average power output $P_{e,ave}$, can thus be computed as expressed in [13] as:

$$P_{e,ave} = P_{eR}\left(\frac{e^{-\left(\frac{v_c}{c}\right)^k} - e^{-\left(\frac{v_r}{c}\right)^k}}{\left(\frac{v_r}{c}\right)^k - \left(\frac{v_c}{c}\right)^k} - e^{-\left(\frac{v_f}{c}\right)^k}\right) \tag{23}$$

While the capacity factor $C_f$ of a wind turbine can be calculated thus [11,13]:

$$C_f = \frac{P_{e,ave}}{P_{eR}} \tag{24}$$

where $v_c$, $v_r$, $v_f$ are the cut-in wind speed, rated wind speed and cut-off wind speed respectively.

All the above calculations were carried out using MS excel. The results of these analyses for the selected locations are presented and discussed in Section 'Results and discussion'.

## 3. Results and discussion

In this section, the annual, monthly and seasonal variations of the wind speed characteristics in all the sites considered are presented. In addition, the performance of small to medium size commercial wind turbines operating in these sites is examined.

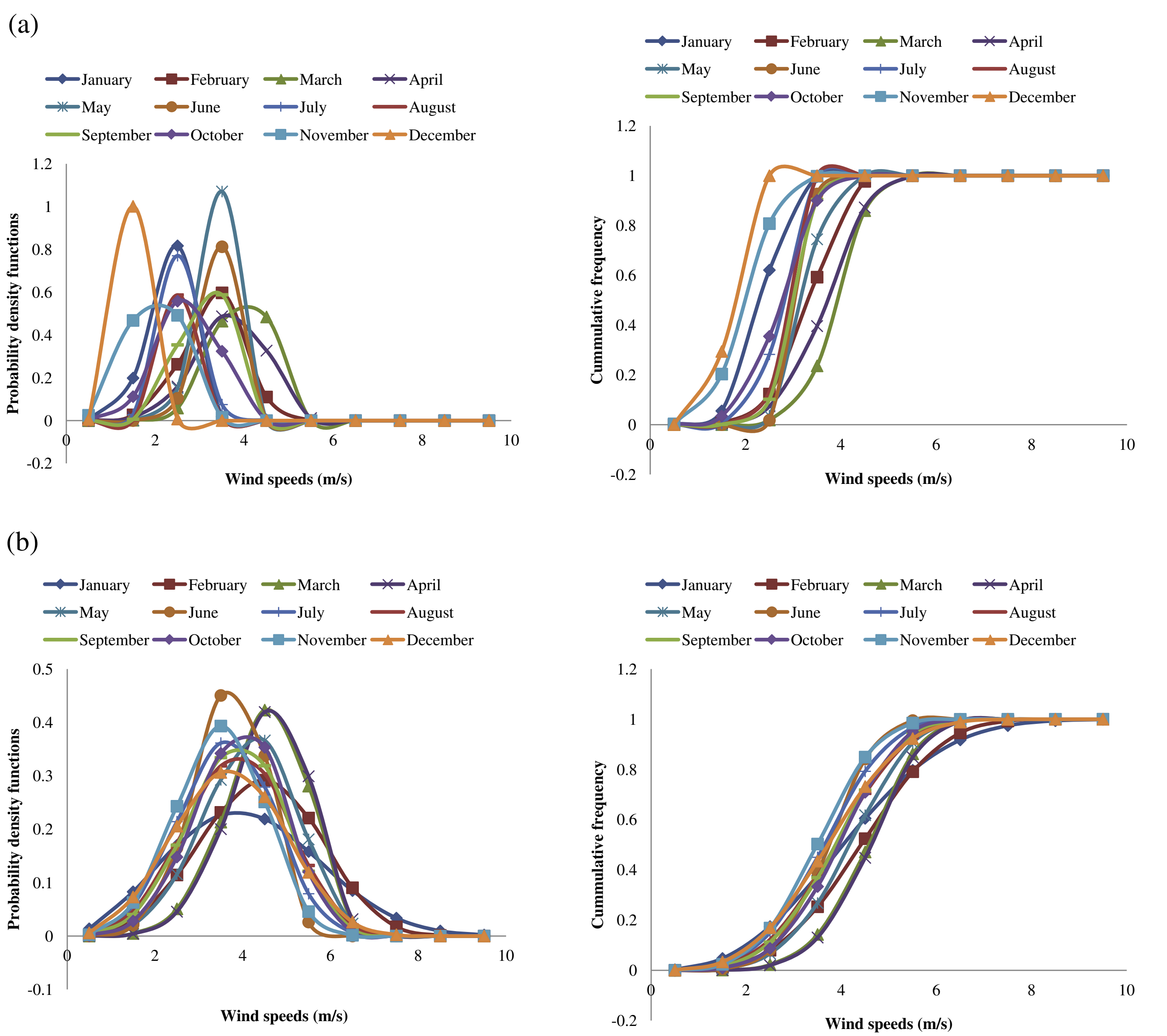


**Fig. 3.** Monthly wind speed probability density and cumulative distribution functions for (a) Ikom (b) Ogoja (c) Calabar (d) Port Harcourt (e) Warri (f) Benin and (g) Asaba for the whole year.

