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Assessment, Characterization And Evaluation Of Wind Energy Potentials In The North East Sub-Region Of Nigeria

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Abstract:
The North-East sub-region of Nigeria has numerous untapped energy resources that encompass majorly renewable energy sources and, to some limited extent, conventional energy sources. The missing nexus, however, is how best to deploy the viable energy resources to underpin sustainable economic resources of the sub-region. This will, naturally, call for the development of credible energy resource database for their management and optimal utilization for decentralized power generation to meet the needs of various underserved communities. Wind energy potential of this sub-region was also investigated with wind speeds falling between 1.25m/sec and 5.48m/sec and average power density of 0.19kW/m^{2}as determined via statistical analysis of a ten-year wind data. Undoubtedly, wind energy potentials of this sub-region are classified as low regime which largely offer prospects for distributed micro applications such as rural water pumping schemes, wind turbine driven battery chargers, etc. However, in the northern fringes of the study area, characterized by higher mean wind speeds greater than 4.2m/sec with less than 10% calm periods, several wind farms each spanning 1km^2 in the area are proposed for electrical power generation with rated capacity of 430kW per wind farm.

Key Word: *Statistical analysis; Underserved Community; Wind Energy Potentials; Wind Turbine*

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I. Introduction

Nigeria falls into the low to medium wind regime, which is an effect from the uneven heating of the earth's surface by the sun and its resultant pressure inequalities. Wind power involves converting wind energy into electricity by using wind turbines. Wind energy conversion systems (wind turbines, wind generators, wind plants, wind machines, and wind dynamos) are devices which convert the kinetic energy of the moving air to rotary motion of a shaft, that is, mechanical energy. Wind comes from atmospheric changes; changes in temperature and pressure makes the air move around the surface of the earth; all of which is triggered by the sun.

Wind speeds in Nigeria range from a low 1.4 m/s to 3.0 m/s in the Southern areas and 4.0 m/s to 5.12 m/s in the extreme North. Wind speeds in Nigeria are generally weak in the South except for the coastal regions and offshore locations. In Nigeria, peak wind speeds generally occur between April and August for most sites[1]. Presently, the country is only in the developmental stages of policy generation, as there is still no physical presence of working wind energy resources for power generation within the country except one or two pilot projects used in time past to drive water pumps. The technologies for harnessing this energy have, over the years been tried in the northern parts of the country, mainly for water pumping from open wells in many secondary schools of old Sokoto, Kano, Katsina, as well as in Bauchi and Plateau States. A 5kW wind electricity conversion system for village electrification has been installed at Sayyan Gidan Gada, in Sokoto State. Other areas of potential application of wind energy conversion systems in Nigeria are in "green electricity" production for the rural community and for integration into the national grid system. It has been reported that an average annual wind speed of not less than 5 m/s at a height of 10m above ground level is the feasible speed for the exploitation of wind energy at today's cost. Such initiatives include that by the Energy Commission of Nigeria (ECN). The average wind speed contour lines constructed for Nigeria is shown in Figure 1. Note that northeast sub-region has fair share of wind energy potential which can be exploited for power generation at various localities.

The power output of a turbine is a function of the cube of the wind speed, so as wind speed increases, power output increases dramatically. Areas where winds are stronger and more constant, such as offshore and high-altitude sites are preferred locations for wind farms[2]. Assuming an air density of 1.1 kg/m^3, wind energy intensity, perpendicular to the wind direction, ranges between 4.4 W/m^2 at the coastal areas and 35.2 W/m^2 at the far northern region.

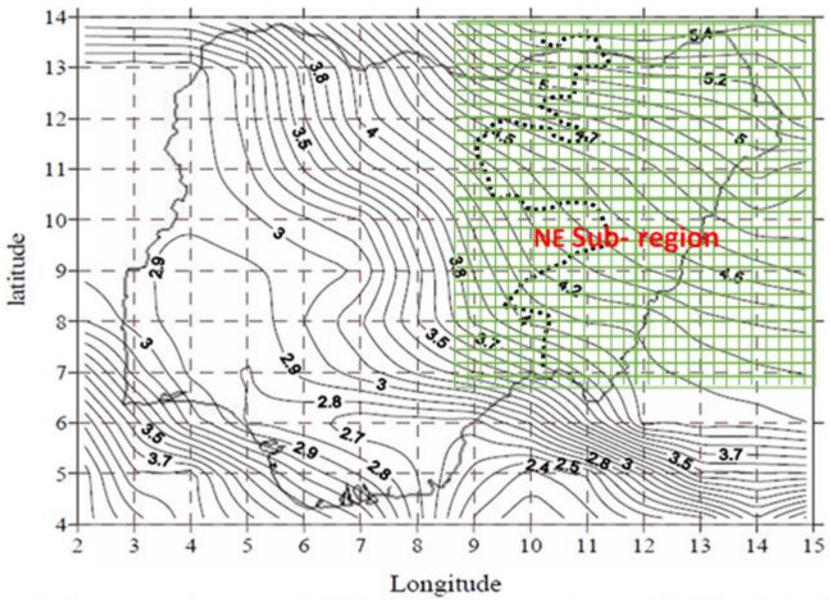


Figure 1: Average Wind Speed Contour Lines for Nigeria (Source: ECN)

The North-East sub-region of Nigeria has numerous untapped energy resources that encompass majorly renewable energy sources and, to some limited extent, conventional energy sources. The missing nexus, however, is how best to deploy the viable energy resources to underpin sustainable economic of the sub-region. This will, naturally, call for the development of credible energy resource database for their management and optimal utilization for decentralized power generation to meet the needs of various underserved communities. A well-researched energy resource database for the entire north-east sub-region is not readily available and this is without prejudice to the existing research investigations on identified energy resource entities in some specific localities of north-east sub-region. For the avoidance of doubt, the various available energy resources in the North-East sub-region include solar, hydro, biomass (agro waste), wind and emerging discoveries of fossil fuels but lack in-depth evaluation from utilization sustainability standpoint. The prime focus of this research work is to develop a viable road map for the utilization of the indigenous energy resources, in coordinated manner, for sustainable distributed power generation applications in the North-East sub-region. The main task of this research work is to carry out comprehensive evaluation and characterization of different energy resource potentials in northeast sub-region of Nigeria. The overriding goal concerns sustainable electricity productions for plethora of geographically dispersed rural communities, across the entire northeast sub-region, that currently lack electricity delivery from the national grid. Hence, the need to evaluate and characterize wind energy resource potentials in the North-East sub-region of Nigeria for sustainable electricity generation. The key objective of this work is to develop the short to long term wind power density scenarios for the entire North-East sub-region of Nigeria based on ten-year raw data obtained from NASA data web site. This paper is limited to wind data collection from North-East sub-region of Nigeria.

