BERKELEY PUBLICATION AND RESEARCH INTERNATIONAL

12.31.2022

Journal of African Research & Sustainability Studies Vol. 20 No.2

ESTIMATION OF WIND LOAD AND WIND POWER DENSITY FOR SOME SELECTED CITIES IN NIGERIA BASED ON TWO PARAMETRIC MODELS

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ABSTRACT

Wind is freely available in all seasons and locations without seasonal variations, unlike the hydropower plant that can provide steady electricity during raining season, if not, load shedding. In this study, we used two models based on the Weibull probability distribution function (PDF) and log-normal probability distribution functions (PDF) to predict the wind characteristics of two selected stations (Abuja, Plateau, Bauchi, Maiduguri, Katsina, Sokoto, Enugu, Owerri, Cross River, Benin City, Abeokuta, and Lagos) across the six geopolitical zones in Nigeria. We also estimate wind load, wind power density, shape parameters, and scale parameters for each geopolitical zones in Nigeria. Twenty years (2000 – 2020) of average wind speed data were used and obtained at NIMET Headquarters Abuja. The wind speed data were fitted with the Weibull probability distribution function (pdf) and log-normal probability distribution function (pdf) governed by statistical analysis to predict which model is found to be the best fit for a particular location. The result of root means square error (RMSE) and coefficient of the goodness of fit (R^2) show that both models are positively and strongly correlated with a value ranging from 0.6813 – 0.9827 and 0.6542 – 0.9919. The computed wind load for North – East, North – West, North – Central, South – South, South – West, and South – East were

Introduction:

The need for energy in Nigeria is on an increase daily Celik, A.N. (2011). This increasing demand can be met by exploring new energy resources. Wind energy is a renewable energy resources created from a clean energy source with almost zero or little emission of greenhouse gases (Fyrippis *et, al.,* 2010) and (Zindong *et, al.,* 2017). Wind energy contributes very little to Nigeria's energy mix because is at its early stage of development which can provide the energy security of any country, when properly assessed, predicted, and estimated. Unlike conventional energy which fluctuates due to volatile prices associated with the shortage of water from dams as well as the importation of fossil fuels, which is a huge burden on Nigeria's economy (Manga *et, al.,* 2022). The price of the energy produced by wind does not increase as much as that of conventional energy which oscillates with the seasonal or unstable market price of oil (Ding *et, al.,* 2019).

given as 1.149(kN/m^2), 2.196(kN/m^2), 1.098(kN/m^2), 0.026(kN/m^2), 0.879(kN/m^2) and 0.529(kN/m^2) respectively. Similarly the computed wind power density for North – East, North – West, North – Central, South – South, South – West, and South – East as 17.201 (W/m^2), 17.453 (W/m^2), 8.744 (W/m^2), 3.396 (W/m^2), 7.643 (W/m^2) and 5.759 (W/m^2) respectively. The results of this study can be used for surface wind electrification.

Keywords: wind speed; wind load; wind power density; log-normal probability distribution function and Weibull probability distribution function.

According to Yaniktepe et, al., (2013) said, the energy that can be extracted from the wind is directly proportional to the cube of the wind speed, so an understanding of the characteristics of wind (velocity, direction, variation) is critical to all aspects of wind energy generation, from the identification of suitable sites to predictions of the economic viability of wind farm projects to the design of wind turbines themselves, all is dependent on characteristics of wind profile of any location (Edafienene *et al*, 2010). The most striking characteristic of the wind is its stochastic nature or randomness (Lepri *et, al.,* 2017). The wind is highly variable, both geographically and temporally. Moreover, this variability exists over a very wide range of scales, both in space and time. This is important because extractable energy from wind varies with the cube of wind velocity (Melchers *et, al.,* 2018). This variability is due to different climatic conditions in the world also the tilt of the earth on its axis and its spinning results in different wind distributions across the world (Loredo Souza *et, al.,* 2017).

In this research, wind data such as its velocity, variant, loads, and power density for Bauchi, Maiduguri, Sokoto, Katsina, Abuja, Plateau, Abeokuta, Lagos, Benin City, Cross River Enugu, and Owerri. Where investigated by using statistical analysis to perform a goodness of fit test (mert *et, al.,* 2015). Furthermore, Weibull probability density functions (pdf) and log-normal probability density functions (pdf) were adopted to define the wind speed distributions across each location and the wind load and wind power density were computed based on statistical analysis results for surface wind electrification (Manga *et, al.,* 2021).

Materials and Methods

Source of Data

The wind speed data were obtained from NIMET Head Quarter Abuja. The daily average wind speed data of twelve selected stations across six geopolitical zone for a period of twenty years (2000 - 2020) were used.

Wind Speed Prediction

The measured wind speed at a height of 3 m may not be sufficient to set turbines into mechanical rotation. Higher wind speeds obtainable at greater heights have to be considered. Therefore, the Hellman power law is used to predict the wind speeds at heights 15, 30, 40, 50, 60, 70, and 80 m. this law is given (Arik *et, al.,* 2019) as:

$$v_h = v\left(\frac{h}{h_0}\right)^{\propto} \qquad (1)$$

where α = ground surface friction coefficient (0.40)

h_0 = reference height (3 m)

$h =$ height at which v_h is predicted.

Wind Power Density

In assessing the wind power potentials of a candidate site, it is the root-mean-cube (rmc) wind speed that is considered. This is because different stations may have the same average wind speed but different rmc power densities. The available wind power density at a rotor efficiency, C_p = 50% is given by (Manga *et, al.,* 2021):

$$P_a = \frac{1}{2} c_p \rho v_{rmc}^3 \quad (2)$$

Where v is the wind speed and ρ is the air density

The mean air density

The air density depends on temperature and pressure (and thus altitude) and can vary by as much as 10–15% seasonally. If the site pressure is measured, the air density can be calculated from the ideal gas law given by (Ayin, D. 2018):

$$\rho = \frac{P}{RT} \quad (\text{kg}/m^3) \quad \ldots (3)$$

Where P = site air pressure (Pa or N/m^2)
R = specific gas constant for dry air (287.04 J/kgK)
T = the air temperature in degrees Kelvin (^{0}C+273.15).

If the site pressure is not available (as is usually the case), the air density can be estimated as a function of the site elevation and temperature, as follows (Cantelli *et, al.,* 2017):

$$\rho = \left(\frac{P_0}{RT}\right) e^{\left(\frac{-gx}{RT}\right)} \quad (\text{kg}/m^3) \quad \ldots (4)$$

Where P_0 = Standard sea-level atmospheric pressure in Pascal (101,325 Pa); T = Air temperature (K); T (K) =T (^{0}C) +273.15; g = gravitational constant (9.807 m/s^2); z = the elevation of the temperature sensor above mean sea level (m).

After substituting the numerical values for P_0, R, and g, the equation becomes:

$$\rho = \left(\frac{353.05}{T}\right) e^{-0.0341\frac{z}{T}} \quad (\text{kg}/m^3) \quad \ldots (5)$$

While this equation is quite accurate (to within 0.2 % at most sites), the error increases with increasing elevation because the air pressure does not follow the exponential function exactly (Elshaer *et, al.,* 2019).

Wind load

The destruction of buildings is threatened by high wind speeds in open areas, especially mechanical structures, wind turbines, and stationary poles (Elshaer *et, al.,* 2019). Wind loads are calculated by using wind speed, mass air density, pressure coefficient, and parameters based on statistical data (Firat and Yücemen 2012); for different structures, the wind load can be rewritten as follows

$$W = c.c_p E_z G V^2 \quad \ldots (6)$$

ISSN: 1213-4977

Where: Wind load (W); the constant associated with air mass density (c); Coefficient of Pressure based on NACA 4415(c_p); Coefficient of exposure(E_z); gust factor(G); wind speed (V)

Perhaps the pressure factor depends on the 2D geometry generated from the Ansys gambit for NACA4415. This coefficient of pressure is said to change proportionally to buildings or obstructions (Dogbey et, at., 2010).

E Z is the coefficient of the exposure this depends on the terrain topography such as a city with tall buildings, closed valleys, and hills. G Is the gust factor that depends on turbulence? These features are all put into consideration in assessing the wind load for two selected cities across the six geopolitical zone of Nigeria (Elshaer *et, al.,* 2019).