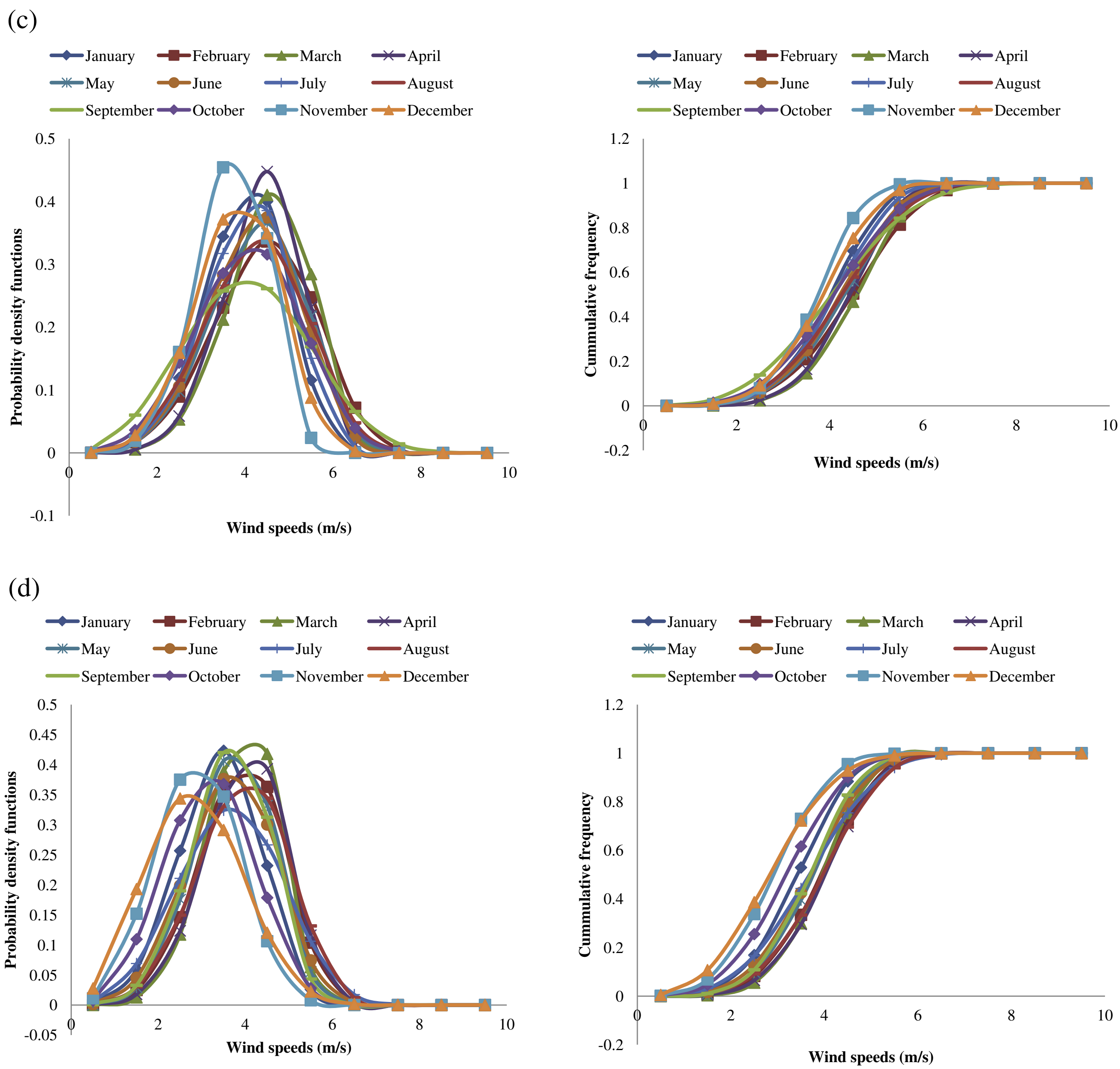


**Fig. 3** (*continued*)

### 3.1. Annual and monthly mean wind speed

Tables 2–8 depict the monthly wind characteristics of Ikom, Ogoja, Calabar, Port-Harcourt, Warri, Benin-city and Asaba at 10 m heights. It can be deduced from these tables, that the monthly minimum mean wind speed ($v_m$) in this region is 1.66 m/s at Ikom (December) while the maximum is observed in April at Ogoja as 4.56 m/s. The tables further show that the monthly minimum values of wind speed carrying maximum energy ($v_{maxE}$) and most probable wind speed ($v_{mpb}$) are computed as 1.87 and 1.73 m/s respectively in December both at Ikom whereas the maximum values are got at Ogoja as 5.56 m/s (January) and 4.77 m/s (April) for the $v_{maxE}$ and $v_{mpb}$ in that order. Furthermore, wind considerations based on the respective locations show that $v_m$, $v_{maxE}$ and $v_{mpb}$ have the minimum values as 1.66, 1.87 and 1.73 m/s, respectively in December and maximum as 3.89, 4.25 and 4.06 m/s respectively in March for Ikom (Table 2). For the remaining locations, the maximum and minimum values of these wind speed parameters can thus be seen in Tables 3–8.

In addition, results obtained for wind power density using Eq. (18) on the seven locations at 10 m altitude are also shown in Tables 2–8. The average monthly power densities for the locations considered, follow a similar pattern with the mean wind speeds. The monthly mean power density in the region ranges from 3.04 W/m$^2$ in December (Ikom) to 65.4 W/m$^2$ at Ogoja in February. According to PNL wind power classification scheme [17], all the sites considered in the region exist under Class 1 wind resource category having power density less than 100 W/m$^2$ in all the months of the year.

According to CIA world factbook [18], the early invasion of moist Atlantic South-West (SW) monsoon winds, every February/March usually lead to the early beginning of the rainy season (March to November) in the Niger Delta region of Nigeria, and is typically marked by the incidence of high winds and heavy squalls.

