

## Assessment of Wind Energy Potential for Small Communities in South-South Nigeria: Case Study of Koluama, Bayelsa State

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### Abstract

Although the concept of wind energy potential assessments has matured considerably, there is only limited application and adoption in regions of energy crisis where electricity demand far exceeds supply. For Nigeria, seeking alternate sources of energy to meet its energy demand is essential and must be met in a sustainable practice. This study analyzed the electricity generation potential from wind at Koluama, Bayelsa State, Nigeria using a combination of 10-m monthly mean wind speed and direction data (1984-2013) and five year daily wind speed data (2009-2013). The data were subjected to different statistical tests and also compared with the two-parameter Weibull probability density function. Maximum mean day of year (DOY) wind speed recorded was 5.25 m/s and minimum wind speed was 0.92 m/s, while seasonal mean wind speed during the dry months (DJF) is estimated to be 4.05 m/s and 4.32 m/s during the wet months of June, July August and September (JJAS) for the 30-year period considered. Wind power density (WPD) ranged from 82 W/m<sup>2</sup> to 145 W/m<sup>2</sup> in November and August respectively.

Lastly, small scale wind-to-electricity power generation was assessed using six (6) practical wind turbines. The AV 928 turbine had the maximum energy yield, despite relatively low capacity factor of less than 10%.

**Keywords:** Wind variability; Wind power potential; Capacity factor; Turbine output

### Introduction

Despite abundant fossil fuel resources available both globally and in Nigeria, the electricity demand of the Nigerian population is still much larger than the present supply [1]. This coupled with the threat of foreseen fossil fuel depletion, changing climate, air pollution and oil price volatility [2-4], implies that alternative approaches to electricity generations are being constantly considered. These alternatives approach are majorly renewables because they offer a sustainable solution and are quite immune to energy security concerns [4,5]. Energy security concerns can be broadly viewed under the indices of availability, affordability and resilience [5]. The energy mix has witnessed an increasing share of renewables towards attaining sustainability, better air quality and mitigating climate change [6-10]. Installed capacity of wind energy has increased with previous studies highlighting the wind energy growth regime [7-14]. Furthermore, [15] stated that “wind energy assessment is a topic of both scientific interest and an issue of relevance with ecological, economic and political implications”. While wind energy has been continually exploited by nations with large wind resources [15-20], there exists limited evidence of such studies in Nigeria where electricity supply is still below demand [1]. Residential power supply in small communities and rural environments have been severely impacted by this crisis thereby posing a challenge to comfort, health and productivity of residents, culminating in high poverty levels and low Gross Domestic Product (GDP).

This study seeks to investigate the wind energy resources in Koluama, Bayelsa State, Nigeria (4.47°N; 5.77°E; altitude 6.1m; air density 1.225 kg/m<sup>3</sup>) using 30 years historical data to establish the trend and variability of wind speed and direction, estimate wind power density and potential via a range of turbines and make recommendations based on results. The results from this study will provide an analysis of the possible impact of local meteorology on the adoption and use of wind energy for powering small communities both in Nigeria and regions where a transition to renewables is required or electricity supply is short of demand.

### Study Area

The study area as shown in Figure 1 is Koluama, situated in Bayelsa State within the eastern region of Niger Delta, Nigeria. Geographically, it is located between latitude 04°47'N and longitude 5°77'E. The location features a tropical monsoon climate with a lengthy and heavy rainy seasons and a very short dry season from December to January. The Harmattan, which climatically influences many cities in West Africa is less pronounced over the region. Koluama's heaviest rainfall occurs during September with an average of 367 mm of rain and the lowest rainfall occurs during December with an average rainfall of 20 mm. Temperature throughout the year varies from 25 to 28°C. The vegetation is mainly mangrove and salt water swamps, but a major part had largely been destroyed by oil exploration [21,22].