On the same note, the evaluation of wind energy potential involves comparing wind speed cubes. The overall energy can be expressed as (Edafianene *et, al.,* 2010).

$$E_v = \int_0^\infty P_v f(v) dv \qquad \text{... (7)}$$

Whereby $f(v)$ is the wind speed distribution of probability density (Hou *et, al.,* 2012)

Log-Normal distribution methods

The density of the wind stream of air velocity based on Log-Normal can be expressed as (Manga *et, al.,* 2021)

$$f(x) = exp\left[-\frac{1}{2}\left(\frac{In(v)-\mu}{\sigma}\right)^2\right] x \frac{1}{\sigma v\sqrt{2\pi}} \qquad \text{... (8)}$$

Where v is the wind speed, σ is the scale parameter and μ is the mean wind speed of the location Log – Normal distribution gives us the probability of dispersion of a random variable which said to be valid or not valid by inspecting the available plot of the wind speed data on the histograms (Tavares *et, al.,* 2014).

Two-parameter Weibull Distribution

The Weibull distribution is a mathematical function that is often used to represent the frequency distribution of the wind speed at a site. In the Weibull distribution, the probability density (i.e. the probability that the speed will fall in a bin of unit width centered on speed (v) is given by the equation (9) (Weibull, 1951) and (Manga *et, al.,* 2021) as:

$$\text{f}(v) = \frac{K}{c}\left(\frac{v}{c}\right)^{K-1} e^{-\left(\frac{v}{c}\right)^K} \qquad \text{...(10)}$$

The corresponding cumulative distribution function is given by equation (11) as:

$$\text{F}(v) = 1 - e^{-\left(\frac{v}{c}\right)^K} \qquad \text{... (11)}$$

Where k is a dimensionless factor that determines the shape of the curve; c (m/s) is the scale parameter related to wind speed. The parameters c and k are collectively known as the Weibull parameters.

Errors Analysis

In this research, we assessed the degree of linear relationship between the wind speed data and the gamma probability distribution function and Log – Normal probability density function by checking the level error and coefficients of the goodness of fit (R^2) statistically. The Root Mean Square Error is calculated as follows (Mert *et, al.,* 2015)

$$RMSE = \left[\frac{1}{N}\sum_{i=1}^{N}(y_i - x_i)^2\right]^{0.5} \quad \dots (12)$$

$$R^2 = 1 - \frac{\sum_{i=1}^{N}(y_i - x_i)^2}{\sum_{i=1}^{N}(y_i - \bar{y})^2} \quad \dots (13)$$

Where N is total interval numbers, y_i is the observed wind velocity frequency, x_i probability density value is the mean of the wind speed data. In this case, if the RMSE value is low while R^2 is large the result is more valid or the proposed model will be accepted (Manga *et, al.,* 2022).

Results and Discussions

The results of the annual average wind speed, standard deviation, shape parameters, and scale parameters across the six geopolitical zones were given in table 1.

Parameter's	North-Central	North-East	North-West	South-South	South-East	South-West
μ	2.6204	3.4767	3.4675	2.3063	2.4546	2.6266
δ	0.8319	0.7329	0.8064	0.3897	0.3945	0.6085
α	0.9153	1.2243	0.0541	0.6931	0.8852	0.9396
β	0.3099	0.2085	0.1875	0.1896	0.1597	0.2286
K	3.4762	5.4228	4.8745	6.0239	7.2795	4.8955
C	2.9170	3.7692	3.7851	2.1923	2.6091	2.8665

Table1. Estimated parameters for calculation of Weibull and log-normal probability distribution function.

It was clearly shown that the highest monthly average wind speed was recorded in the North-East and North-West with a value of 3.4767m/s and 3.4675m/s with a corresponding standard deviation of 0.7329 and 0.8064 for both stations. This is a way forward to justify the argument by many researchers on the availability of wind potential in some parts of Nigeria. On the same note α, β, K and C are shape parameters and Scale parameters for both Weibull and log-normal probability density functions as presented in figures 1-3.

The calculated monthly average wind speed data was interpolated to give the wind speed characteristics of the selected stations across the six geopolitical zones in Nigeria as shown in figure 1. The results show that Abuja, Plateau, Katsina Sokoto, Bauchi, and Maiduguri have a recorded high availability of wind energy potential in January, February, March, and November with a value ranging from 4.03m/s – 4.98m/s while Benin City, Abeokuta, Lagos, Cross – River, and Owerri has its highest wind speed in July, August and September with a value ranging from 2.17m/s – 2.91m/s. On the other hand, the lowest value was recorded for Abuja, Plateau, Katsina

Sokoto, Bauchi, and Maiduguri in August and September ranging from 1.60m/s – 2.64m/s while in Enugu, Benin City, Abeokuta, Lagos, Cross-River and Owerri has a lowest recorded wind speed in October and November with a value ranging from 1.45m/s – 1.95m/s

Figure 2-3 is the plots of probability density functions across the six geopolitical zones in Nigeria. The result shown, give the wind profile of each zone based on shape and scale parameter as required in the Weibull probability distribution function (pdf) and log-normal probability distribution function (pdf). It also governed the ability of a wind machine to perform the desired function without breakdown for surface wind electrification.

Statistical analysis was conducted on the two models based on Weibull (pdf) and log-normal (pdf) to assess the degree of a linear relationship between the two models. The result shows that the North-Central, North-East, North-West, South-South, South-East, and South-West have recorded R^2 values of 0.7721, 0.8922, 0.9823, 0.6823, 0.7448 and 0.7678 with a recorded Root Mean Square Error (RMSE) of 0.8786, 0.9446, 0.9911, 0.8260, 0.8630 and 0.8762 for both Weibull (pdf) and log-normal probability distribution function (pdf). The result also shows that the two models are positively and strongly correlated with the available wind speed data for each selected station. The two models were found to be valid and accepted for surface wind electrification.

Figure 4-7 is the plot of computed wind load and computed wind power density across the six geopolitical zones in Nigeria. The result shows that the extractible wind energy by the rotor blade dynamic machine varies with wind velocity, surface roughness, and height above the ground. It was also shown that there is a trend between the monthly average wind speed (m/s), wind power density (W/m^2) wind load (KN/m^2). As the wind speed increases, the wind load and wind power density also rise across the selected stations

