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# Evaluation of Wind Power Density in North West Nigeria

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**ABSTRACT**
*In this paper, the wind speed data for northwest Nigeria (Kano and Sokoto) were collected from meteorological station NIMET, Abuja for the period of 1990 – 2006 at 10m height. The study was carried out using Weibull and Rayleigh models distribution function. The shape factor for Kano and Sokoto varies between 4.45 – 10.68 and 3.30 – 9.27 while the scale factor varies between 7.34 – 11.24ms$^{-1}$ and 5.54 – 9.32ms$^{-1}$ respectively. The average Weibull probability density functions were obtained as 0.484 and 0.482 while Rayleigh was obtained as 0.849 and 0.791 respectively. In Kano the power density for Weibull varies between 281.41W/m$^2$ – 983.97W/m$^2$ and Rayleigh varies between 390.06 W/m$^2$ – 1497.2W/m$^2$. In Sokoto the Weibull power density varies from 124.88W/m$^2$ – 567.12W/m$^2$ and Rayleigh power varies from 157.27W/m$^2$ – 829.25W/m$^2$. The error in estimating power density for Weibull have an average value of 23.33% and for Rayleigh is 61.29% in Kano, while for Sokoto the error in estimating power density for Weibull have an average value of 30.95% and for Rayleigh is 65.18%.*

**Keywords**: Analysis, Power density, Nigeria, Wind energy, Wind class, Rayleigh, Weibull

## INTRODUCTION

Winds of earth are caused primarily by unequal heating of the earth surface by the sun which produces pressure difference in the atmosphere causing the wind to blow from high pressure regions to low pressure regions. During the day, the air over the oceans and lakes remains relatively cool, since much of the sun's energy is consumed in evaporating water, or is absorbed by the water itself. Over the land, the air is heated more during the day since the land absorbs less sunlight than the water and evaporation is less. The heated air over the land expands, becomes lighter and rises, the cooler, heavier air from over the water moves to replace it. In this way, local breezes on a shore line are created [9].

During the night, these local seashore breezes reverse themselves, since the land cools more rapidly than the water and does the air above it. The cool air blows seaward to replace the warm air that rises from the surface of the water. Similar local, breezes occur on mountain sides during the day as heated air rises along the warm slopes heated by the sun. During the night, the relatively cool heavy air on the slopes flows down into valley [9].

Wind energy can be harnessed by modern wind turbines to generate electricity. Wind turbines do not consume fuel due its operations. It does not produce emissions such as carbondioixide, sulphur dioxide, mercury, particulates or any other type of air pollution [1]. Wind energy is the world's fastest growing energy source and it can power industry, business and homes with clean, renewable electricity for many years to come. The demand of energy is increasing day by day in the whole world as well as in Nigeria due to rapid depletion of fossil fuel [5].

Akpinar [4] presented a work on statistical analysis of wind energy potential on the basis of the Weibull and Rayleigh distribution for Agin- Elazig, Turkey. The work covers 5years measured wind speed data based on the models. From the study, the Weibull distribution provides better power estimation in all twelve months than the Rayleigh model.

Celik [6] presented work on statistical analysis of wind power density based on the Weibull and Rayleigh models at the southern region of Turkey. In his study, one year monthly measured wind speed data was used, in the analysis Weibull model returns smaller error in values in calculating the power density when compared to the Rayleigh model.

In this study, wind energy potential in two locations of northwest Nigeria were analyzed using wind speed data at 10m height collected from Nigeria meteorological station NIMET, Abuja covering the period 1990 – 2006. These locations are characterised by different geographical and climatological conditions.

This study provides detail information for the development of wind sites in northwest Nigeria in order to boost the present electricity supply in Nigeria.

## MATERIALS AND METHODS

### Wind Speed Data Collection And Characteristics

Winds at virtually all sites have some remarkably uniform characteristics. At any given site, there will be a length of time when there is absolutely no wind. For some other length of time, the wind will blow at an average speed and for another length of time perhaps only a few minutes over an entire year, it will blow at its maximum speed.

In the present study, monthly wind speed data for Kano and Sokoto northwest Nigeria covering the period (1990-2006) have been analysed. The wind speed data were recorded continuously at a height of 10m using a cup generator anemometer and was obtained from Nigeria Metrological Agency (NIMET), Abuja. Table 1 shows the geographical data for Kano and Sokoto in northwest part of Nigeria.