Many researchers have worked in this area, some of which includes [3] who worked on the assessment on the utilization of wind energy resources in Nigeria. It was found that even though wind energy availability in the South-Western and South-Southern landmass of the country is very low due to heavy vegetation, offshore areas bounded by the Atlantic Ocean and running the entire South–West to the South–South coastline have enormous potential for wind energy cultivation for power generation. The paper also identified outlier northern states and mountainous areas of the central and eastern zones of the country possess huge amount of untapped wind energy potential; capable of contributing about 86% of the available total annual wind energy potential for the country. [4] also assessed wind energy potential of two sites in North-East, Nigeria. Relying on 1987 to 2007 meteorological data for wind, it was established that the two sites (Potiskum and Maiduguri) possess wind regime suitable for power generation for medium scale power generation for both on-grid and off-grid applications. [5] presented the wind power densities in the four states (Adamawa, Bauchi, Borno and Yobe) selected from north-east sub-region and found that the wind regime is generally low and not within the international system of wind classification. Therefore, wind energy potentials in the selected states fell short of being used for electricity generation but for micro non-connected electrical and mechanical applications that include battery charging and water pumping. While in Bauchi, Maiduguri and Potiskum (Yobe state) fall under

Class 2 of the international system of wind classification and as such may be considered marginal for wind power development, while Nguru (Yobe state) and Yola (Adamawa state) each placed under Class 1 could be adequate for off-grid electrical generation and standalone mechanical applications that include battery charging and water pumping.

[4] investigated wind speed pattern and energy potential in Nigeria. In their findings, accurate information about the wind data in a targeted location is pertinent as the power output from a wind turbine is strongly dependent on the wind speed. The annual mean wind speeds in Nigeria range from about 2 to 9.5 m/s and the annual power density range between 3.4 m/s and 520W/m^2.

Ref. [6], worked on the analysis of wind energy potential in north-east sub-region of Nigeria. Two models were used for the determination of power density (Rayleigh and Weibull models). they found that Rayleigh returned higher power density than Weibull and the highest power density is (365.77 W/m^2) for Rayleigh in Borno in the month of June. h

The authors in [7], worked on statistical modeling of wind energy potential in North-East sub-region of Nigeria based on Weibull and Rayleigh Models. Based on the two models used in their research, Rayleigh is the best fit model that describes the wind speed data at 10m height above the sea level. However, Weibull model was found to present the actual probability of the wind speed data for all the locations analyzed. They arrived at the conclusion that Yola (Adamawa) and Bauchi have low wind speed regime than Maiduguri (Borno) and Potiskum (Yobe). North-East sub-region of Nigeria has potential for wind energy harvest with highest power density of 59.96W/m^{2}found to be in Maiduguri, Borno state.

In Ref. [8], the authors worked on the renewable energy potentials in Nigeria for meeting rural energy needs. The researchers worked on the amount of renewable energy potentials in Nigeria to be tapped for useful and uninterrupted electric energy supply. The extent of renewable energy resources is described, and existing government policies are articulated. Various polices, that could possibly incentivize the realization of wider renewable energy applications in rural Nigeria, are proposed. The challenges and future prospects of renewable energy are also discussed. In their findings, distributed and decentralized renewable energy resources will not only improve the wellbeing of rural Nigerian communities, but also enhance Nigeria's energy and economic prospects for potential global investment.

The authors in Ref. [9] developed a pre-assessment analytical model for preliminary study of the wind energy potential in Borno state. Herein, 10-year (2002-2011) monthly mean speeds data for Borno state obtained from *Nigerian* Meteorological Agency (NiMeT) office in Maiduguri was used in developing the model. The authors claimed that the developed model can be used for the assessing of the wind energy potential of any site in Borno state. Although the model was developed using data from Borno state, it could be used for preliminary analysis of any site with similar wind speed profile. The model can be used as a tool for preliminary prediction of the wind energy potential for the purposes developing wind energy system.

In Ref. [10], an assessment of wind energy potential in Maiduguri, Nigeria. This paper present an evaluation of wind power potential of Maiduguri in North-Eastern part of Nigeria based on the Weibull and Rayleigh models using 15-year monthly wind speed covering period of 1998 to 2012 obtained from Nigeria Metrological Agency. Its monthly variation recorded for the speed has maximum value of 12.98m/s in the year 2006 whilst the minimum value of 1.12m/s occurred in year 2012. It is observed that Maiduguri and its environs have wind regime between 2.2 and 6.4m/s and still confirms that it falls into moderate wind regime band. The annual mean power density ranges from 6.3 to 160.9 W/m^2.These results indicate that wind speed has the viable potential for wind-to-electricity at height of 10 m.

The authors in [11] presented a statistical analysis of wind speed for electrical power generation in some selected sites in Northern Nigeria: It aimed at comparing different probability distribution function models for fitting the wind-speed data. The probability distribution functions used includes the Weibull, Rayleigh, and gamma distributions.

The authors of [12] and [13] evaluated wind energy potential of a specific location in Yemen based on Weibull and Rayleigh models with Weibull distribution returning better fit to the available monthly data than the Rayleigh distribution for the whole years. The Weibull distribution provides better power density estimations in eleven months than the Rayleigh distribution. The mean value of wind speed and energy intensity measured at the location reveals that the current technology does not provide economical electricity production from wind power and that the measurements should be evaluated in the long term in accordance with technological developments and reduction in the cost of turbines. The result derived from this study supports utilization of the wind energy potential in this location.