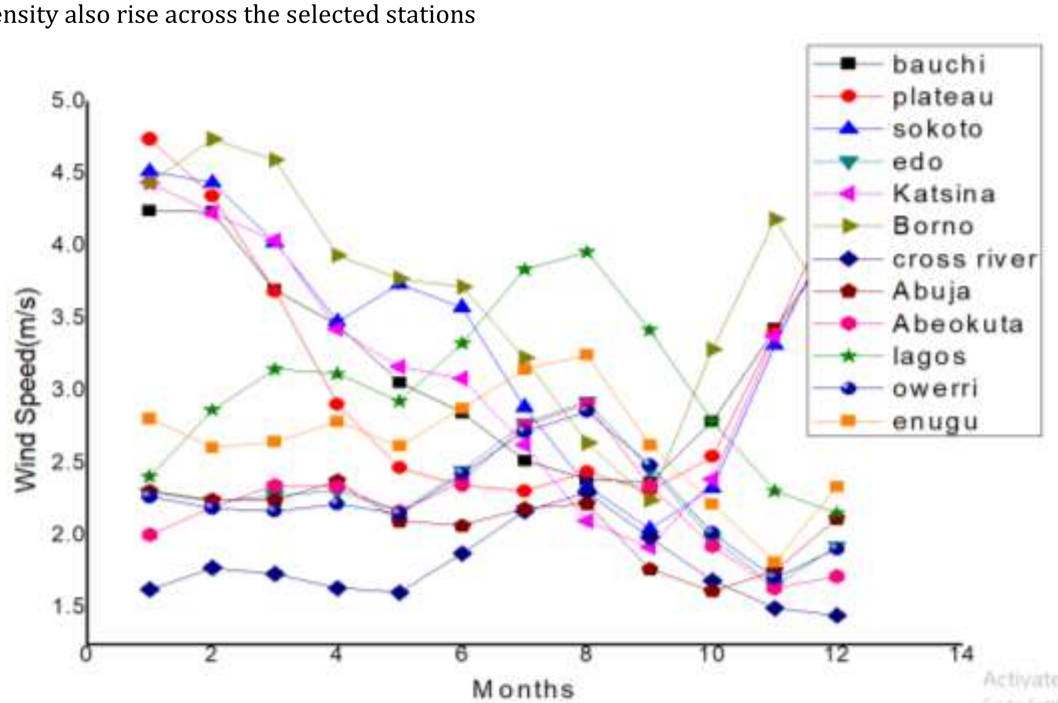
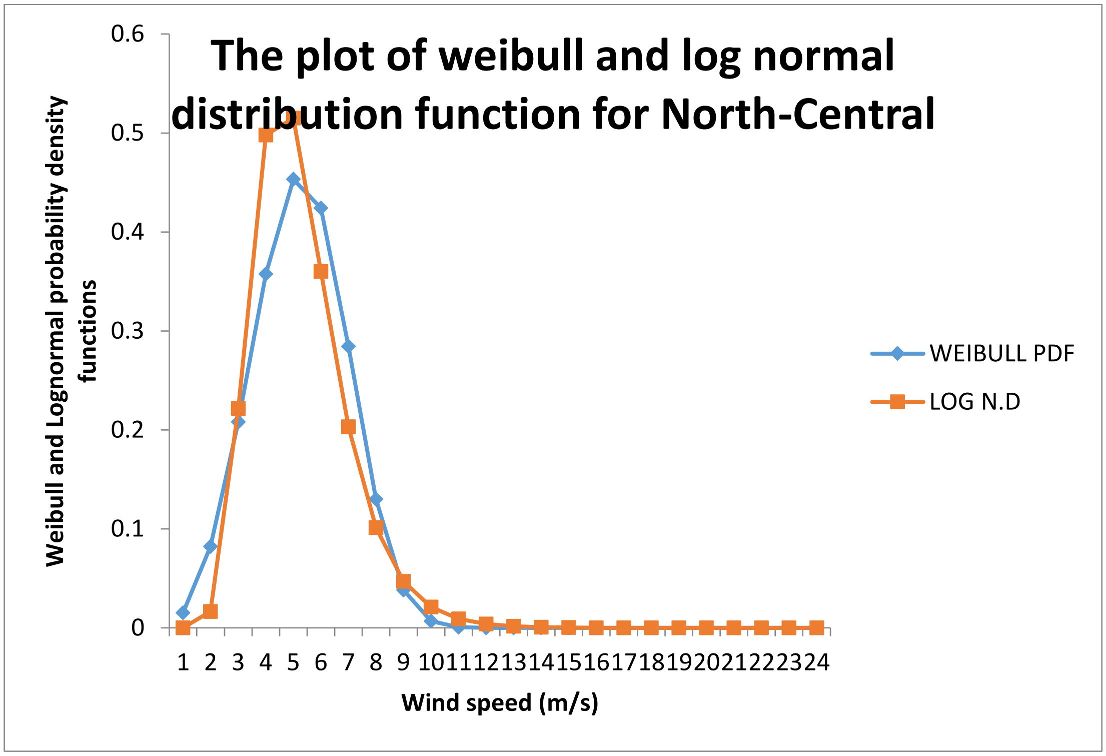
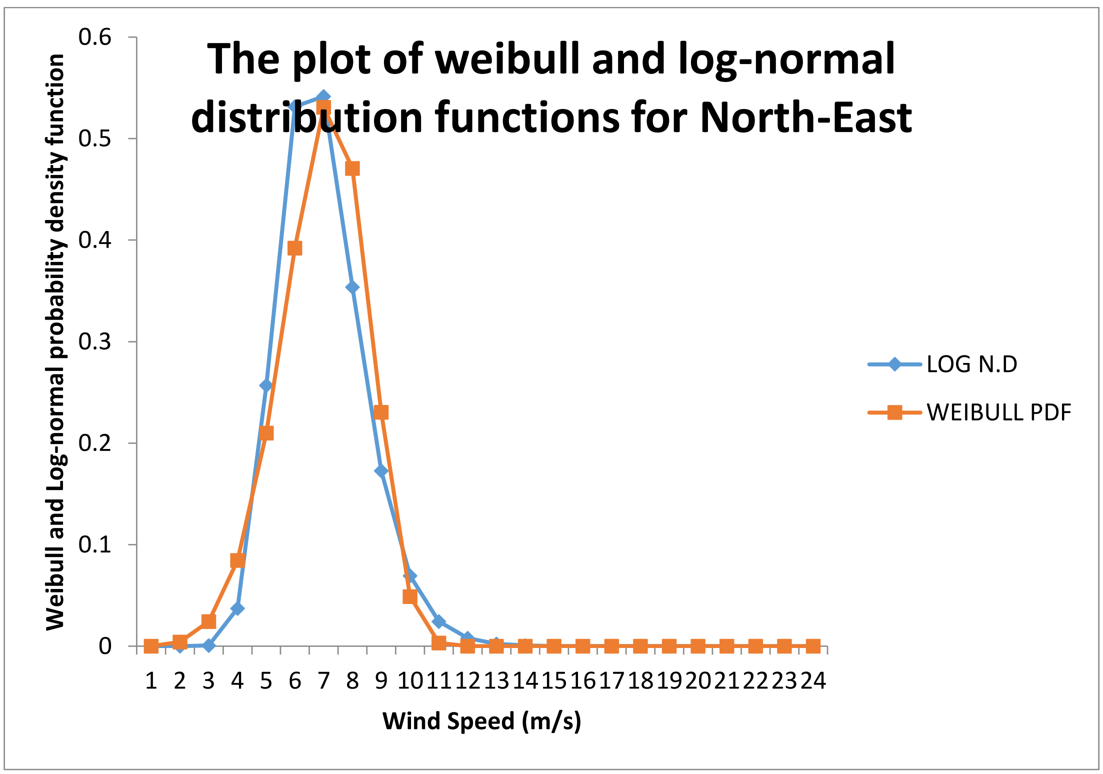


Fig1. The Plot of Monthly Average Wind Speed data for twelve selected stations across the six geopolitical zones in Nigeria


The plot of weibull and log normal distribution function for North-Central
Weibull and Lognormal probability density functions
0.6
0.5
0.4
0.3
0.2
0.1
0
1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24
Wind speed (m/s)
WEIBULL PDF
LOG N.D


The plot of weibull and log-normal distribution functions for North-East
Weibull and Log-normal probability density function
0.6
0.5
0.4
0.3
0.2
0.1
0
1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24
Wind Speed (m/s)
LOG N.D
WEIBULL PDF