**Table 1:** Geographical data of the locations

| Locations | State | Latitude (N) | Longitude (E) | Altitude (m) |
|---|---|---|---|---|
| Kano | Kano | $11^{o}59'47$ | $8^{c}31'0$ | 476 |
| Sokoto | Sokoto | $13^{o}3'5$ | $5^{c}13'45$ | 272 |

The continuously recorded wind speed values and the standard deviations can be calculated from the available monthly wind speed data using equations (1) and (2) shown below [3];

$$v_m = \frac{1}{N}\left[\sum_{i=1}^{N} v_i\right] \tag{1}$$

$$\sigma = \left[ \frac{1}{N-1} \sum_{i=1}^{N} \left( v_i - v_m \right)^2 \right]^{1/2} \quad (2)$$

where $v_m$ (m/s) is wind mean speed, $N$ is the number of months in the period considered, and $\sigma$(m/s) is the standard deviation.

**Weibull Distribution Model**

Determination of the Weibull probability density function and cumulative function requires the knowledge of two parameters: *k* and *c* (shape and scale factors), respectively. Both of these parameters are function of $v_m$ and $\sigma$. The Weibull probability density function and the cumulative distribution function is given by [6];

$$f_w(v) = \left( \frac{k}{c} \right) \left( \frac{v}{c} \right)^{k-1} \exp\left[ -\left( \frac{v}{c} \right)^k \right] \quad (3)$$

The Weibull parameters (scale and shape factors) can be calculated analytically from the available wind speed data using the relations below;

$$F_w(v) = 1 - \exp\left( v/c \right)^k \quad (4)$$

$$c = \left[ \frac{k^{2.6674}}{0.184 + \left( 0.816^{k\,2.73859} \right)} \right] \quad (5)$$

$$k = \left[ \frac{\sigma}{v} \right]^{-1.090} \quad (6)$$

**Rayleigh Distribution Model**

This is the simplest velocity probability distribution to represent the wind resource since it requires only knowledge of the mean wind speed $v_m$. The probability density function and the cumulative distribution functions of the Rayleigh model are given by [8];

$$f_R(v) = \frac{\pi}{2} \frac{v}{v^2{}_m} \exp\left[ -\left( \frac{\pi}{4} \right) \left( \frac{v}{v^2{}_m} \right)^k \right] \quad (7)$$

$$F_R(v) = 1 - \exp\left[ -\left( \frac{\pi}{4} \right) \left( \frac{v}{v_m} \right)^2 \right] \quad (8)$$

where $f_W$ is Weibull probability density function, $F_W$ is the Weibull cumulative distribution function, $f_R$ is the Rayleigh probability density function, $F_R$ is Rayleigh cumulative distribution function, *c* is the scale factor (m/s) and *k* is the shape factor (dimensionless).

**Analysis of Wind Speed Data**

The wind speed probability distribution is in time series usually arranged in the frequency distribution format. The available time series data were translated into frequency distribution format, as shown in Table 2 and 3 for Kano and Sokoto. The wind speed is grouped into classes (bins) as given in the second column of Table 2 and 3. The mean wind speeds are calculated for each speed intervals (third column). The fourth column gives the frequency of occurrence of each speed class. The probability density distribution is presented in fifth column. The probability density function for Weibull and Rayleigh are presented in sixth and seventh column, the cumulative distribution function for both Rayleigh and Weibull are present in eighth and ninth column.