### Data and Methodology

#### Data

Thirty years monthly mean wind speed and direction data at a height 10 m above sea level from (1984-2013) and five years (2009-2013) daily wind data were assessed from the archive of Nigeria Meteorological Agency (NIMET) for the study area. The data were recorded continuously using cup-generator anemometer. These dataset

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Figure 1: Location of Koluama, Bayelsa State, Nigeria (Source: <https://google.com/maps>).

were then analyzed to determine the monthly, seasonal and yearly wind resource potentials for power generation.

## Methods

In previous studies, various statistical distributions exist for describing and analyzing wind resource data. Some of these include normal and lognormal, Rayleigh and Weibull probability distributions to mention a few [23-25]. However, of these statistical methods, the Weibull distribution has been found to be accurate and adequate in analyzing and interpreting the situation of measured wind speed and in predicting the characteristics of prevailing wind profile over a place [26-28]. Thus, in this study, the Weibull two parameter probability density function (PDF) was employed in carrying out the analyses of over the study area and is mathematically expressed as:

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

Where  $k$  is the Weibull shape parameter,  $c$  is the scale parameter and  $f(v)$  is the probability of observing wind speed  $v$  (m/s).

The Weibull Cumulative Density Function (CDF) corresponding to the PDF is given as:

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

Where  $F(v)$  is the cumulative distribution function of observing wind speed  $v$ .

The mean value of the wind speed  $V_{weibull}$  and standard deviations  $\sigma$  for the Weibull distribution as defined in terms of the Weibull parameter  $k$  and  $c$  are given as:

$$V_{weibull} = c\Gamma\left(1 + \frac{1}{k}\right) \quad (3)$$

and

$$\sigma = \sqrt{c^2 \left\{ \Gamma\left(1 + \frac{2}{k}\right) - \left[ \Gamma\left(1 + \frac{1}{k}\right) \right]^2 \right\}} \quad (4)$$

Where  $\Gamma(x)$  is the gamma function of ( $x$ )

**Evaluation of wind power density (WPD):** The WPD evaluation can be carried out in two forms. One based on available power in the wind as captured by the wind conversion system and estimated directly from the wind speed  $v$  (m/s) and the other based on the Weibull two-parameter method. These two approaches are given as

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

$$p(v) = \frac{P(v)}{A} = \frac{1}{2} \rho c^3 \Gamma\left(1 + \frac{3}{k}\right) \quad (6)$$

Where,  $P(v)$  is the wind power ( $W$ ),  $p(v)$  is the wind power density ( $W/m^2$ ),  $\rho$  is the air density ( $kg/m^3$ ) at the site and  $A$  is the swept area of the rotor blade ( $m^2$ ).

However, to simulate the electrical power output of a model wind turbine requires using:

$$P_e = \begin{cases} 0 & v < V_c \\ P_{eR} \frac{v^k - V_c^k}{V_R^k - V_c^k} & V_c \leq v < V_R \\ P_{eR} & V_R \leq v \leq V_F \\ 0 & v > V_F \end{cases} \quad (7)$$

Where  $P_{eR}$  is the rated electrical power,  $V_c$  is the cut-in wind speed,  $V_R$  is the rated wind speed and  $V_F$  is the cut-out speed respectively of the model wind turbine.

Also, the average power output ( $P_e, ave$ ) from a turbine corresponding to the total energy production and related to the total income/cost analysis was evaluated from:

$$P_{e, ave} = \left\{ \frac{e^{\left(\frac{V_c}{c}\right)^k} - e^{\left(\frac{V_R}{c}\right)^k}}{\left(\frac{V_R}{c}\right)^k - \left(\frac{V_c}{c}\right)^k} - e^{\left(\frac{V_F}{c}\right)^k} \right\} \quad (8)$$

The capacity factor (CF) which is the ratio of average power output to turbine rated/maximum output [2] is evaluated from

$$CF = \frac{P_{e, ave}}{P_{eR}} \quad (9)$$

Since the standard height for most turbines is 80m, the wind speed over Koluama was estimated to a height of 80 m using