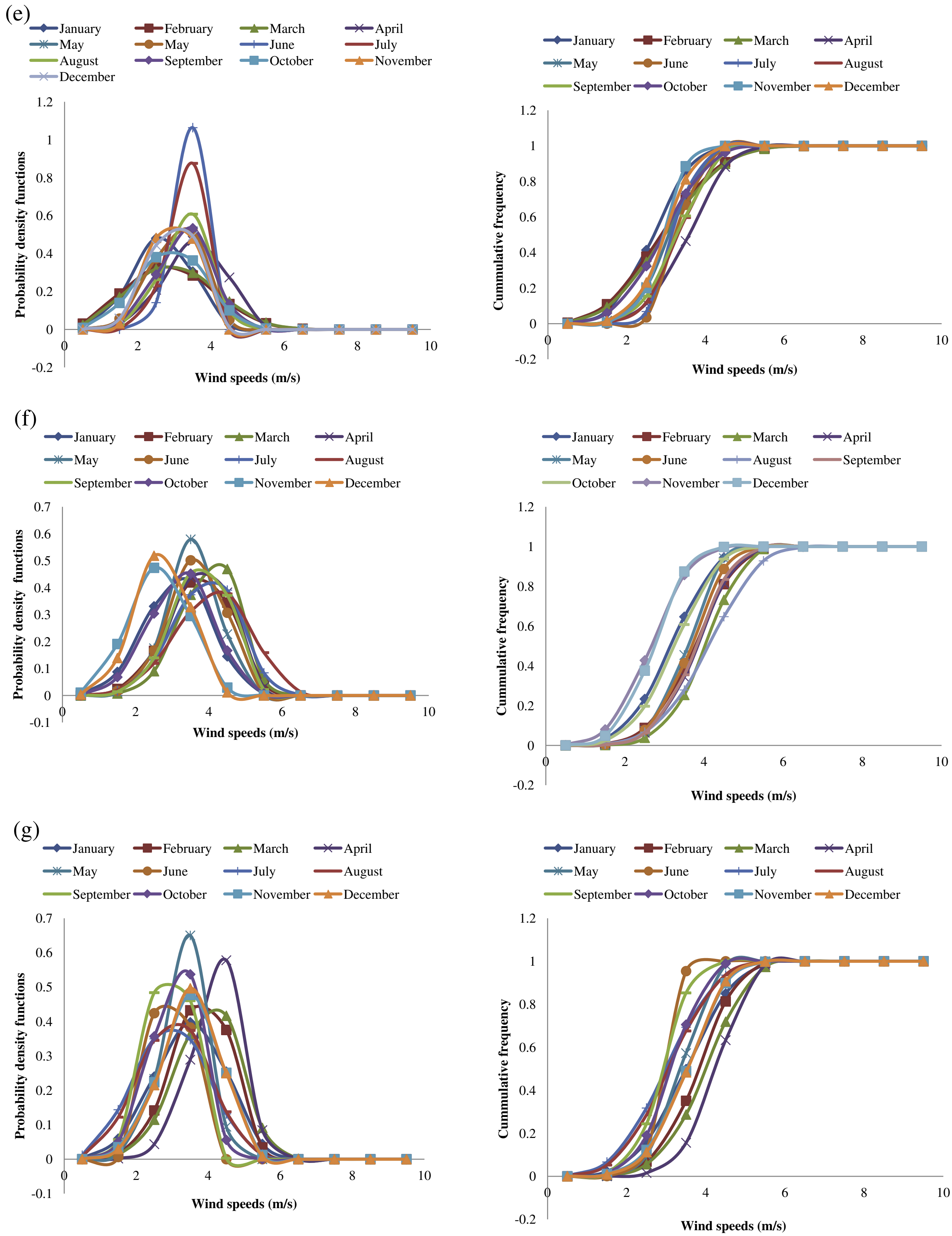


**Fig. 3** (*continued*)

This is noticeable with the sudden upsurge in monthly mean wind speeds in the months of March and April. The month of August is usually characterized by a dip in precipitation and a brief dry-period due to the movement of the SW winds to the Northern region of the country. However, the North-East (NE) trade winds distinguish the months of September to November from the remaining months by bringing a season of clear skies, moderate temperatures and lower humidity which is responsible for the fall in trend of the graph observed from September to November. Furthermore, these tables reflect an increase in wind speed from December to February (dry season) due to the aggressive NE winds blowing strongly over the region from the Sahara [18].

The monthly Weibull parameters $k$ and $c$ calculated analytically from the available data using Eqs. (8) and (9) are also presented in Tables 2–8. It can be observed that the Weibull scale and shape parameters $c$ and $k$ vary from 1.78 m/s in December (Ikom) to 4.99 m/s in April (Asaba) and 2.61 in June (Ikom) to 14.82 in January (Ogoja) in the region respectively.

The annual characteristics of wind speeds for the region are presented in Table 9. The table indicates that the annual mean wind speed lies between 2.87 m/s in Ikom and 4.15 m/s in Calabar while the annual mean power density varies from 17.69 to 51.78 W/m$^2$. The annual power density is also less than 100 W/m$^2$ for all the locations and hence, these locations in Niger Delta region can be categorized as Class 1 wind energy resource. This class of wind energy resource is in general, unsuitable for large scale wind turbine applications but may be adequate for small scale stand-alone energy conversion systems, battery charging and mechanical applications like water pumping. In addition, the wind energy in this region can be used as part of hybrid energy systems, such as the combination of wind-solar-battery-diesel generator energy system.

### 3.2. Seasonal wind speed characteristics

Table 10 depicts the seasonal variations of wind characteristics in the region for the respective periods under study. It can be observed that the minimum seasonal mean wind speed is 2.43 m/s in the dry season at Ikom while the maximum value is obtained as 4.17 m/s during the dry periods in Calabar. Furthermore, $v_{maxE}$ and $v_{mpb}$ range from 2.77 and 2.54 m/s at Ikom (dry season) to 4.30 m/s in Calabar (rainy) and 5.27 m/s in Ogoja (dry) whereas the computed power densities in W/m$^2$ are given as 11.98 and 56.65 during the dry season of the year for the minimum and maximum values in Ikom and Calabar, respectively.