**Table 2:** Arrangement of the measured monthly series data in frequency distribution for Kano in month of January.

| $j$ | $vj$ | $vmj$ | $f_j$ | $f_{(vj)}$ | $f_{W(vj)}$ | $f_{R(vj)}$ | $F_{R(v)}$ | $F_{W(v)}$ |
|---|---|---|---|---|---|---|---|---|
| 1 | 0 – 0.9 | 0.45 | 0 | 0.000 | 6.4094E-08 | 4.9119E-135 | 1 | 4.60419E-09 |
| 2 | 1 – 1.9 | 1.45 | 0 | 0.000 | 3.01585E-05 | 5.1742E-13 | 1 | 6.98563E-06 |
| 3 | 2 – 2.9 | 2.45 | 0 | 0.000 | 0.000475938 | 6.00314E-05 | 0.999974486 | 0.000186287 |
| 4 | 3 – 3.9 | 3.45 | 0 | 0.000 | 0.002876447 | 0.005726742 | 0.995173749 | 0.001586522 |
| 5 | 4 – 4.9 | 4.45 | 0 | 0.000 | 0.010904314 | 0.02890183 | 0.959476263 | 0.07781827 |
| 6 | 5 – 5.9 | 5.45 | 0 | 0.000 | 0.031045179 | 0.05609319 | 0.882031172 | 0.027407208 |
| 7 | 6 – 6.9 | 6.45 | 2 | 0.118 | 0.07149146 | 0.073806714 | 0.782590046 | 0.076679353 |
| 8 | 7 – 7.9 | 7.45 | 2 | 0.118 | 0.135751977 | 0.081072571 | 0.681396447 | 0.178539571 |
| 9 | 8 – 8.9 | 8.45 | 3 | 0.176 | 0.207957003 | 0.81299872 | 0.58897591 | 0.351231526 |
| 10 | 9 – 9.9 | 9.45 | 7 | 0.412 | 0.241501352 | 0.077684965 | 0.50879281 | 0.58165871 |
| 11 | 10 – 10.9 | 10.45 | 1 | 0.059 | 0.190889234 | 0.072315089 | 0.44085348 | 0.80518956 |
| 12 | 11 – 11.9 | 11.45 | 0 | 0.000 | 0.087328167 | 0.06637814 | 0.383830531 | 0.944891326 |
| 13 | 12 – 12.9 | 12.45 | 2 | 0.118 | 0.018411491 | 0.060495588 | 0.336063525 | 0.992520361 |
| 14 | 13 – 13.9 | 13.45 | 0 | 0.000 | 0.00131585 | 0.054964739 | 0.295967254 | 0.999643951 |
| 15 | 14 – 14.9 | 14.45 | 0 | 0.000 | 2.13282E-05 | 0.049906555 | 0.26216821 | 0.999996042 |

**Table 3:** Arrangement of the measured monthly series data in frequency distribution for Sokoto in month of January.

| $j$ | $vj$ | $vmj$ | $f_j$ | $f_{(vj)}$ | $f_{W(vj)}$ | $f_{R(vj)}$ | $F_{R(v)}$ | $F_{W(v)}$ |
|---|---|---|---|---|---|---|---|---|
| 1 | 0 – 0.9 | 0.45 | 0 | 0.000 | 1.18186E-08 | 1.7584E-106 | 1 | 7.43829E-10 |
| 2 | 1 – 1.9 | 1.45 | 0 | 0.000 | 1.5766E-05 | 2.61636E-10 | 1 | 3.19731E-06 |
| 3 | 2 – 2.9 | 2.45 | 0 | 0.000 | 0.000396846 | 0.000492249 | 0.999765 | 0.000135991 |
| 4 | 3 – 3.9 | 3.45 | 0 | 0.000 | 0.003252479 | 0.015608443 | 0.9852 | 0.001570612 |
| 5 | 4 – 4.9 | 4.45 | 1 | 0.059 | 0.015435157 | 0.050376437 | 0.920526 | 0.009653239 |
| 6 | 5 – 5.9 | 5.45 | 0 | 0.000 | 0.052023539 | 0.078111584 | 0.815164 | 0.40485117 |
| 7 | 6 – 6.9 | 6.45 | 1 | 0.059 | 0.133119443 | 0.090389517 | 0.700419 | 0.128756485 |
| 8 | 7 – 7.9 | 7.45 | 5 | 0.294 | 0.251944128 | 0.09162758 | 0.59485 | 0.320431131 |
| 9 | 8 – 8.9 | 8.45 | 6 | 0.353 | 0.310891146 | 0.087096752 | 0.504558 | 0.613517435 |
| 10 | 9 – 9.9 | 9.45 | 3 | 0.176 | 0.193026768 | 0.80165626 | 0.429667 | 0.879384748 |
| 11 | 10 – 10.9 | 10.45 | 1 | 0.059 | 0.038653482 | 0.72620616 | 0.368215 | 0.986988908 |
| 12 | 11 – 11.9 | 11.45 | 0 | 0.000 | 0.001237289 | 0.065312359 | 0.317845 | 0.999762585 |
| 13 | 12 – 12.9 | 12.45 | 0 | 0.000 | 2.21353E-06 | 0.058597804 | 0.276402 | 0.999999746 |

| | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| 14 | 13 – 13.9 | 13.45 | 0 | 0.000 | 4.87309E-11 | 0.052588578 | 0.242098 | 1 |
| 15 | 14 – 14.9 | 14.45 | 0 | 0.000 | 1.59534E-18 | 0.47280961 | 0.213499 | 1 |