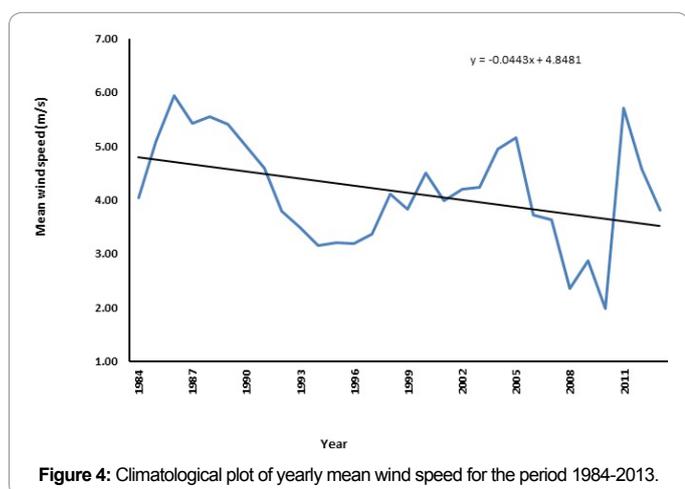
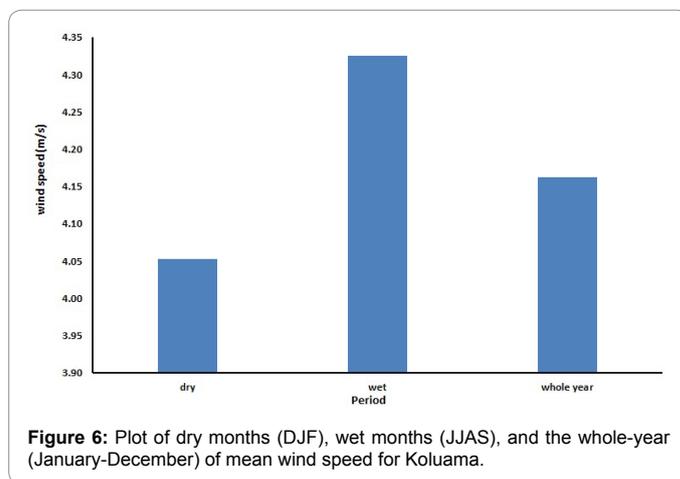
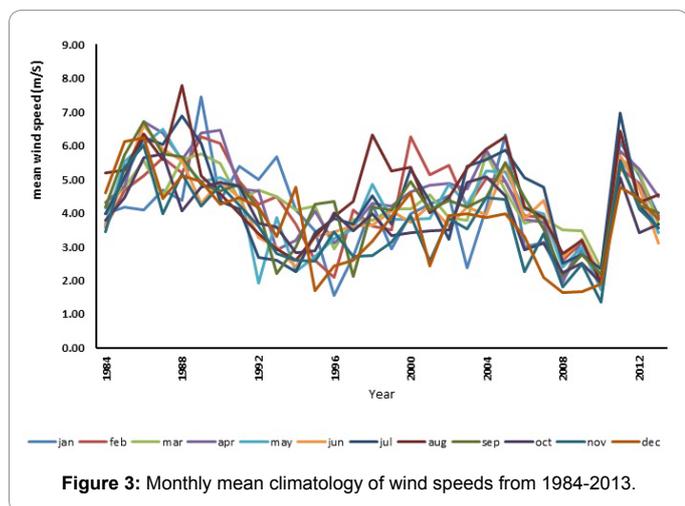
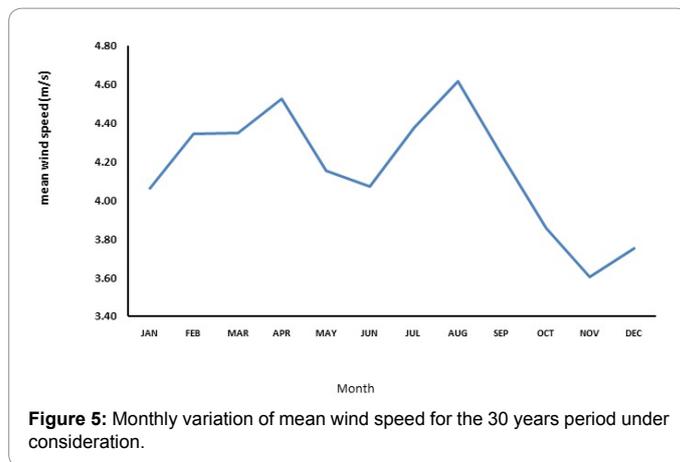
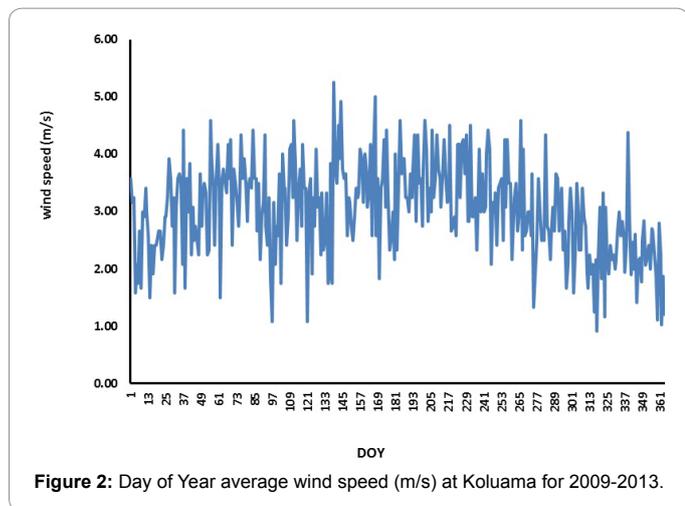
$$V_{ref} = V_{10} \left( \frac{h_{80}}{h_{10}} \right)^\alpha \quad (10)$$