II. Material And Methods

This section presents comprehensive documentation of the materials and methods deployed to realize the aim and objectives of this research. The data collection procedures are anchored firstly on structured survey-based studies to enable collection of credible raw wind data from National Aeronautics and Space

Administration (NASA) website. comprehensive methodology was developed to carry out statistical characterization and energy potential derivable from wind energy regimes for the northeast sub-region. The integral components of materials and methods are set forth in the subsequent sections that follow in sequel.

Material

Long-term monthly wind speed data were collected in the northeast sub-region of Nigeria. More specifically, Ten-year (2009-2018) monthly average wind speed data were downloaded from NASA website and used to determine the energy potential of the energy source entertained for the entire study area. Additionally, similar ground measurement data comprising monthly wind speed for some selected sites were collected from NiMeT offices in northeast sub-region of Nigeria to validate corresponding NASA website data. Alternatively, monthly wind speed data from existing publications for some states in northeast sub-region could be utilized to validate NASA website data or replace bad or missing data.

The computer made use in this research is Dell with Pentium (R) Dual Core CPU, 2.2 GHz Processor and having RAM memory of 4GB and 40GB Hard disk memory storage. The software packages deployed for large data processing, computational solution of formulated mathematical problems, etc. comprised the following, amongst other software codes developed for different scenario studies:

a) Excel spreadsheet for large data analytics;
b) MATLAB software tools for computational solution;
c) Origin 50 for bad data detection, data gaps, etc.; and
d) C++ and FORTRAN programming Languages.

The utilization of the foregoing software tools to implement methodologies outlined in the next section is central to accomplishing the research objectives.

Wind Energy Potential Estimations

Ideally, each cell area allocated to each state within the study area ought to have a dedicated anemometer for wind speed measurements. However, the practical scenario is that some selected locations in a given state would have weather monitoring stations built with provisions made for the hourly monitoring of and wind speed. The availability of daily or monthly mean wind speed data is critical for the assessment of their technically feasible energy potentials. Herein, the relevant equations developed for pragmatic estimation of wind energy potentials for each state in the study area are set forth in the subsections that follow. The wind energy potential of state i, considering temporal and spatial variability of wind speeds between k^{th} and $(k+1)^{th}$ cell areas can be cast as in Eqn. (1).

$$\mathbb{E}_{i_{wind}} = \sum_k f(V_k) \times \mathrm{P}_{\mathrm{w}}^{(\mathrm{i})}(V_k) \times \zeta_k \quad i \in \{1, n\} \tag{1}$$

Where; $\mathbb{E}_{i_{wind}}$ is the i^{th} state wind energy potential per annum, V_k is the wind speed, $f(V_k)$ is the assumed wind model (Weibull, Rayleigh, Gaussian etc.), ζ_k is the number of hours per annumabove cut-in speed for wind turbine and $\mathrm{P}_{\mathrm{w}}^{(\mathrm{i})}(V_k)$ is the wind power passing through a perpendicular area A_k as expressed in Eqn. (2):

$$\mathrm{P}_{\mathrm{w}}^{(\mathrm{i})}(V_k) = \frac{1}{2}\rho_k A_k V_k^3 \qquad k = 1, 2, \ldots\ M_i \tag{2}$$

Where;

ρ_k : is the air density in k^{th} cell area. The average wind power for i^{th} state $\overline{\mathrm{P}}_{\mathrm{w}}^{(\mathrm{i})}$ is then given by Eqn. (3):

$$\overline{\mathrm{P}}_{\mathrm{w}}^{(\mathrm{i})} = \frac{1}{M_i}\left[\frac{1}{2}\sum_{\mathrm{k}=1}^{M_i}(\rho_k \times A_k \times V_k^3)\right] \quad i = 1,2, \ldots n \tag{3}$$

And the weighted average power for the study area is given by Eqn. (4)

$$P_{SA_w} = \frac{1}{n}\sum_{i=1}^{n}\left(\overline{\mathrm{P}}_{\mathrm{w}}^{(\mathrm{i})} \times M_i\right) \tag{4}$$

The wind average power density $\bar{\partial}_{\mathrm{w}}^{(\mathrm{i})}$ for the i^{th} state is obtained from Eqn. 3 by simply setting $A_k = 1$; to result in Eqn. (4):

$$\bar{\partial}_{\mathrm{w}}^{(\mathrm{i})} = \frac{1}{M_i}\left[\frac{1}{2}\sum_{\mathrm{k}=1}^{M_i}(\rho_k \times V_k^3)\right] \quad i = 1,2, \ldots n \tag{5}$$

The weighted wind power density $\bar{\partial}_{\mathrm{SA_w}}$ for the entire study area is computed as by Eqn. (6):

$$\bar{\partial}_{\mathrm{SA_w}} = \frac{1}{\mathrm{n}}\sum_{\mathrm{i}=1}^{\mathrm{n}}\left(\bar{\partial}_{\mathrm{w}}^{(\mathrm{i})} \times M_i\right) \tag{6}$$

Referring to Eqn. (1), the wind model is to be selected from the well-established models that have been widely studied in the literature.