## Wind Power Density

The power of wind can be estimated by using the equation below [1];

$$P(V) = \frac{1}{3}\rho A V^3 \quad (9)$$

where $P$ is the power in Watts, $A$ is the area perpendicular to the wind speed vector in $m^2$, $V$ is the wind speed in m/s, and $\rho$ is the average density of the air in $kg/m^3$.

Wind power density of a site based on the Weibull and Rayleigh models can be expressed using equation (10) and (11) respectively [7];

$$\frac{P}{A} = \int_0^\infty P(V) f(V) dV,\ P_W = \frac{1}{2}\rho c^3 \Gamma\left(\frac{k+3}{k}\right) \quad (10)$$

$$P_R = \frac{3}{\pi}\rho v^3{}_m \quad (11)$$

where $P_W$ is Weibull power, $P_R$ is Rayleigh power, and $\Gamma$ is the gamma function.

## Error in Calculating Power Density

The errors in calculating the power densities using the models in comparison to those using the measured probability density distribution and the yearly average error can be obtain using equation 12 and 13 respectively, [3];

$$Error\ (\%) = \frac{P_{W,R} - P_{mR}}{P_{mR}} \quad (12)$$

$$Error\ (\%) = \frac{1}{12}\sum_{i=1}^{12}\left[\frac{P_{WR} - P_{mR}}{P_{mR}}\right] \quad (13)$$

## RESULTS AND DISCUSSION

Fig. 1 shows graph of average wind speeds against months for the two locations (Kano and Sokoto). It can be seen from the graph that Kano returns the highest wind speed in all the months as compared to Sokoto. The highest value of wind speed for Kano was found to be 10.86m/s in the month of June and the lowest value of wind speed was 6.94m/s in the month of October. The highest value of wind speed for Sokoto was found to be 8.92m/s in the month of June and the lowest value of wind speed is 5.12m/s in the month of September.

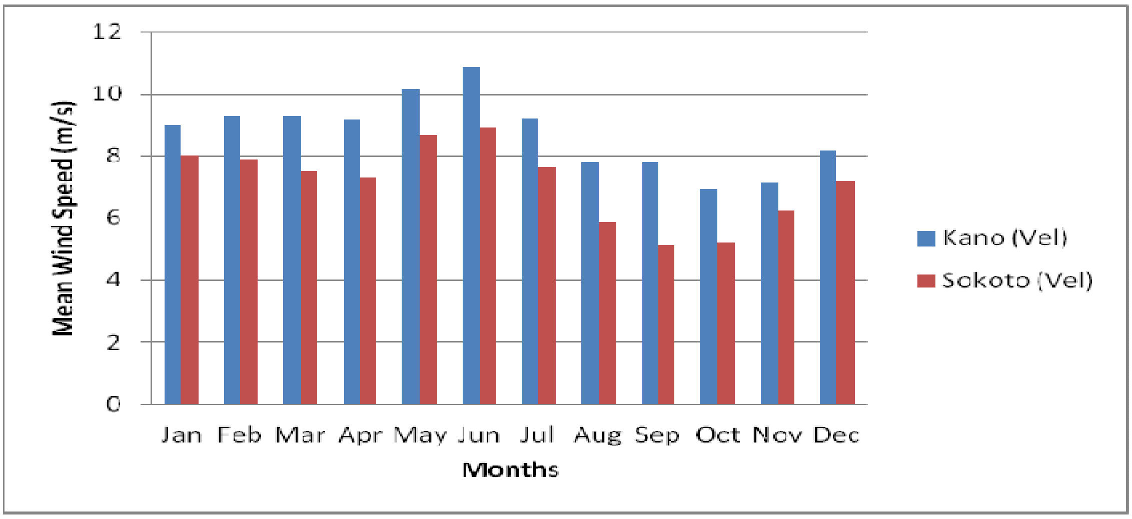


**Fig. 1:** Graph of mean wind speed Vs months for Kano and Sokoto

Table 4 presents the values of gamma function for Kano and Sokoto, it can be observed that all the values are less than one, this shows an indication that the wind speed data obtained for the analysis were taken with high level of accuracy. Table 5 shows the values of scale factor (*c m/s*) with values ranging from 8.28 -11.24m/s for Kano and values ranging from 5.54 – 9.32 m/s for Sokoto. Table 6 shows the shape factor (*k*) for Kano and Sokoto with values ranging from 4.45 –m 10.68 for Kano and values ranging from 3.30 – 9.27 for Sokoto.