Where  $V_{ref} = V_{80}$  = wind speed at 80 m,  $V_{10}$  = wind speed at 10-m height,  $h_{80}$  = 80 m height,  $h_{10}$  = 10 m height and  $\alpha$  = wind shear coefficient for the sites = 0.147 [26]. The mathematical expressions in equations 1-10 can also be found in previous available data [14-20,27,28].

## Results and Discussion

### Mean climatology

The wind climatology over the study area for the years 2009 to



2013 was investigated and shown in Figure 2 using average day of the year (DOY) wind speed (m/s). For the period considered, maximum mean DOY wind speed was approximately 5.25 m/s recorded on Julian day 139 while the minimum was 0.92 m/s recorded on Julian day 319. On the overall, mean wind speed distribution at the study site can be

broadly described as  $3.03 \pm 0.82$  m/s with a range of 4.33 m/s. Considering the thirty years monthly wind speed climatology, a decline in monthly mean wind was observed over the study area as shown in Figure 3. Also, a decline in yearly mean wind speed measurements from 1984-2013 was observed in Figure 4. The peak value of 5.95 m/s was observed in 1986, a low of 1.98 m/s in 2010 and a decreasing trend in wind speed at the rate of  $-0.044$  m/s per year is evident over the study area. Furthermore, the monthly variation of mean wind speed over the study area is presented in Figure 5. The highest observed value of mean wind speed is 4.62 m/s in August and the lowest of 3.60 m/s in November. Additionally, the mean wind speed during the dry months (December, January and February) and wet season (June, July, August and September) from 1984 to 2013 is presented in Figure 6. The average wind speed varies from 4.05 m/s in the dry months to 4.32 m/s in the wet months. This stronger wind regime during the wet season is expected have impact on rainfall and other weather related events considering Koluama's proximity to the Atlantic Ocean.