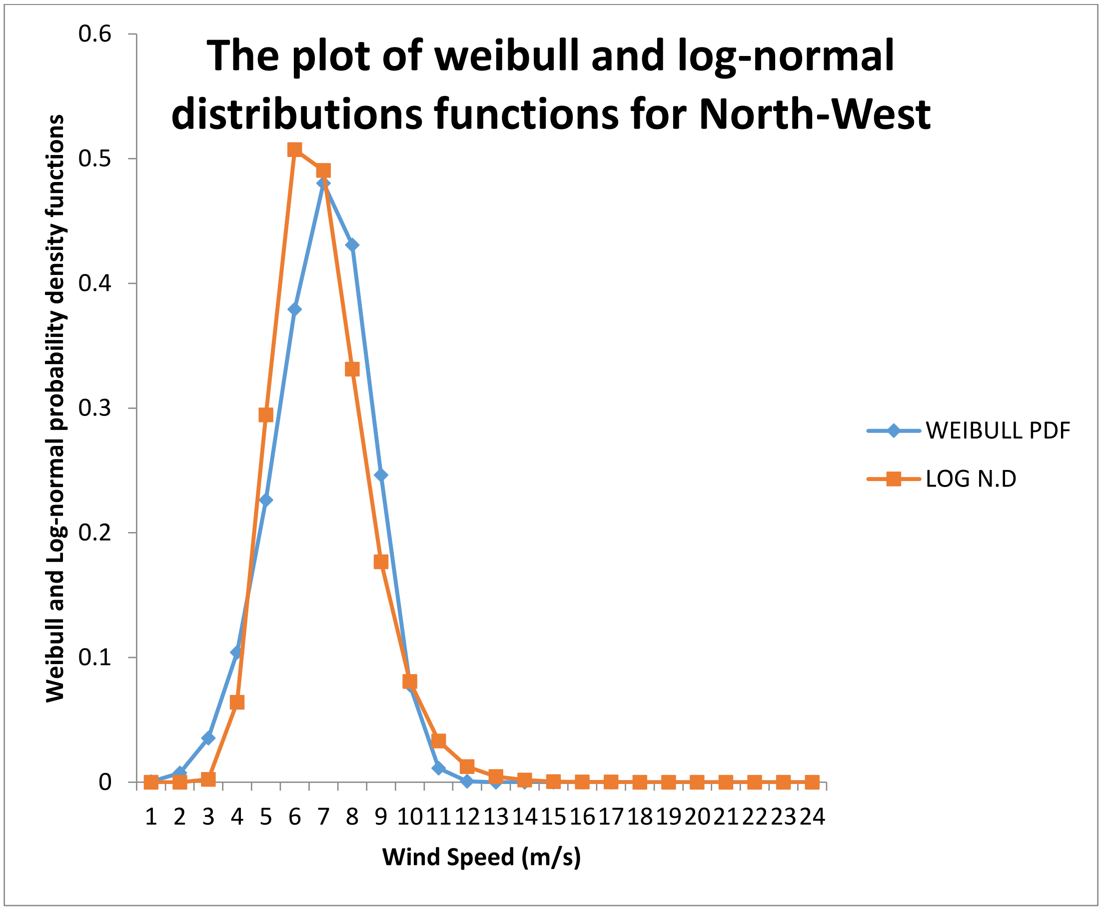
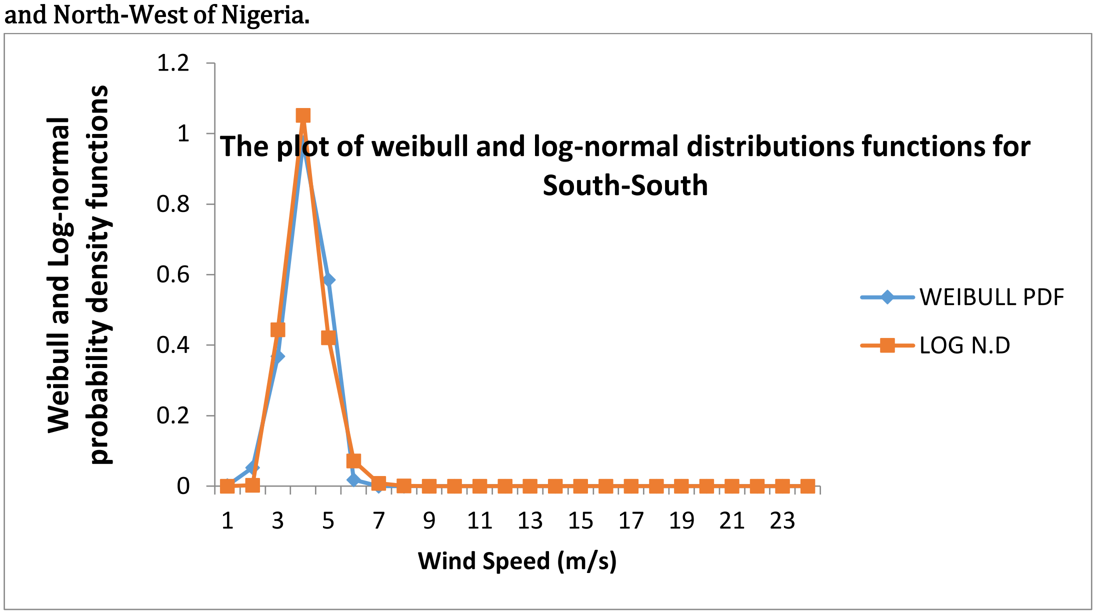


Fig 2. The plot of Weibull and log-normal distribution functions for North-Central, North-east, and North-West of Nigeria.



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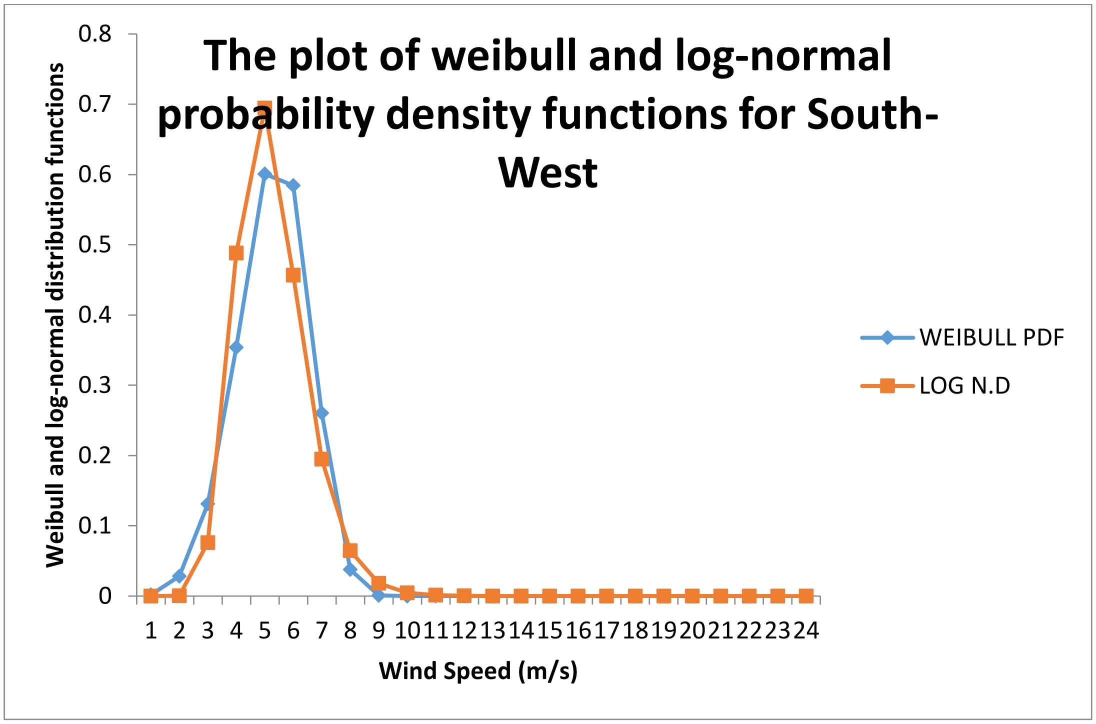