In this research, both Weibull and Rayleigh wind models have been adopted for modeling the wind potential in the study area as proposed in the first seminar and repeated here for convenience. Here, the Weibull density function is used to describe the wind speed frequency distribution. The Rayleigh distribution is a special case of the Weibull distribution. The generalized form of the two-parameter Weibull probability density function and cumulative function are mathematically expressed in Eqn. (7) and Eqn. (8), respectively.

$$f(V) = \frac{k}{c} \times \left(\frac{V}{c}\right)^{k-1} \times exp\left[-\left(\frac{V}{c}\right)^{k}\right] (V > 0, k > 0 \;\&\; c > 0) \quad (7)$$

$$F(V) = \int_0^{\infty} f(V)dV = 1 - exp\left[-\left(\frac{V}{c}\right)^{k}\right] \quad (8)$$

Where;

$f(V)$: is the probability of having a wind speed of $V\ (m/s)$, k is a dimensionless shape factor, and c is the scale factor with units of speed (m/s). According to Adaramola and Oyewola, (2011), the two parameters of Weibull functions k and c can be estimated based on the mean speed$V_m$and standard deviation σ of long-term wind data as given in Eqns. (9) and (10), respectively:

$$k = \left(\frac{\sigma}{V_m}\right)^{-1.086} (1 \leq k \leq 10) \quad (9)$$

$$c = \frac{V_m}{\Gamma\left(1+\frac{1}{k}\right)} \cong V_m\left(0.568 + \frac{0.433}{k}\right)^{-\frac{1}{k}} or \left(\frac{V_m k^{2.6674}}{0.184+0.816k^{2.73855}}\right) \quad (10)$$

Where;

Γ: is the gamma function with an alternative approximate expression for the computation of $c$provided in eq. 37(Pam et al, 2008). The most probable wind speed V_{mp} and wind speed bearing maximum energy $V_{max,E}$ based on Weibull distribution modeling of wind data are given in Eqn. (11) and Eqn. (12), respectively.

$$V_{mp,Weibull} = c \times \sqrt[k]{\left(\frac{k-1}{k}\right)} \quad (11)$$

$$V_{max,E,Weibull} = c \times \sqrt[k]{\left(\frac{k+2}{k}\right)} \quad (12)$$

The estimation of wind power density $\partial_{V_{Weibull}}$ based on Weibull wind model is given by Eqn. (13):

$$\partial_{V_{Weibull}} = \frac{1}{2}\rho c^3 \Gamma\left(1 + \frac{3}{k}\right) \times 10^{-3}\ kWm^{-2} \quad (13)$$

For the sake of completeness, we provide similar equations for Rayleigh distribution function-based wind modeling that has also been utilized by some researchers for some selected sites in the Northeast sub-region. The Rayleigh distribution density function is derived from Weibull distribution density function by setting $k = 2$ in Eqn. (13) to yield Eqn. (14).

$$f(V) = \left(\frac{V}{2c}\right) \times exp\left[-\left(\frac{V}{c}\right)^{2}\right] \quad (14)$$

And its cumulative distribution function is then given by Eqn. (15).

$$F(V) = \int_0^{\infty} f(V)dV = 1 - \exp\left[-\left(\frac{V}{c}\right)^{2}\right] \quad (15)$$

The single parameter c, the scale factor, is determined in terms of the mean speed V_m of the wind data is as Eqn (16)

$$c = 2 \times \frac{V_m}{\sqrt{\pi}} \quad (16)$$

Still on Rayleigh distribution function, the most probable wind speed and the wind speed carrying maximum energy denoted as $V_{mp,Ray}$and $V_{max,E,Ray}$, respectively are given by:

$$V_{mp,Ray} = V_m \times \sqrt{\frac{2}{\pi}}\ ;\ V_{max,E,Ray} = V_m\sqrt{\frac{8}{\pi}} \rightarrow V_{mp,Ral} = \frac{V_{max,E,Ral}}{2} \quad (17)$$

Finally, the wind power density based on Raleigh distribution function is derived from Eqn. (14) by setting $k = 2$upon recognizing that$\Gamma(5/2) = 3 \times (\sqrt{\pi}/4)$ and substituting for c using Eqn. 16 to yield Eqn. 18.

$$\partial_{V_{Ray}} = \frac{1}{2}\rho c^3 \Gamma\left(\frac{5}{2}\right) = 3 \times \rho \times \frac{v_m^3}{\pi}\ Wm^{-2} \quad (18)$$

In the next subsection, we consider the design of wind farms for areas that have sufficient wind power density to sustain electricity generation for cluster of communities or injection into nearby national grid. Of course, where wind power is considered to be very low, other micro applications of wind for pumping water for rural areas and irrigation schemes.

Methods

This subsection is devoted to theoretical analysis of wind energy potential in the northeast sub-region comprising six states. For the sake of generalization, consider an arbitrary study area comprising northeastern states. The entire study area is divided into M cell areas where i^{th} state has M_i area cells $i = 1,2 \ldots, \ldots n$ such that $\sum_{i=1}^{n} M_i = M$ the land mass of i^{th} state is then given by $A_i = \sum_{k=1}^{M_i} a_k^{(i)}$ and $a_k^{(i)}$ is the k^{th} cell area dimensioned $L \times L\ (m^2)$.The cell area should be carefully chosen to justify the assumption of uniform solar irradiance received and wind speed within it. Figure 2 illustrates northeast land mass divided into fairly large number of cell areas.