Fig. 2 shows the monthly variations of mean wind speeds of the sites, taken at two synoptical hours of 9:00 and 15:00 for the whole year. It can be observed from the trend of plotted curves that higher mean wind speeds occur in the afternoon hour in the region except at Ogoja and Ikom that have some months with higher wind speeds in the morning. Further observation reveals that Ikom and Ogoja have higher wind speeds in the dry season than the rainy periods. In addition, Calabar, Port Harcourt, Warri and Benin-city have higher wind speeds at the onset of the rainy season in March and August during the SW wind crossing to the northern region. Irrespective of the period of the day in the region, occurrence of higher wind speed is more prevalent in the rainy than the dry season.

### 3.3. Weibull frequency distributions

In observing the Weibull distribution of the seven sites, the Weibull monthly probability density and cumulative distributions derived from the time series data for the whole year are presented in Fig. 3. It is reflected from Fig. 3 that all the curves are similar for the whole year period for each of the locations. There is also a tendency of obtaining wind speeds not exceeding 6 m/s in some months at Ikom, Warri, Benin-city and Asaba whereas Ogoja, Calabar and Port Harcourt will have the likelihood of wind speeds between 6 and 7 m/s for some months throughout the year.

**Table 11**
Characteristics of the selected wind turbines [18–21].

| | G-3120 | P19-100 | WES-30 | ZEUS 500 |
|---|---|---|---|---|
| Rated power (kW) | 35 | 100 | 250 | 500 |
| Hub height (m) | 42.7 | 60 | 49 | 47.2 |
| Rotor diameter (m) | 19.2 | 19.1 | 30 | 46.1 |
| Cut-in wind speed (m/s) | 3.5 | 2.5 | 2.7 | 3.5 |
| Rated wind speed (m/s) | 8 | 12 | 12.5 | 14 |
| Cut-off wind speed (m/s) | 25 | 25 | 25 | 25 |

### 3.4. Wind turbine performance

It was shown in the previous sections that wind resource in Niger Delta region can be classified into Class 1, hence, the potential for wind energy development is limited. However, there are possibilities for low capacity wind turbine applications in rural and small communities that scatter across the region. Wind turbine can be operated as stand-alone system to supply electricity for these communities and if operated as wind farm (combinations of two or more wind turbines), the system can produce electricity for bigger communities. Four small to medium sized wind turbine models namely: Polaris America (AP) model P19-100, Endurance Wind Power (EWP) model G-3120, Wind Energy Solution (WES) model WES-30, Zeus Energy model ZEUS-500 with rated power ranging from 35 to 500 kW [19–22], are selected to simulate their performance in all the locations considered in this study. The characteristic properties of the selected wind turbine models are given in Table 11.

The annual energy outputs and capacity factors for the four wind turbines operating at their designed parameters in all the sites are presented in Table 12 and further shown graphically in Fig. 4. The performance of any wind turbine is generally dependent on its design wind speed parameters (cut-in, rated and cut-off wind speeds) and the site wind speed characteristics. The annual energy output ranges from about 4.1 MWh in Ikom with P19-100 to 145.6 MWh in Ogoja using ZEUS-500 (Fig. 4a). The annual energy output for Ikom ranges from 4.07 MWh using P19-100 to 10.5 MWh with G-3120. In the case of Ogoja, the annual energy output lies between 80.5 MWh with P19-100 and 145.6 MWh using ZEUS-500. It can further be observed from Table 12 that energy output using G-3120 model (with least rated power, 35 kW) is almost comparable with energy generated by WES-30 (250 kW) and ZEUS-500 (500 kW) and higher than that of P19-100 (100 kW) for all the sites considered. This is due to its low rated wind speed of 8 m/s, which is significantly low when compared with turbines P19-100, WES-30 and ZEUS-500 models that are 12, 12.5 and 14 m/s, respectively.