The prevailing wind direction at Koluama for January-December is shown in Figure 7. The dominant wind direction over the study area is southerly and south westerly winds throughout the year. It is important to note that there were few cases of strong northerly wind during the dry months of December and January. These observed wind directions over the study area is partly modulated by sea breezes from the Atlantic Ocean, while the seasonal wind reversal (monsoon) is responsible for the dominant south westerly wind in the wet season. However, during

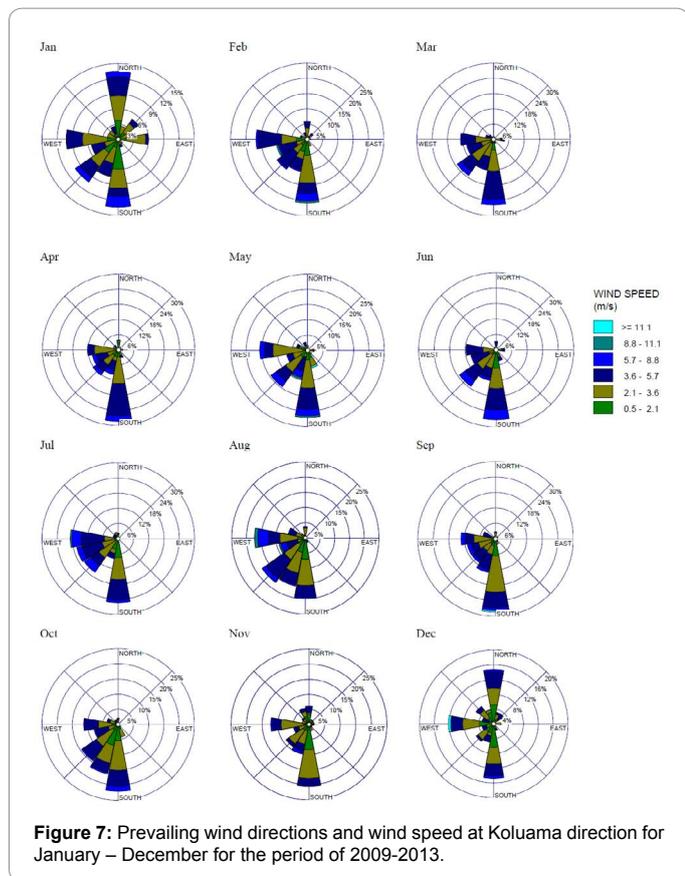


Figure 7: Prevailing wind directions and wind speed at Koluama direction for January – December for the period of 2009-2013.

Period	$V_m$ (m/s)	C	K	Weibull (m/s)	$\sigma$ actual (m/s)	$\sigma$ Weibull (m/s)
Jan	4.065	4.529	3.328	4.085	1.343	1.346
Feb	4.342	4.82	3.576	4.442	1.168	1.348
Mar	4.348	4.827	3.581	4.248	0.849	1.348
Apr	4.523	5.009	3.738	4.523	1.232	1.349
May	4.153	4.623	3.407	4.253	1.232	1.347
Jun	4.073	4.539	3.336	4.173	1.069	1.346
Jul	4.376	4.856	3.606	4.296	1.365	1.348
Aug	4.615	5.105	3.821	4.715	1.339	1.35
Sep	4.235	4.708	3.48	4.235	1.156	1.347
Oct	3.856	4.309	3.143	3.896	0.971	1.344
Nov	3.605	4.041	2.921	3.705	1.118	1.342
Dec	3.752	4.199	3.051	3.852	1.25	1.343
Dry	4.053	4.517	3.318	4.123	1.254	1.346
Wet	4.325	4.802	3.56	4.385	1.232	1.348
Whole year	4.162	4.632	3.415	4.192	1.174	1.347

Table 1: Weibull results and estimation parameters using 30 years wind speed data.

the dry months of December and January, the north easterly trade wind flows towards the ocean as a result of the monsoon retreat, which explains the observed strong northerly wind in the dry months.