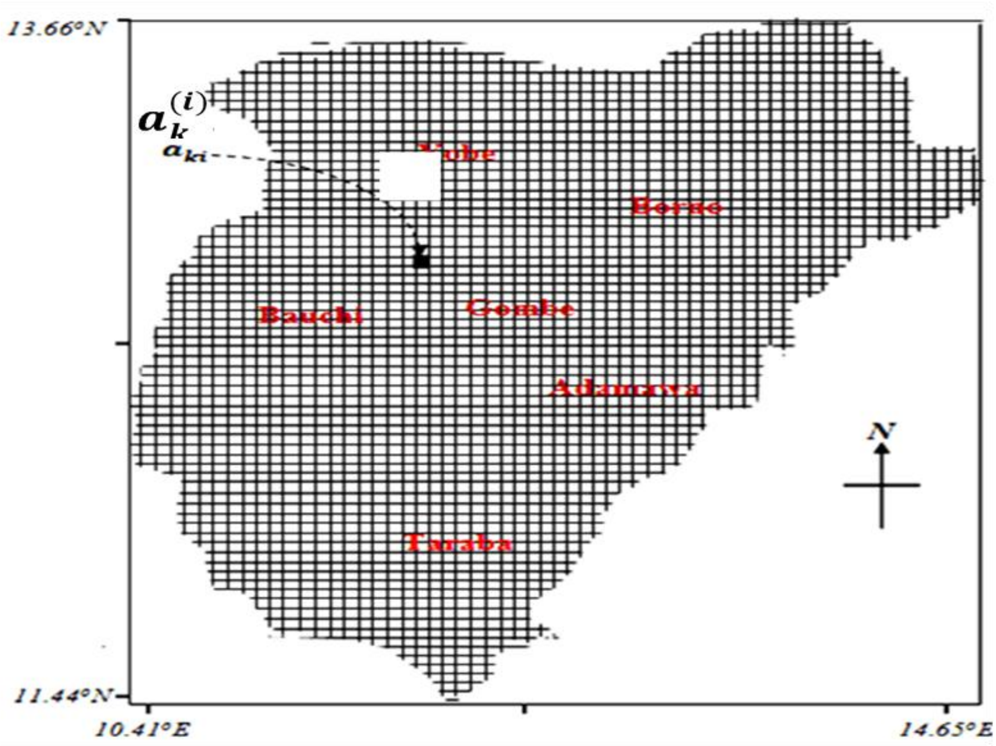


Figure 2: Northeast Sub-region Showing Cell Areas with Constant Wind Speed

In the next subsection, we consider the design of wind farms for areas that have sufficient wind power density to sustain electricity generation for cluster of communities or injection into nearby national grid. Of course, where wind power is considered to be very low, other micro applications of wind for pumping water for rural areas and irrigation schemes.

Design of Wind Power Farms

For a given arbitrary area with rich wind energy potential, let the proposed wind farm (WF) to harness its energy, comprise$N$ rows of wind turbines (WTs), such that each row has$M$ wind turbines as illustrated schematically in Fig. (3). It can be shown that the electrical power output of WT located in i^{th} row and j^{th} column denoted as$P_{e,WT_{ij}}$ is given by Eqn. (19)

$$P_{e,WT_{ij}} = C_{PR_{ij}} \eta_{mR_{ij}} \eta_{g_{ij}} \frac{\rho_{ij}}{2} A_{ij} V_{R\,ij}^{3} \times 10^{-3} \;\; kW: \; \forall\, i \in \{1, N\}, j = 1,2 \ldots . M \quad (19)$$

Where;

$C_{PR_{ij}}$: is the coefficient of performance of WT_{ij} at rated wind speed$V_{R_{ij}}$.$\eta_{mR_{ij}}$: is the mechanical transmission efficiency at rated power, $\eta_{g_{ij}}$: is the generator efficiency at rated power, ρ_{ij}: is the air density in the area allocated to wind turbine at location(i, j) and $A_{ij} = \pi D_{ij}^{2}/4$: is the turbine blade area sweep with span diameter ofD_{ij}.

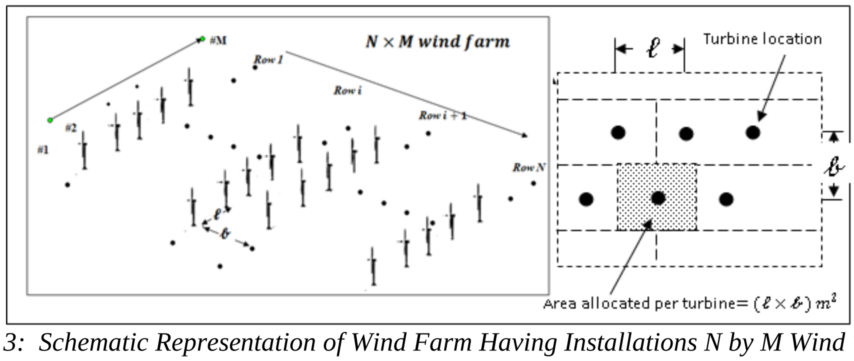


Figure 3: Schematic Representation of Wind Farm Having Installations N by M Wind Turbines

The area occupied by WT at location (i, j) is $(\mathcal{A}_{ij} = b_i \times \ell_j)\; m^2$and its power per unit area covered is then given by Eqn. (20).

$$\partial_{WT_{ij}} = \frac{P_{e,WT_{ij}}}{\mathcal{A}_{ij}} \ kWm^{-2} : \forall\, i \in \{1, N\}1,2 \ldots . M \tag{20}$$

The wind farm power per unit area covered can then be computed as in Eqn. (21):

$$P_{e,WF} = \sum_{i=1}^{N} \sum_{j=1}^{M} P_{e,WT_{ij}} \tag{21}$$

The wind farm power per unit area covered can then be computed as in Eqn. (22):

$$\partial_{WF} = \frac{P_{e,WF}}{\left(\sum_{i=1}^{N} \sum_{j=1}^{M} \mathcal{A}_{ij}\right)} \tag{22}$$

It is desired to maximize the power output from the WF via optimal selections of spacing ℓbetween adjacent WTs in a row and spacing $\mathscr{b}$between adjacent rows of WTs. The task is to mitigate the impacts of the so-called wake effects (Rehman et al., 2020) on wind velocities on downstream WTs. The problem of positional distribution of WTs within a WF can be cast as follows:

Maximize: $\left\{\mathbb{F}_{\text{obj}} = P_{e,WF}(V, \ell, \mathscr{b})\right\}$ (23)

Subject to the following constraints:

$$\left.\begin{array}{c} V_o - \Delta V \le V \le V_o \\ m_0 \times D \le \mathscr{b} \le m_1 \times D \end{array}\right\} n_0 \times D \le \ell \le n_1 \times D \tag{24}$$

Where in Eqn. (23) and Eqn. (24):

$\mathbb{F}_{\text{obj}}$: is the cost function of the optimization problem; V_o: is the initial wind speed; ΔV: is the allowable downstream wind speed deviation due to wake effect; D: is diameter of WT; n_0 and n_1: are specified lower and upper number of WT diameters, respectively allowed for the inter WT spacing in a row; whilst m_0 and m_1 : are specified lower and upper number of WT diameters, respectively allowed for the spacing between adjacent rows of WTs. Herein we sought for heuristic solution to the foregoing formulation of WF design.