Irrespective of the site, G-3120 (35 kW) turbine has the highest value of capacity factor among the models considered. The $C_f$ values for this model are 15.3%, 16.6%, 35.6%, 3.4%, 33.7%, 22.8% and 8.9% for Asaba, Benin-city, Calabar, Ikom, Ogoja, Port-Harcourt and Warri, respectively (Fig. 4b). Since the performance of a wind turbine depends on its designed speed parameters, G-3120 wind turbine's excellent performance in the region when compared with other models considered may be related to its rated (designed) wind speed of 8 m/s being the lowest among the selected wind turbines. In addition, the rated wind speed is closer to the wind speed carrying maximum power for G-3120 turbine in all the locations than other models at their respective hub heights; furthermore, the least capacity factor recorded with ZEUS-500 among the

**Table 12**
Annual energy output and capacity factor for the selected wind turbines for all the locations.

| | G-3120 | | P19-100 | | WES-30 | | ZEUS 500 | |
|---|---|---|---|---|---|---|---|---|
| | $C_f$ (%) | Ewt (MWh/yr) | $C_f$ (%) | Ewt (MWh/yr) | $C_f$ (%) | Ewt (MWh/yr) | $C_f$ (%) | Ewt (MWh/yr) |
| Asaba | 15.30 | 46.90 | 2.83 | 24.79 | 1.64 | 35.98 | 0.81 | 35.42 |
| Benin-city | 16.62 | 50.94 | 3.03 | 26.58 | 1.73 | 37.87 | 0.83 | 36.33 |
| Calabar | 35.60 | 109.16 | 8.26 | 72.38 | 5.04 | 110.40 | 2.67 | 116.95 |
| Ikom | 3.41 | 10.47 | 0.46 | 4.07 | 0.24 | 5.25 | 0.10 | 4.30 |
| Ogoja | 33.65 | 103.19 | 9.19 | 80.52 | 5.91 | 129.48 | 3.32 | 145.57 |
| Port-Harcourt | 22.78 | 69.84 | 5.70 | 49.89 | 3.54 | 77.60 | 1.88 | 82.33 |
| Warri | 8.93 | 27.39 | 2.60 | 22.75 | 1.67 | 36.55 | 0.90 | 39.41 |