**Table 4.** Gamma function for Kano and Sokoto

| Months | Jan | Feb | Mar | Apr | May | Jun | Jul | Aug | Sep | Oct | Nov | Dec |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Kano | 0.803 | 0.754 | 0.776 | 0.829 | 0.834 | 0.883 | 0.832 | 0.830 | 0.816 | 0.836 | 0.755 | 0.744 |
| Sokoto | 0.824 | 0.712 | 0.772 | 0.748 | 0.857 | 0.863 | 0.817 | 0.835 | 0.787 | 0.755 | 0.688 | 0.773 |

**Table 5**. The results for the Weibull scale factor *c* (m/s) in Kano and Sokoto

| Months | Jan | Feb | Mar | Apr | May | Jun | Jul | Aug | Sep | Oct | Nov | Dec |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Kano | 9.66 | 10.16 | 10.01 | 9.72 | 10.76 | 11.24 | 9.77 | 8.28 | 8.35 | 7.34 | 7.82 | 8.99 |
| Sokoto | 8.51 | 8.74 | 8.20 | 8.01 | 9.07 | 9.32 | 8.17 | 6.19 | 5.54 | 5.70 | 6.95 | 7.92 |

**Table 6.** The results for the Weibull scale factor *k* in Kano and Sokoto

| Months | Jan | Feb | Mar | Apr | May | Jun | Jul | Aug | Sep | Oct | Nov | Dec |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Kano | 6.26 | 4.70 | 5.34 | 7.38 | 7.26 | 10.68 | 7.51 | 7.39 | 6.76 | 7.72 | 4.74 | 4.45 |
| Sokoto | 7.15 | 3.76 | 5.20 | 4.55 | 8.86 | 9.27 | 6.81 | 7.67 | 5.70 | 4.72 | 3.30 | 5.24 |

Fig. 2 shows graph presenting the comparison between power for Weibull in Kano and Sokoto. It can be clearly seen that Kano returns a higher power density in all the twelve months than Sokoto.

From the graph, the highest value for power density in Kano has a maximum value of 983.97W/m$^2$ in the month of June and Sokoto has the lowest value was of 124.88W/m$^2$ in the month of September. Fig. 3 shows graphical presentation of Rayleigh power for Kano and Sokoto, it can be observed that Kano shows the highest power density in all the twelve months as compared to Sokoto. The highest value of 1497.2W/m $^2$ was found in Kano in the month of June and lowest value of 157.27W/m$^2$ was found in Sokoto in the month of September.