This is reduced to specifications of n_0,n_1,m_0&m_(1)to enable feasible selections of optimum values for l and b based on good engineering judgment of the WF area and the prevailing wind regime potential for the area.

$$\begin{cases} 0 & \text{if } \left(\mathrm{V} < \mathrm{V_{c,in}}\right) \\ \alpha + \beta V^k & if\ \left(V_{c,in} \le V \le V_R\right) \\ P_{eR} & if\ \left(V_{c,in} < V \le V_R\right) \\ 0 & if\ \left(V > V_{c,off}\right) \end{cases} \tag{25}$$

Where;$\mathrm{V_{c,in}}$ is the cut-in wind speed; $\mathrm{V_{c,off}}$ is the cut off wind speed; P_{eR} is the rated electrical power and $\mathrm{V_R}$ is the rated wind speed and $k$and$C$ are the Weibull shape and scale parameters previously defined. Powell (1981) derived the coefficients $a$and b to be $\left(P_{eR}V_{c,in}^k\right)/\left(V_{c,in}^k - V_R^k\right)$ and$\left(P_{eR}V_{c,in}^k\right)/\left(V_R^k - V_{c,in}^k\right)$, respectively. It is shown in (Johnson, 2006) that the average electrical power delivered by WT based on the assumption of its Weibull wind model is given by:

$$P_{e,ave} = P_{eR}\left\{\frac{e^{-\left[\frac{V_{c,in}}{C}\right]^k} - e^{-\left[\frac{V_R}{C}\right]^k}}{\left[\frac{V_R}{C}\right]^k - \left[\frac{V_{c,in}}{C}\right]^k} - e^{-\left[\frac{V_{c,off}}{C}\right]^k}\right\} = cf \times P_{eR} \tag{26}$$

Where;

cf: is the capacity factor of the WT formally defined as follows:

$$cf \triangleq \frac{P_{e,ave}}{P_{eR}} = \frac{e^{-\left[\frac{V_{c,in}}{C}\right]^k} - e^{-\left[\frac{V_R}{C}\right]^k}}{\left[\frac{V_R}{C}\right]^k - \left[\frac{V_{c,in}}{C}\right]^k} - e^{-\left[\frac{V_{c,off}}{C}\right]^k} \tag{27}$$

The capacity factor is an important parameter widely used to assess the cost effectiveness of WT. In this study, the capacity factor is deployed to assess the viability of WF for specific locations in the study area.

Statistical Analysis of Wind Data for the Study Area

The availability of long-term wind data for the study area is starting point to engender firstly preprocessing algorithm to secure data integrity, devoid of bad and/or missing data gaps. The long-term data implied could be derived from satellite weather databases on the study area or on-site distributed weather monitoring stations. As the main computational engine of data preprocessing algorithm, we propose a combination of raster plots of sequentially segregated data blocks to remove any outliers and deployment of weighted moving average technique to fill-in identified missing data-gaps. The principal reason for embarking on data preprocessing is to secure improved data integrity and accuracy. This is a sine qua non to achieving very sound assessment of wind energy harvest for cost-effective electricity generations.

The post-processing of wind speed data for the study area entails statistical computations of their averages, variances, modes and medians, minima, maxima denoted respectively by $\bar{x}, s^2, Mo, Md, Min$ & Max, for different locations. For a given data sample $\{x_1, x_2 \dots\dots x_i, \dots\dots\dots x_N\} \in \mathcal{R}^N$, the generalized expressions for the statistical parameters are as follows.

$$\bar{x} = \frac{1}{N}\sum_{i=1}^{N} x_i\,; \quad s^2 = \frac{1}{N-1}\left(\sum_{i=1}^{N}(x_i - \bar{x})^2\right) \tag{28}$$

$$Mo = Most\ frequent\ number\ of\ \left\{\begin{matrix} x_1, x_2 \dots\dots x_i, \dots \\ \dots\dots x_N \end{matrix}\right\}$$

$$Md = Center\ number\ of\ numerically\ ordered\ \left\{\begin{matrix} x_1, x_2 \dots \\ \dots x_i, \dots \\ \dots\dots x_N \end{matrix}\right\}$$

$$Max = Maxmum\ \{x_1, x_2 \dots\dots x_i, \dots\dots\dots x_N\}$$

This work relied principally on ten-year monthly irradiation and wind speed data sourced from NASA global databases as well as monthly wind speed data obtained from NiMeT supplemented by recent publications on wind characterizations for selected locations in the study area. The salient steps adopted in the analysis of ten-year data for wind speed for each state in the northeast sub-region of Nigeria are depicted in the comprehensive flowchart of Fig. (3). In the next section, we present the results obtained based on the methodologies developed herein.