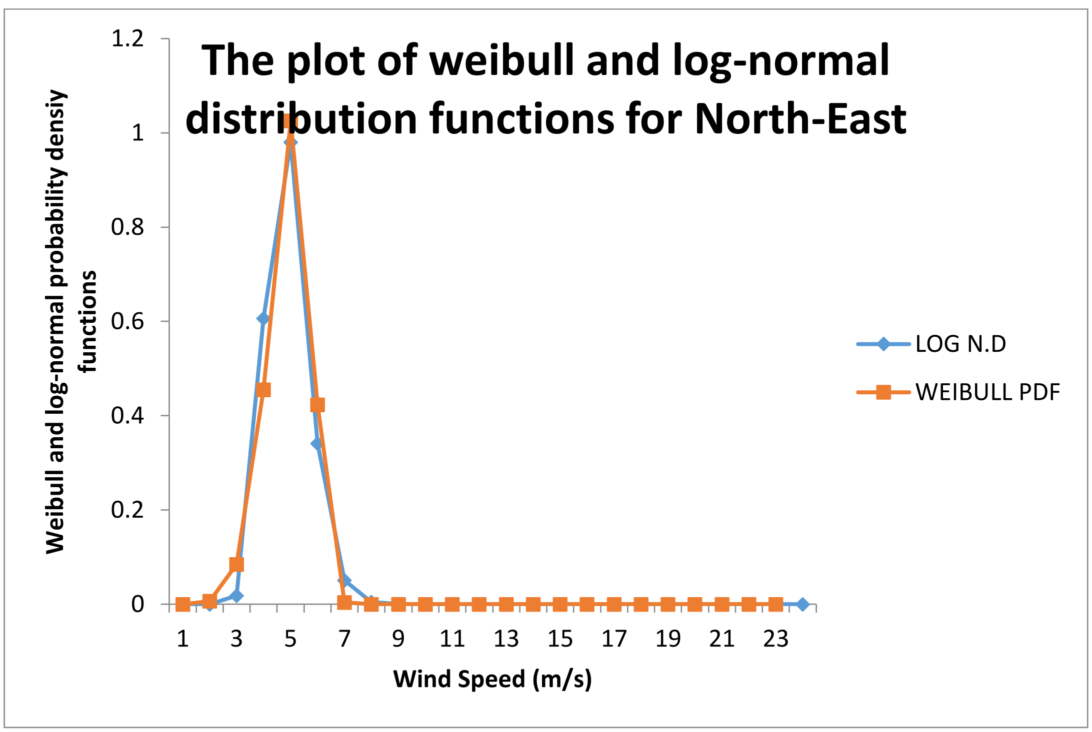
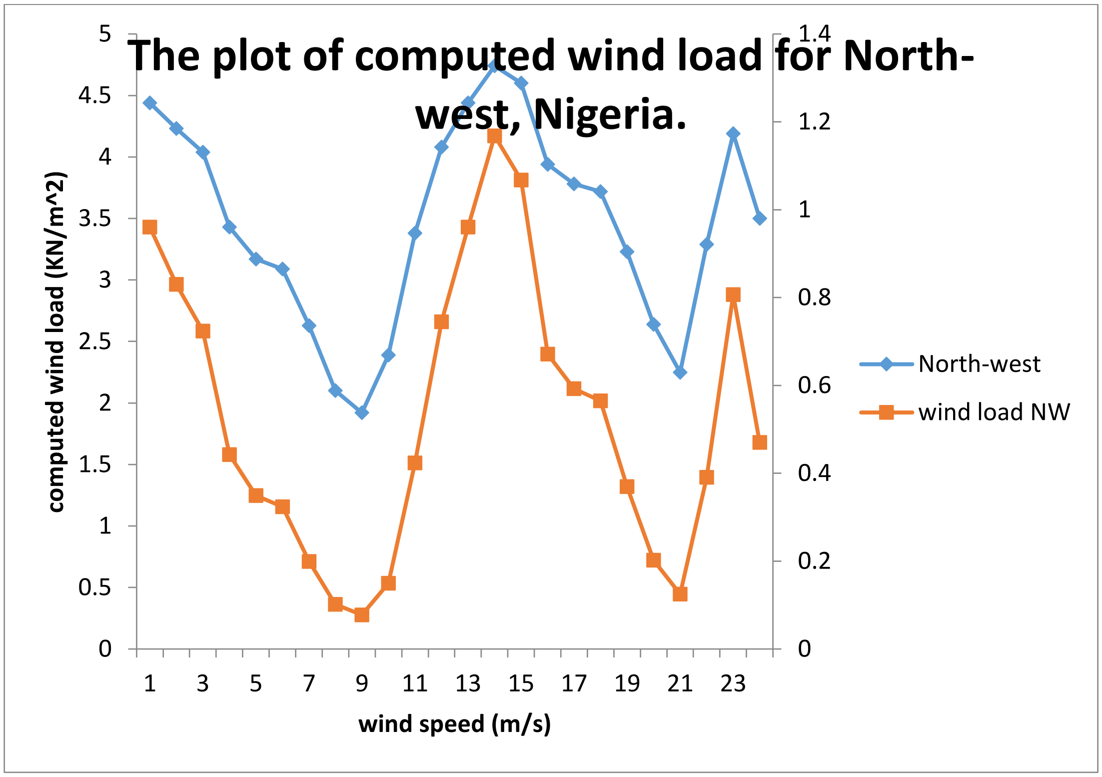
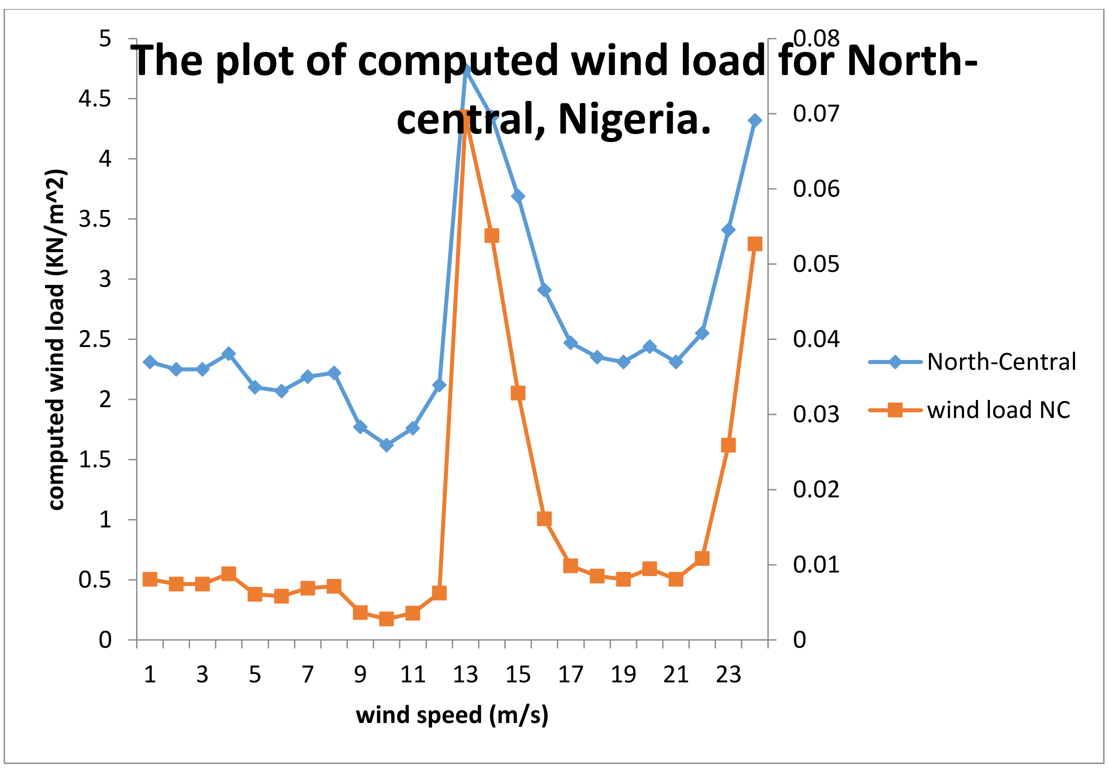


Fig 3. The plot of Weibull and log-normal distribution functions for South-South, South-East, and South-West of Nigeria.


The plot of computed wind load for North-west, Nigeria.
computed wind load (KN/m^2)
wind speed (m/s)
North-west
wind load NW


The plot of computed wind load for North-central, Nigeria.
computed wind load (KN/m^2)
wind speed (m/s)
North-Central
wind load NC