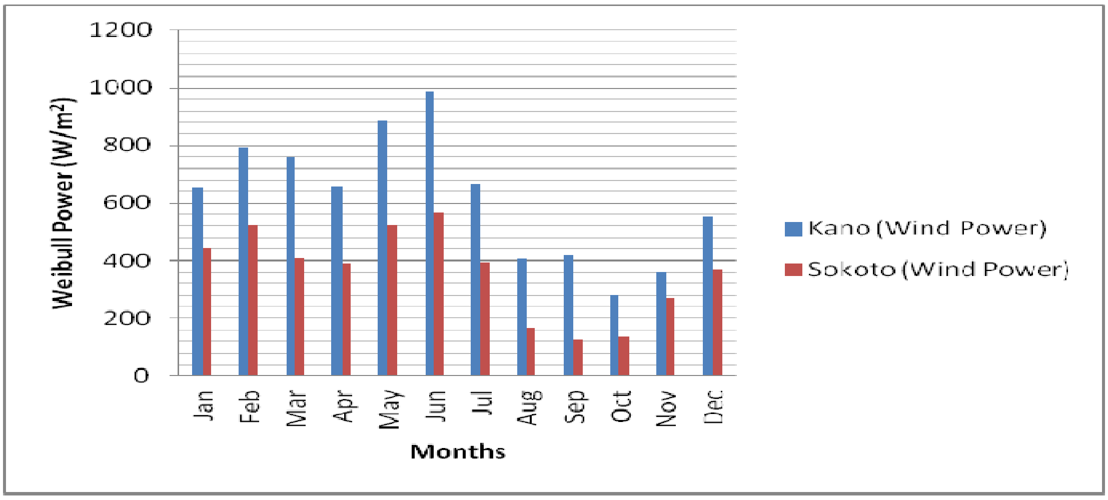


**Fig. 2:** Comparison of Weibull Power for Kano and Sokoto

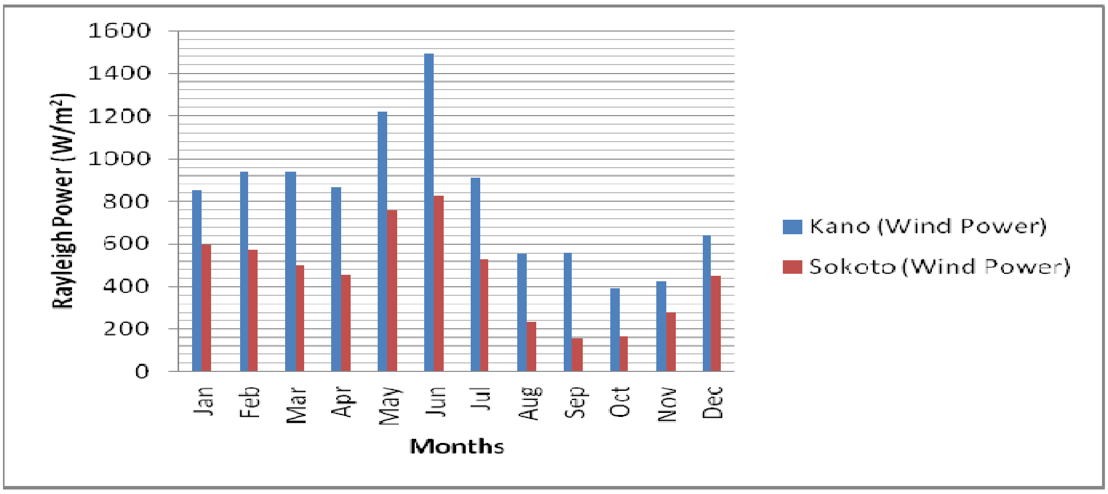


**Fig. 3:** Comparison of Rayleigh Power for Kano and Sokoto

From the graph in Figure 4, it can be seen that Weibull returns the lowest percentage error in all the twelve months as compared to Rayleigh that returns the highest values in error estimation. The lowest values were found to be -46.2% for Weibull in the month of April and the highest value was found to be 86.2% for Rayleigh in the month of July. Figure 5, also presents Weibull to have the lowest value in all the twelve months and Rayleigh with the highest value, the lowest value for Weibull is 20.9% in the month of August and the highest value for Rayleigh is 95.86% in the month of June.