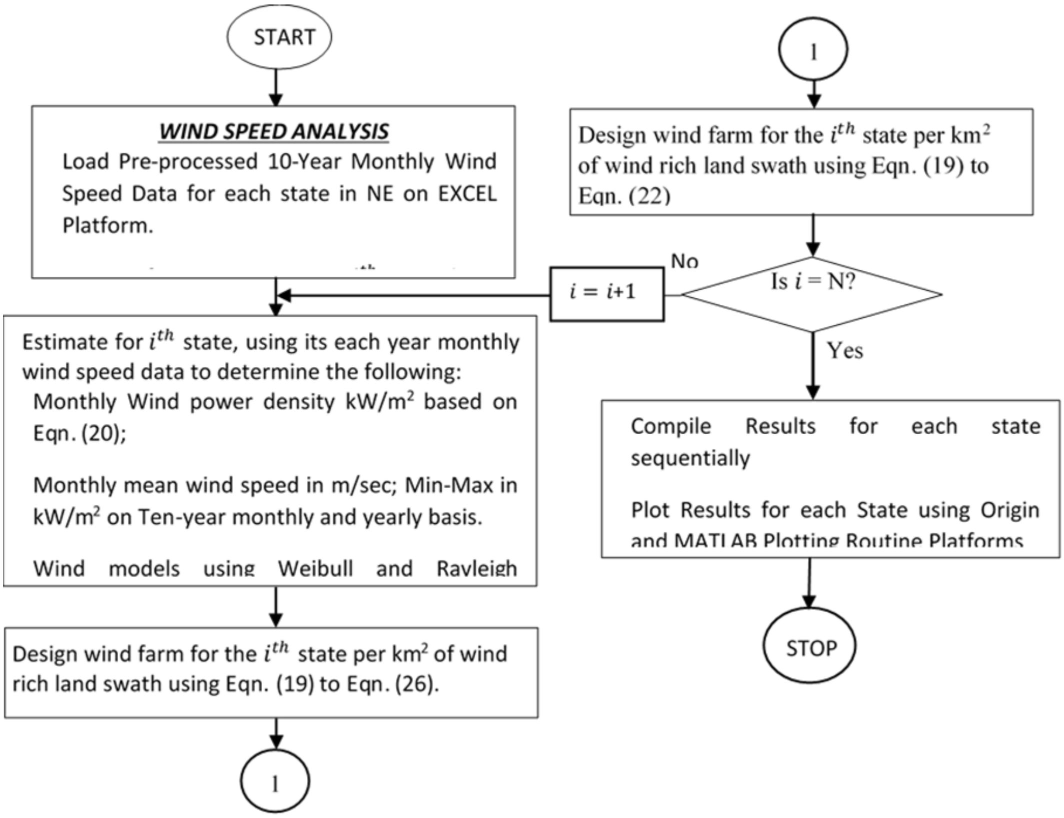


Figure 4: Functional Flowchart for Solar and Wind Energy Statistical Analysis

III. Result

Wind energy is also one of the renewable energy resources admitted in the North -East sub-region of Nigeria to mitigate the prevailing huge energy poverty; most especially in the rural areas. Consequently, 10-year annual mean wind speed data for six states of North-East downloaded from NASA website and wind speeds recorded at 10m height for some specific locations were comprehensively analyzed. The results obtained are presented in sequel.

Figs. 5 to 6 depict various results of statistical analyses carried out to decipher the diurnal and temporal variability of wind speeds in each of the six northeast states. Specifically, Fig. 7 shows comparative plots of monthly mean wind speeds for all the states in northeast sub-region carried out for two selected years and further reinforced in Figs 8 and 9 to deepen the interpretation of monthly and annual wind speed variability. Fig. 8 depicts 3-D view of monthly min-max plots of wind speeds for the entire northeast states with their corresponding monthly values summarized in Table 1. Figure 5 equally depicts 2-D view of annual min-max wind speed values based on the pre-processed 10-year raw wind data for each state. Tables 2 and 3 present representative baseline data in respect of mean monthly and annual wind speeds, respectively, for each state; and subsequently made use in the computations of Weibull wind model parameters. Tables 4 to 8 provide for each state, respectively, computed wind energy modeling parameters based on Weibull and Raleigh distribution functions and wind power densities. Table 9 offers comparison of wind characteristics for the states in the study area. Table 10 summarizes the leading design parameters for 1km^2 wind farms designed for each state whilst Table 11 presents monthly wind energy realizable per state. Figure 10 shows plots of annual wind energy yield and mean annual capacity factors for the northeastern states. The renewable energy potentials and demographic data of each state are presented in Table 12. Figure 11 depicts per capita electrical energy contributions from green energy per each NE state.

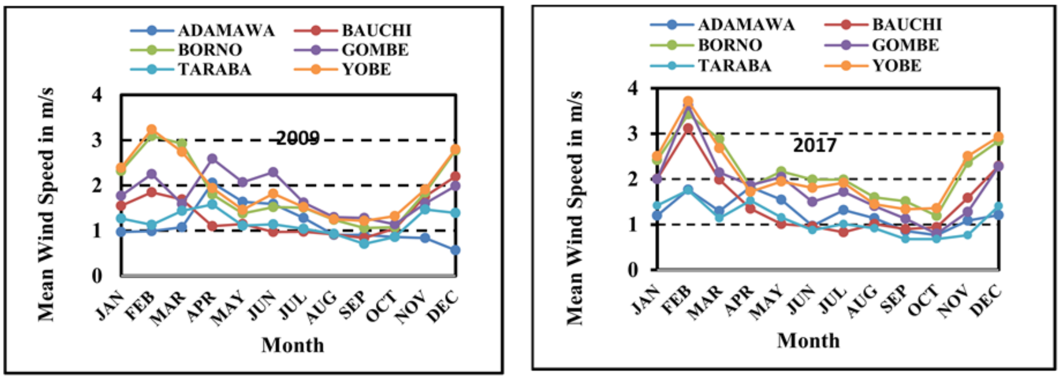


Figure 5: Monthly Mean Wind Speed Profiles for Six Northeast States for Two Selected Years

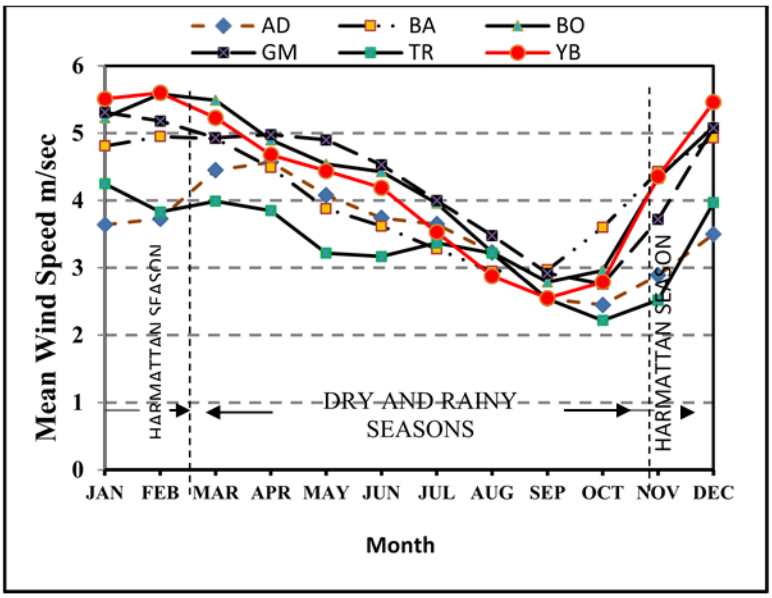


Figure 6: Monthly Mean Wind Speed for Six Northeast States Based on Ten-Year wind Data