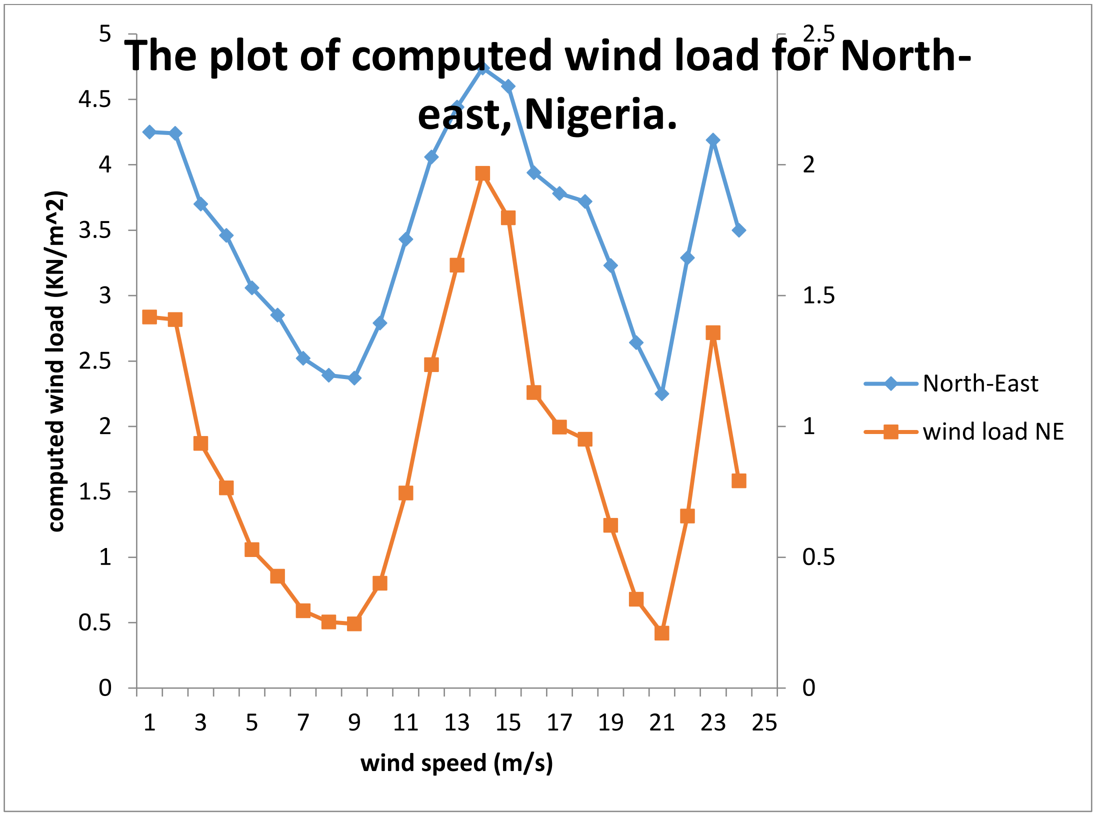
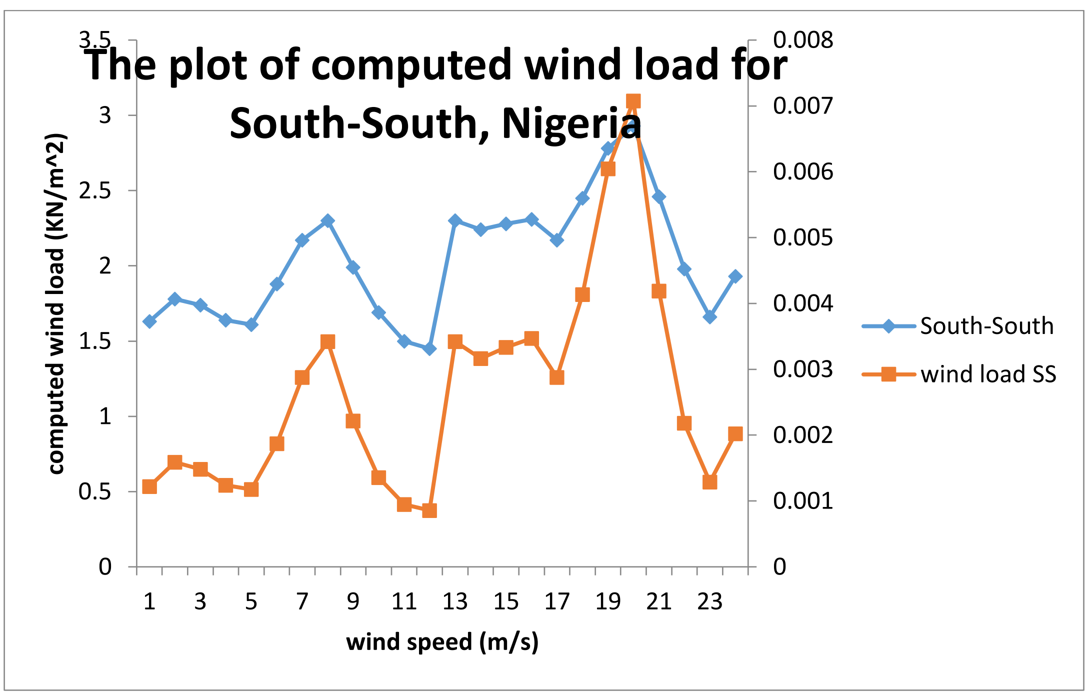
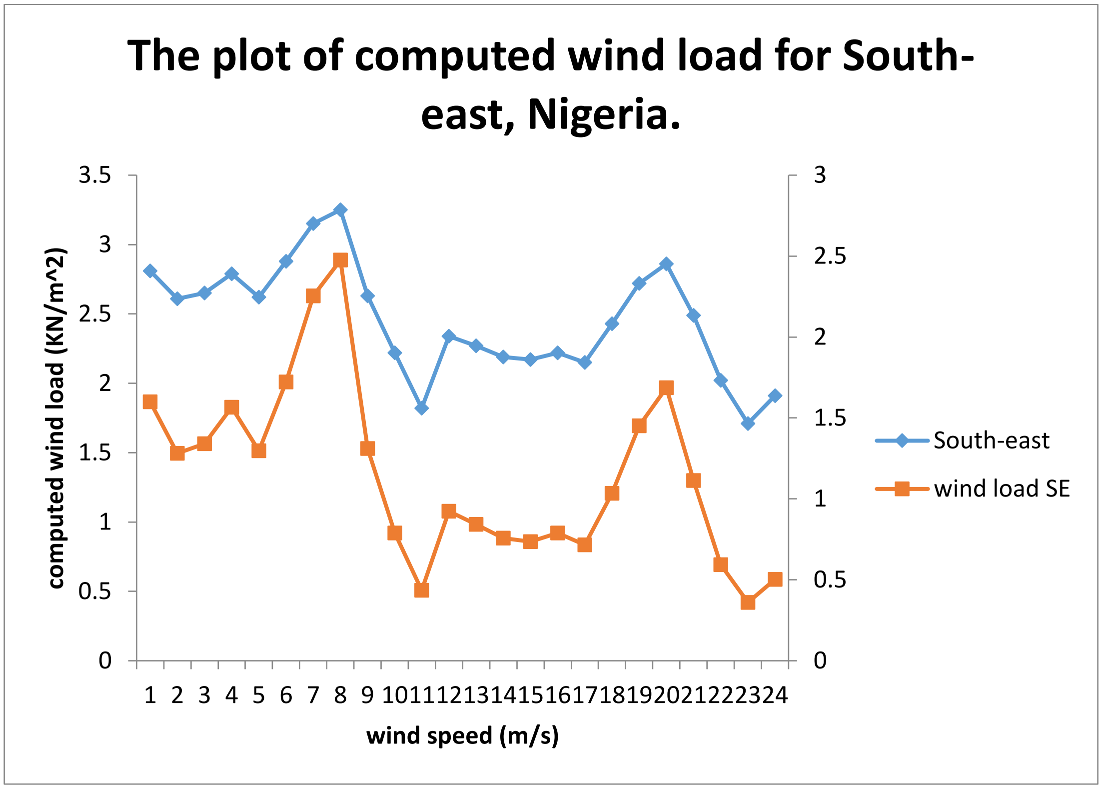


Fig4. The plot of computed wind load for North-East, North-West, and North-Central, Nigeria.