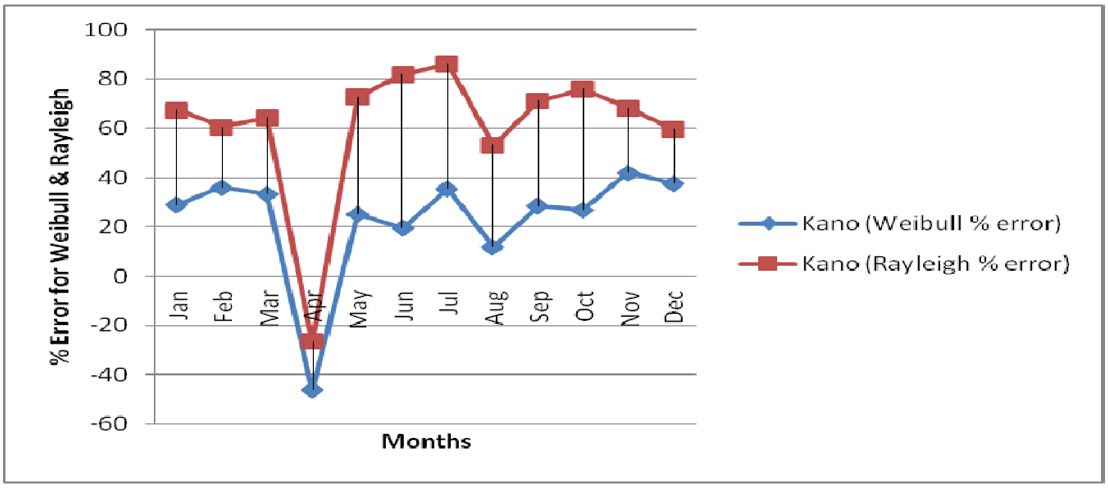


**Fig. 4:** Weibull and Rayleigh % Error estimation for Kano

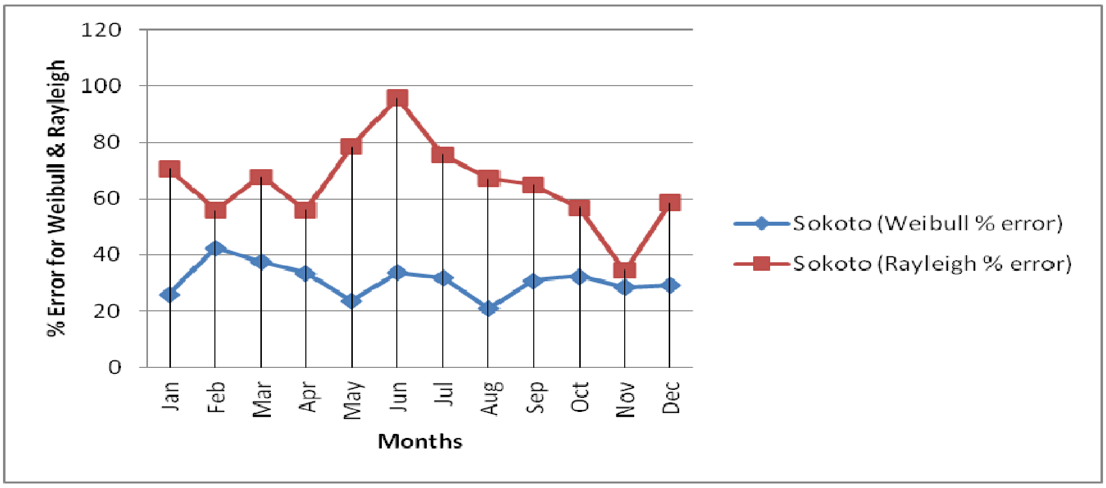


**Fig. 5:** Weibull and Rayleigh % Error estimation for Sokoto

## CONCLUSION

In this research work, monthly measured series wind speed data for Kano and Sokoto northwest Nigeria have been analyzed. The probability density distributions have been derived from the monthly series data and the distributional parameters were identified. Two probability density functions have been fitted to the measured probability distributions on a monthly basis. The wind energy potentials of the locations have been studied based on the Weibull and Rayleigh models. From the wind speed data analysis and calculations, we can conclude that;

(1) In Kano and Sokoto northwest Nigeria, the highest average monthly wind speed was determined to be 10.86m/s in month of June and 8.92m/s in the month of June respectively.
(2) The average value for Weibull parameters ($k$ and $c$) in Kano and Sokoto varies between 4.45 – 10.68 and 7.34 – 11.248m/s, 3.30 – 9.27 and 5.54 – 9.32m/s respectively.

(3) The locations (Kano and Sokoto) were found suitable for electricity generation since the annual average power density in Kano and Sokoto for Weibull and Rayleigh were obtained to be 618.41W/$m^2$ and 816.75 W/$m^2$ and 360.22W/$m^2$ and 460.62W/$m^2$ respectively, this indicates that the two locations correspond to wind power class II, since the average wind power density value are greater than 100W/$m^2$. In these locations wind energy conversion system (WECS) can be installed to supply a reasonable amount of energy using a number of wind turbines.

(4) The Weibull distribution provides better power estimation in almost all 12 months than the Rayleigh model because the Weibull model returns lower error in power estimation.

(5) In calculating the error in power estimation for both models, the Weibull model returns smaller errors in power density estimation than the Rayleigh model.

Finally, Kano and Sokoto northwest Nigeria have wind energy potential that is quite promising for installation of wind turbines.

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