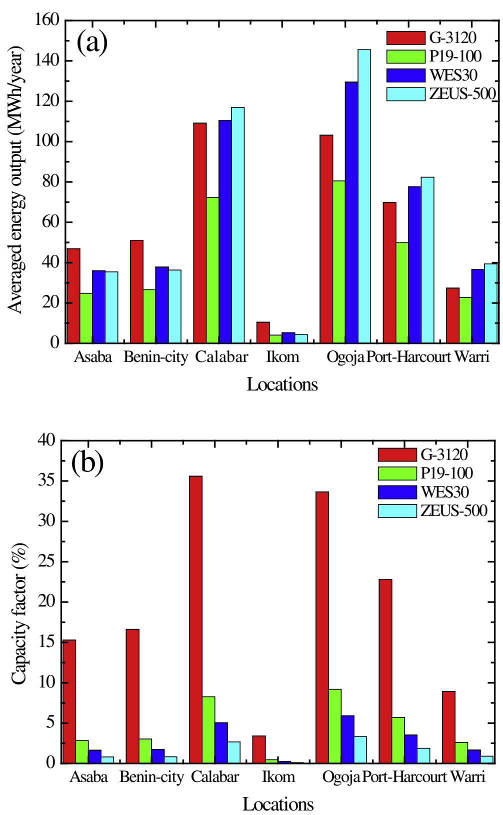


**Fig. 4.** Annual performance of the selected wind turbine models: (a) Annual energy output and (b) capacity factor.

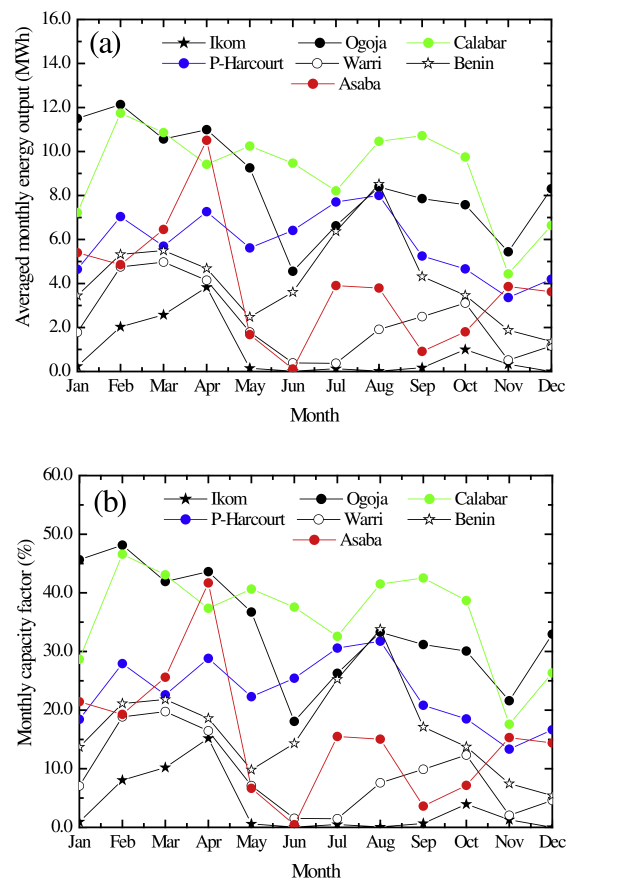


**Fig. 5.** Monthly performance of G-3120 wind turbine model: (a) Energy output and (b) capacity factor.

turbines considered for any given location is due to its high rated wind speed and relatively low hub height.

Therefore, for wind energy development, G-3120 model or wind turbine with similar rated wind speed (and even lower cut-in wind speed) will be most suitable for all the locations considered in this study. Based on electricity usage of 126 kWh per capital per year in Nigeria as at 2008 [23], the energy output from this wind turbine model can serve electricity need of about 370, 400, 860, 80, 820, 550 and 220 people living in Asaba, Benin-city, Calabar, Ikom, Ogoja, Port-Harcourt and Warri, respectively.

The monthly energy output and capacity factor for G-3120 wind turbine model (as a case study) are presented in Fig. 5. It can be observed that for a given site, there is a noticeable variation in the monthly averaged energy output from the wind turbine model (Fig. 5a). This is expected since the mean wind speed varied from one month to the other as earlier shown. The monthly energy output varies from about 2 kWh at Ikom (in December) to 12.1 MWh in Ogoja (in February). It can also be observed that the wind turbines will only generate useful energy in Ikom between the months of February to April and October. The energy output from the wind turbine is observed to be small in the months of June and July in Warri and in the month of June in Asaba.

The monthly capacity factor for this wind turbine model (Fig. 5b) follows the same trend as the monthly energy output. It can be observed that the capacity factor is greater than 10% for each month of the year in Ogoja, Calabar and Port-Harcourt. However, monthly minimum capacity factor of about 5% is observed in Benin-city. Therefore, these locations can be considered as viable sites for wind energy development for either small scale electricity generation or water pumping systems throughout the year. Other sites may only be considered for wind energy development in some months of the year.