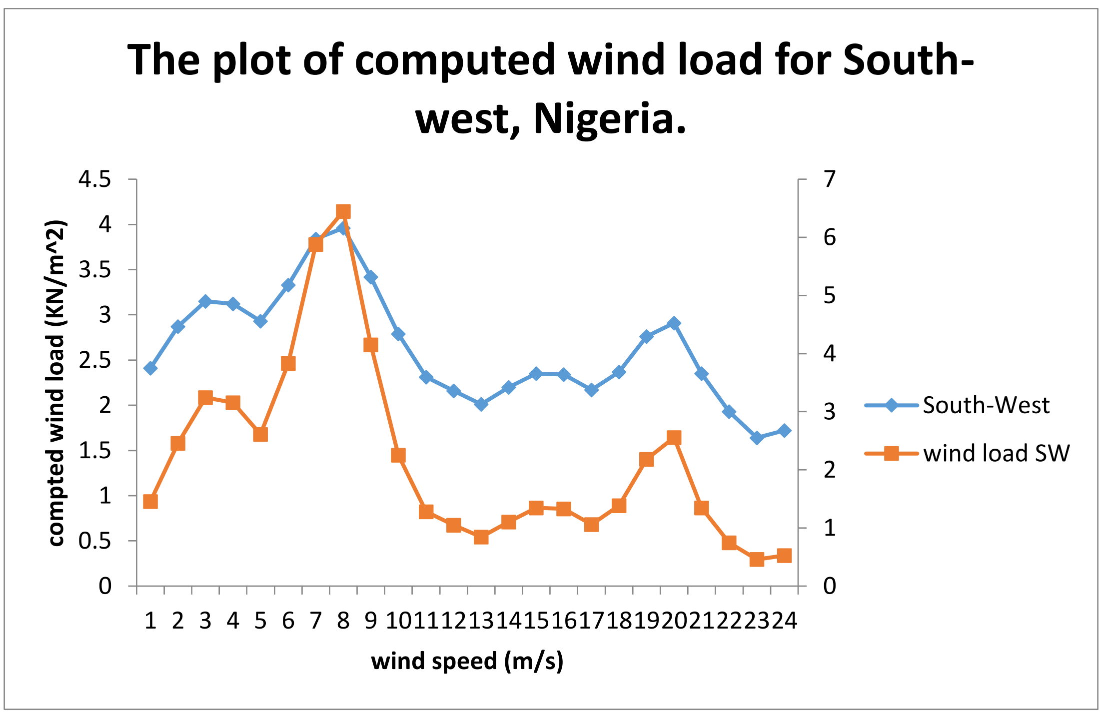
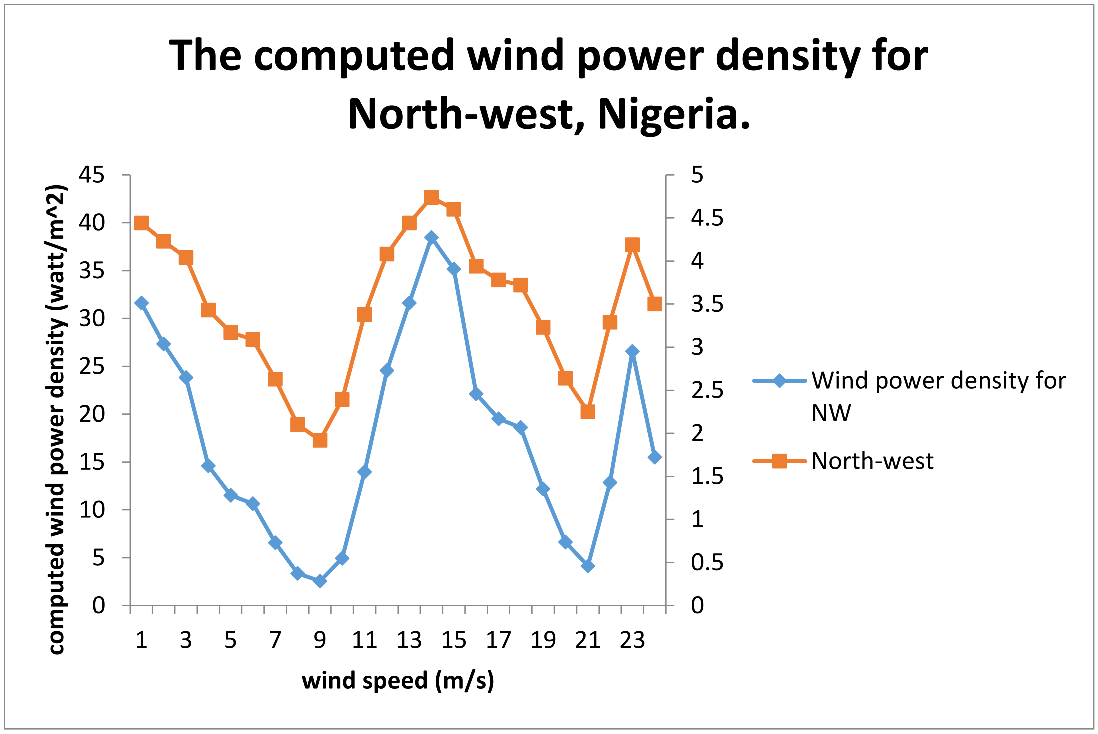
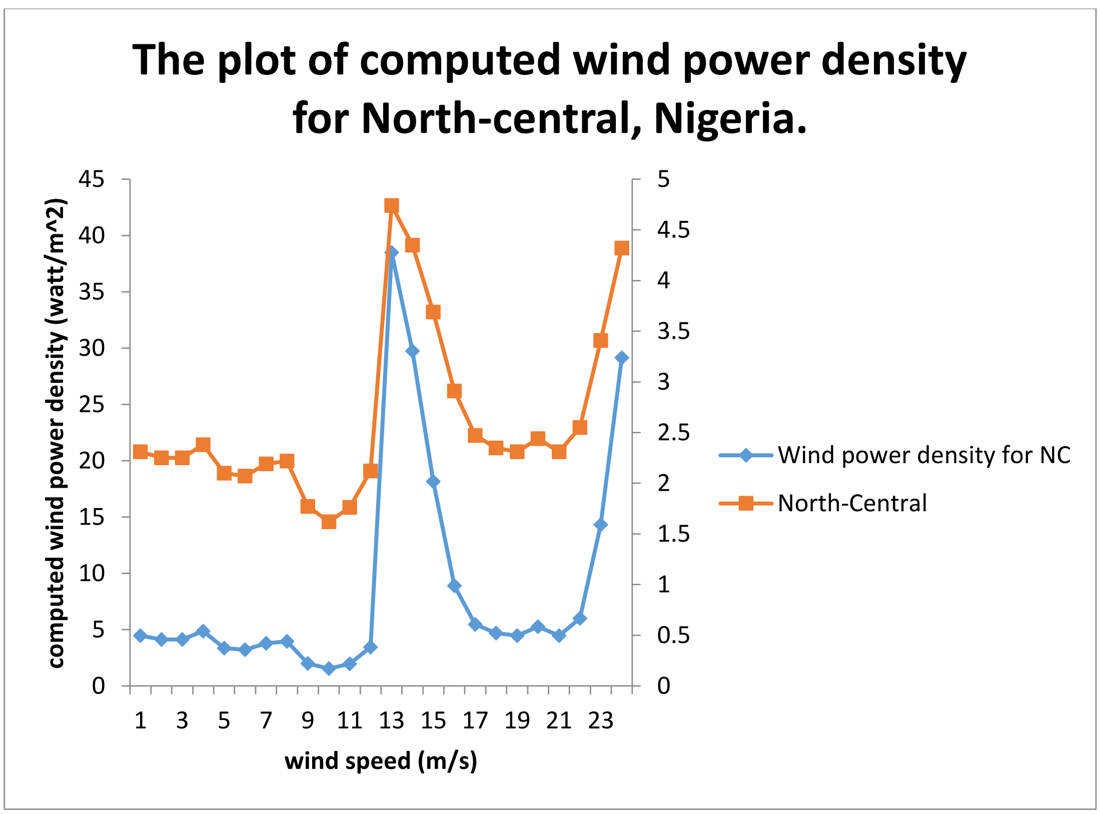


Fig5. The plot of computed wind load South-South, South-East, and South-West, Nigeria


The computed wind power density for North-west, Nigeria.
computed wind power density (watt/m^2)
wind speed (m/s)
Wind power density for NW
North-west


The plot of computed wind power density for North-central, Nigeria.
computed wind power density (watt/m^2)
wind speed (m/s)
Wind power density for NC
North-Central