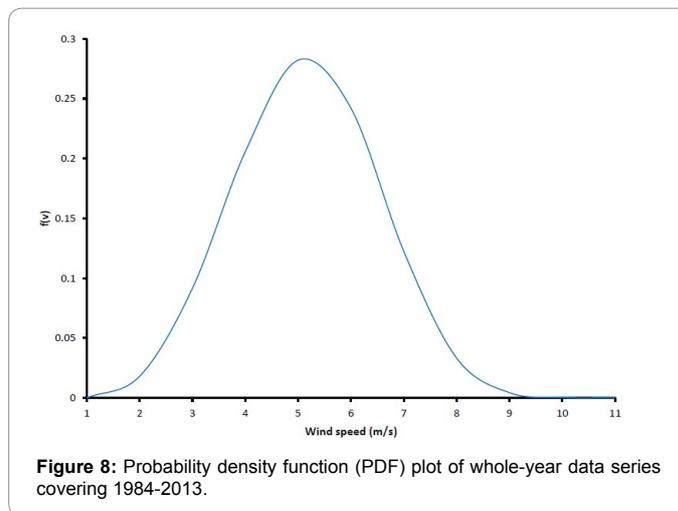


Figure 8: Probability density function (PDF) plot of whole-year data series covering 1984-2013.

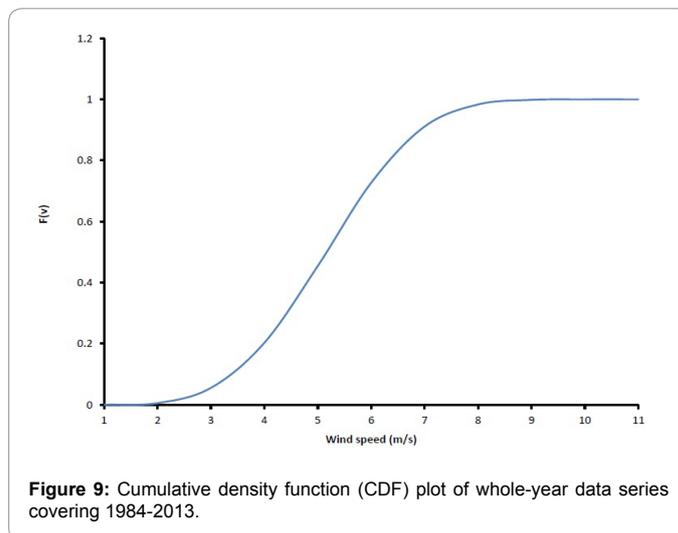


Figure 9: Cumulative density function (CDF) plot of whole-year data series covering 1984-2013.

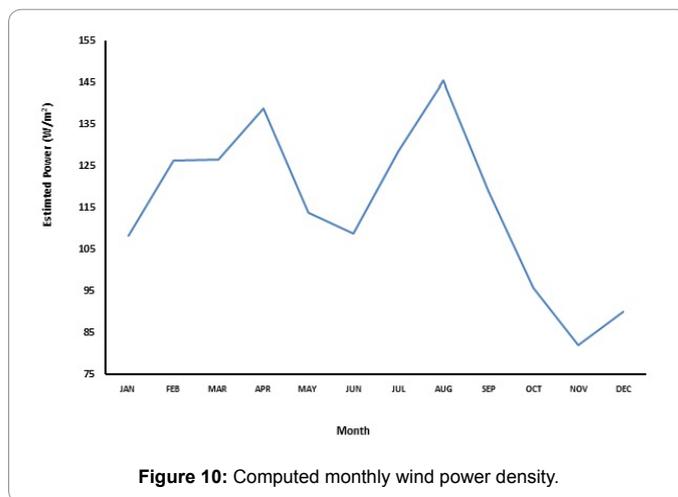


Figure 10: Computed monthly wind power density.

### Wind energy potential assessment

Using wind speed data from 1984 to 2013, Table 1 depicts results of the Weibull statistical analysis and the standard deviation for the predicted Weibull parameters k and c, used for the for corresponding

monthly PDF and CDF plots presented in Figures 8 and 9. The probability distribution function of wind speed is essential in evaluating the availability of wind power at a site. It also permits the selection of appropriate wind machines for exploiting the wind energy. The 30 year average  $k$  and  $c$  Weibull parameters obtained were used in equation 1 to obtain probability distribution for the different wind speeds from 1 m/s to 11 m/s (incremental of 1 m/s) which is then plotted in Figure 8 and the cumulative probability plotted in Figure 9. These figures reveal that up to 70% of the data series ranged from about 2.0 to 5.8 m/s. The most probable wind speed at the site is about 4.2 m/s while wind speed greater than 8.0 m/s shows very low probability.