## 4. Conclusions

From the statistical data and computation of wind energy potential together with the performance assessment carried out on small to medium size commercial wind turbines in seven selected locations covering the Niger Delta region of Nigeria, the following facts were deduced from the study:

- In all the locations considered, the monthly mean wind speed ($v_m$) has the minimum and maximum values as 1.66 and 4.56 m/s at Ikom (December) and Ogoja in April, respectively, whereas the monthly mean power density ranged from 3.04 W/m$^2$ (Ikom) in December to 65.4 W/m$^2$ at Ogoja in February thereby making all the sites to exist under Class 1 category since power density is less than 100 W/m$^2$ in all the months of the year.
- The Weibull scale parameter $c$ ranged from 1.78 m/s in December (Ikom) to 4.99 m/s in April (Asaba) while shape parameter $k$ is between 2.61 and 14.82 in June (Ikom) and January (Ogoja) in the region respectively.
- G-3120 (35 kW) wind turbine has the highest capacity factors of 15.3%, 16.6%, 35.6%, 3.4%, 33.7%, 22.8% and 8.9% for Asaba, Benin-city, Calabar, Ikom, Ogoja, Port-Harcourt and Warri respectively among the models considered.
- Energy output from wind turbine G-3120 (35 kW) is higher than that of P19-100 (100 kW) and almost comparable with energy generated by WES-30 (250 kW) and ZEUS-500 (500 kW) for all the sites considered thus making G-3120 wind turbine most suitable for energy generation in all the locations considered.
- The wind resource in the Delta region is more suitable for small scale stand-alone energy conversion systems and mechanical applications like battery charging and water pumping and also can be used as part of hybrid energy systems in such combination as wind-solar-battery-diesel generator energy system.

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