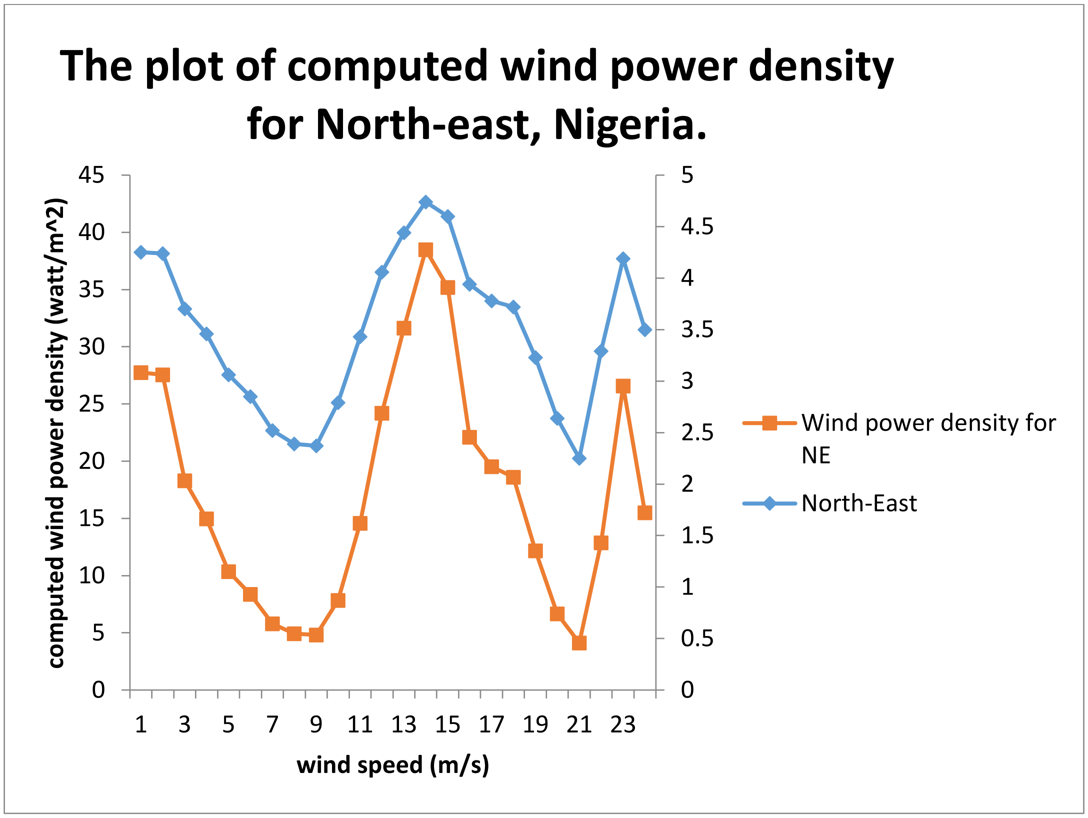
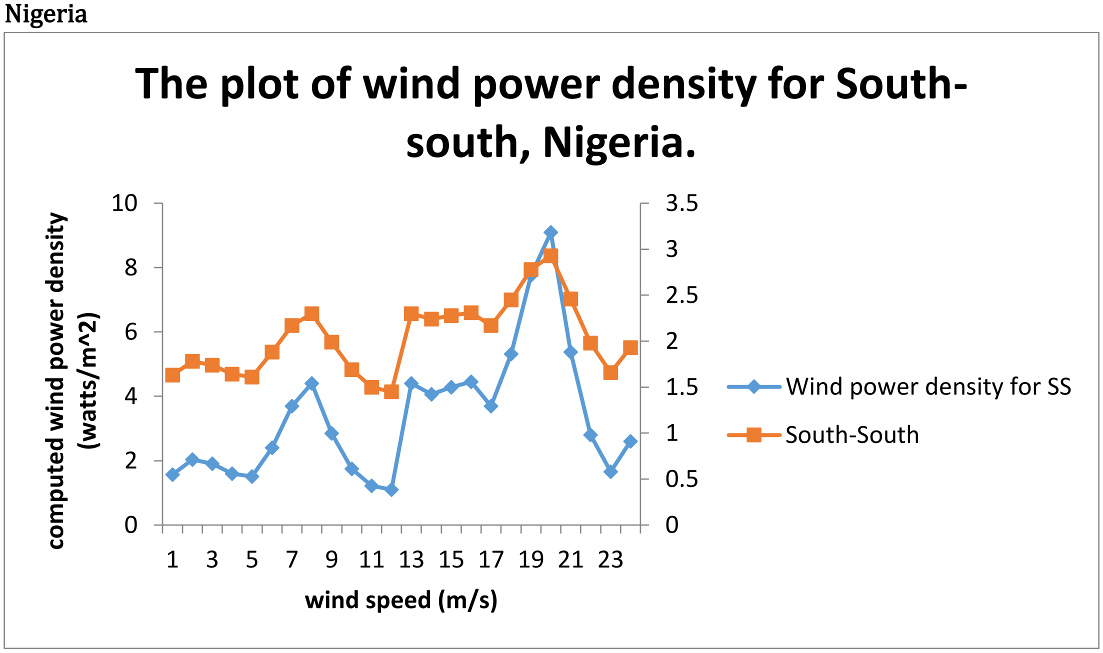


Fig6. The plot of computed wind power density for South-South, South-West, and South-East, Nigeria



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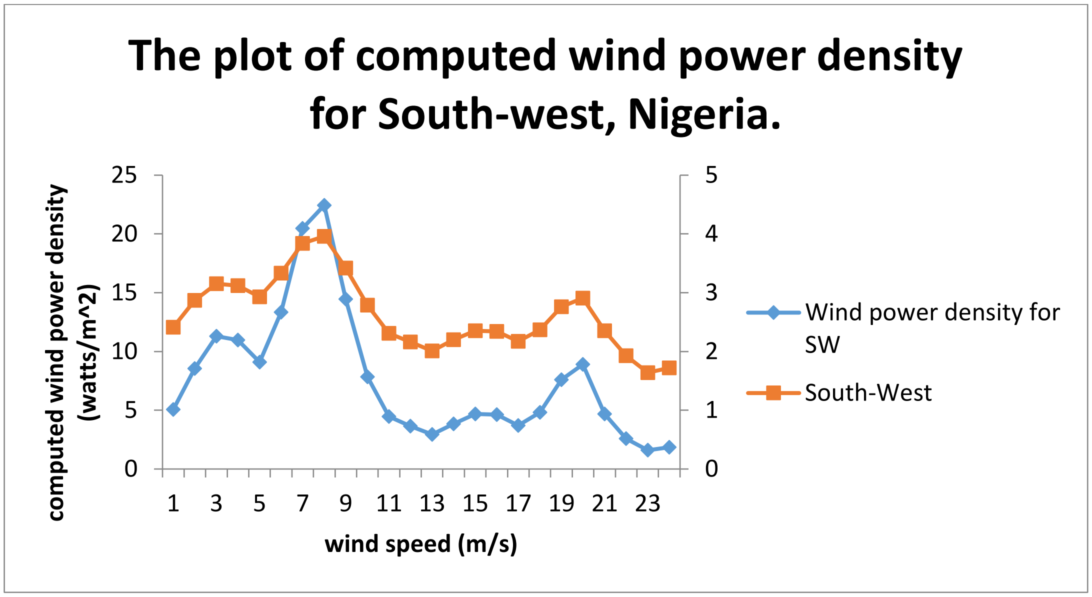

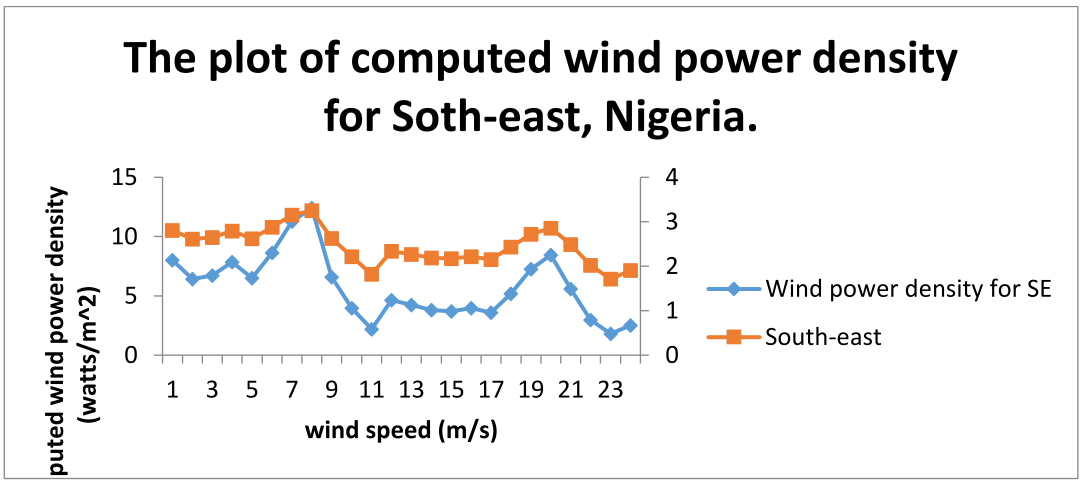

Fig 7: The plot of computed wind power density for South-South, South-West, and South-East, Nigeria.

Conclusion

In this study, two models were developed based on the Weibull probability density function (PDF) and log-normal probability density function (PDF) to predict the wind characteristics, wind load, and wind power density for North-East, North-West, North-Central, South-South, South-West and South-East in Nigeria. The two models were subjected to statistical analysis such as the coefficient of the goodness of fit (R^2) and root mean square error (RMSE), the result shows that both models were perfectly correlated with wind speed data with a recorded value ranging from 0.6813 – 0.9827, while the coefficient of the goodness of fit R^2 has a value ranging from 0.6542 – 0.9919. Table 1 gives us the estimated parameters for wind speed characterization and probability distribution function parameters. The estimated result shows that in the northern region there is a high potential for wind energy, wind load, and wind power density with a wind speed value ranging from 3.82m/s - 4.89m/s. On the other hand, a low value was recorded within the range of 1.23m/s-3.51m/s in the southern part of Nigeria as shown in figures 5-7. All selected stations were found to be suitable for surface wind electrification.

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