Figure 10 depicts the estimated monthly wind power, generated at Koluama. Two peaks occurred in April (139.79 W/m<sup>2</sup>) and August (145.48 W/m<sup>2</sup>) and a low in November (81.94 W/m<sup>2</sup>). Also, two decreasing wind power trends were observed: i) April through June and ii) August through November. Similarly, two increasing wind power trends: i) June through August and ii) November through April. Furthermore, because the majority of the available turbine hub heights are at 80 m, the wind profile characteristics were estimated for this height using equation 10. The speeds at this new height were then employed for Weibull re-analyses. Thus at heights above 10 m, the economic viability of wind energy at the site is best investigated using equation 10. The wind speed profile between heights 10 to 100 m is presented in Figure 11.

### Adapting real wind turbine to Koluama

Previous studies have evidently shown that wind turbine installation is capital intensive [27-29]. Therefore it is important to assess turbine

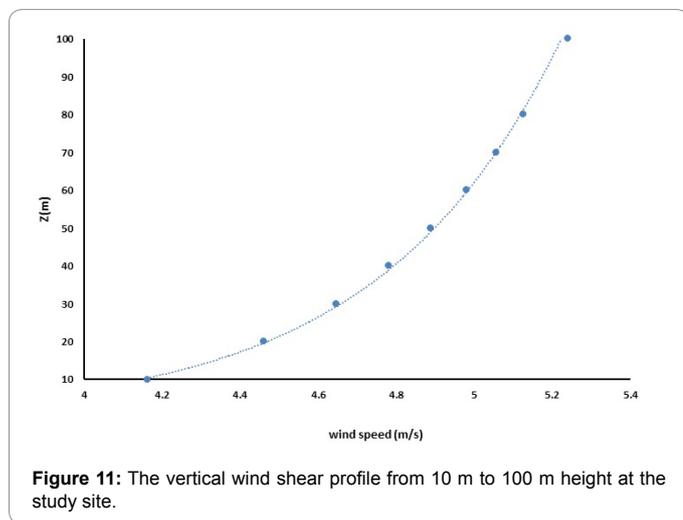


Figure 11: The vertical wind shear profile from 10 m to 100 m height at the study site.

Wind turbine	V <sub>c</sub> (m/s)	VF (m/s)	VR (m/s)	PeR (kW)	Hub Height (m)	Rotor diameter (m)
GE 1.5sle	3.5	25	14	1500	65/80	77
GE 1.5xle	3.5	20	11.5	1500	80	82.5
AV 928	3	25	11.6	2500	80	93.2
AV 927	3	25	13.1	3300	60/80	93.2
V 90	4	25	15	3000	80	90
SWT-3.6.107	3	25	13	3600	80	107

Table 2: Technical details of the wind turbine model.

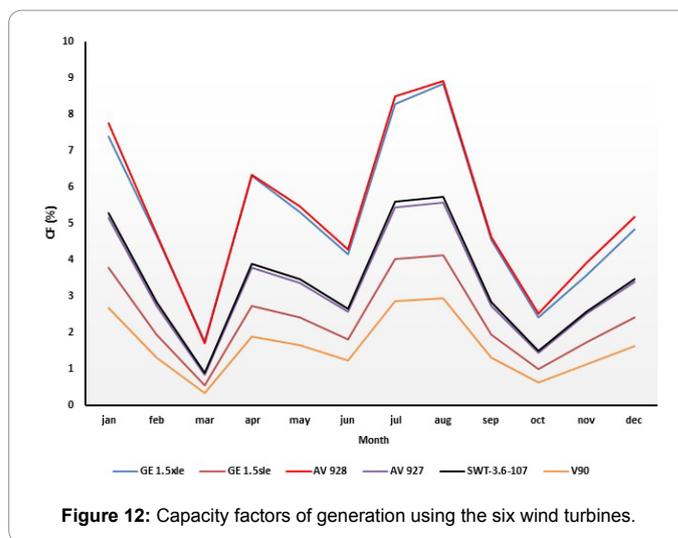


Figure 12: Capacity factors of generation using the six wind turbines.

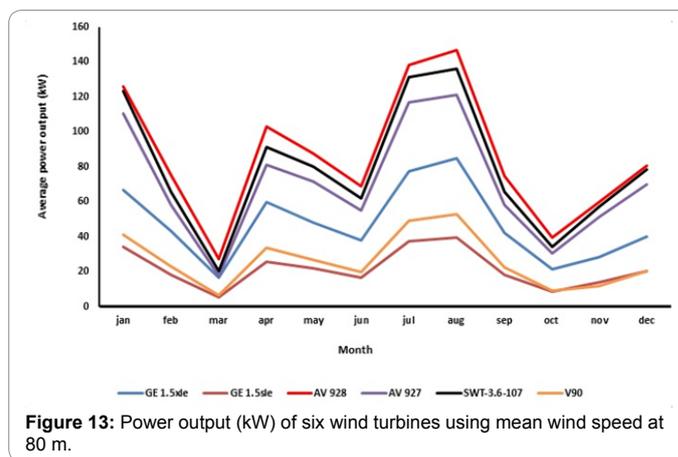


Figure 13: Power output (kW) of six wind turbines using mean wind speed at 80 m.

parameter relative to the site's wind profile. This entails estimating the amount of electrical power that a particular wind turbine will likely generate and thus, the estimated Capacity Factor (CF) is a pointer to the turbine's generation capacity. Based on the above, we assessed six different turbines with technical parameters given in Table 2. Equations 7-9 were then used to evaluate the power output from each of the turbines. Figure 12 depicts the estimated capacity factor of generation for six turbines: GE 1.5xle, GE 1.5sle, AV 928, AV 927, SWT-3.6-107 and V 90. Capacity factors (in %) of generation peaked in August with approximate values of 9, 4, 9, 6 and 3 respectively while been lowest in March. Turbines GE 1.5xle and AV 928 had the highest capacity factors of generation at the study site. The monthly average power output (kW) for the six turbines: GE 1.5xle, GE 1.5sle, AV 928, AV 927, SWT-3.6-107 and V 90 were 47, 22, 86, 70, 71 and 26 respectively as seen in Figure 13. This result indicates that the AV 928 had the highest energy production (kW) of the turbines considered.

### Conclusion

This study assessed the wind energy potential for power generation over Koluama, Bayelsa State, Nigeria. Thirty years of mean wind data at 10 m height were assessed and analyzed. Also, the data was subjected to Weibull two-parameter and other wide range of statistical analyses. The results revealed the following:

- i. Monthly mean wind speeds peaked in August at 4.62 m/s and

were at a low in November at 3.60 m/s. A secondary peak was further observed in April at 4.52 m/s. Some seasonal variability was observed between the dry (DJF) and wet (JJAS) months mean wind speeds, with lower mean wind speed of 4.05 m/s in DJF and a higher value of 4.32 m/s during the wet JJAS period;

ii. Maximum (minimum) recorded annual mean wind speeds was 5.95 m/s (1.98 m/s) in the year 1986 and 2010 respectively. The wind speed exhibited a decreasing trend of -0.044 m/s per year;

iii. Annual prevailing wind direction over the study area was majorly southerly, south-westerly and westerly. This may be attributed to the proximity of the Atlantic ocean;

iv. Maximum estimated wind power density ( $145.48 \text{ W/m}^2$ ) was observed in August and at a low in November with  $81.95 \text{ W/m}^2$ ;

v. Turbine monthly power output peaked in August and was least in March and October. The AV 928 turbine had the maximum energy output followed by the SWT-3.6-107. However, the capacity factor was relatively low (~10%) and this raises concern about the economic viability of large scale wind power project in the study site.

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