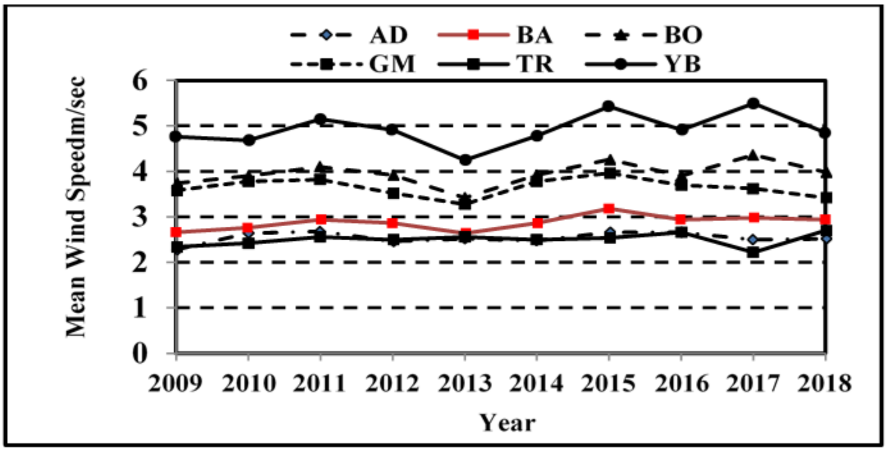


Figure 7: Mean Annual Wind Speed for Six Northeast States from 2009 to 2018

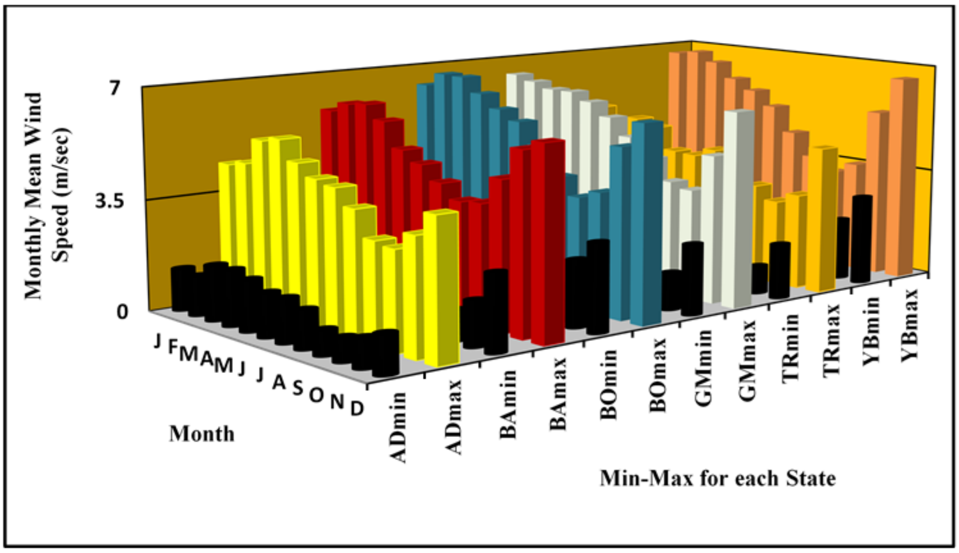


Figure 8: *3-D Plot of Monthly Min-Max Wind Speed Values for Six Northeast States Based on Ten-Year Wind Data*

Table 1: Summary of Monthly Min-Mean-Max Wind Speeds for Each State

State	Parameter Specifications	Monthly Wind Speed Parameter Values (m/sec) for each NE State											
		Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
	Maximum	4.44	4.59	5.4	5.55	4.94	4.57	4.44	3.94	3.15	3.05	3.58	4.3
Adamawa	Mean	3.64	3.73	4.45	4.57	4.08	3.74	3.65	3.23	2.54	2.45	2.89	3.5
	Minimum	1.34	1.26	1.74	1.75	1.61	1.37	1.37	1.19	0.77	0.73	0.9	1.19
	Maximum	5.81	6.12	6.21	5.76	4.97	4.63	4.17	3.73	3.79	4.64	5.63	5.93
Bauchi	Mean	4.81	4.95	4.92	4.49	3.88	3.62	3.28	2.95	2.97	3.6	4.43	4.93
	Minimum	2.31	2.01	1.71	1.29	1.15	1.1	1.05	0.99	0.9	0.97	1.42	.39
	Maximum	6.36	6.8	6.79	6.33	5.91	5.61	4.95	4.08	3.55	3.83	5.34	6.17
Borno	Mean	5.23	5.58	5.49	4.9	4.54	4.43	3.96	3.23	2.79	2.96	4.33	5.1
	Minimum	2.77	2.91	2.66	1.79	1.54	1.85	1.79	1.38	1.19	1.08	2.11	2.78
	Maximum	6.43	6.27	6.09	6.1	5.84	5.43	4.87	4.29	3.64	3.48	4.69	6.17
Gombe	Mean	5.31	5.18	4.93	4.98	4.9	4.53	4	3.48	2.92	2.76	3.72	5.08
	Minimum	2.41	2.35	1.92	2.08	2.44	2.19	1.74	1.37	1.07	0.9	1.2	2.24
	Maximum	5	4.57	4.77	4.57	3.84	3.8	4.08	3.93	3.11	2.69	3.03	4.67
Taraba	Mean	4.25	3.83	3.99	3.85	3.22	3.17	3.37	3.22	2.54	2.22	2.52	3.97
	Minimum	1.87	1.45	1.51	1.56	1.23	1.17	1.13	0.96	0.74	0.72	0.91	1.76
	Maximum	6.69	6.79	6.49	5.98	5.64	5.16	4.33	3.6	3.18	3.55	5.41	6.62
Yobe	Mean	5.51	5.6	5.23	4.68	4.44	4.19	3.53	2.88	2.55	2.79	4.36	5.46
	Minimum	2.86	2.92	2.41	1.75	1.75	2.02	1.72	1.27	1.14	1.1	1.98	2.86

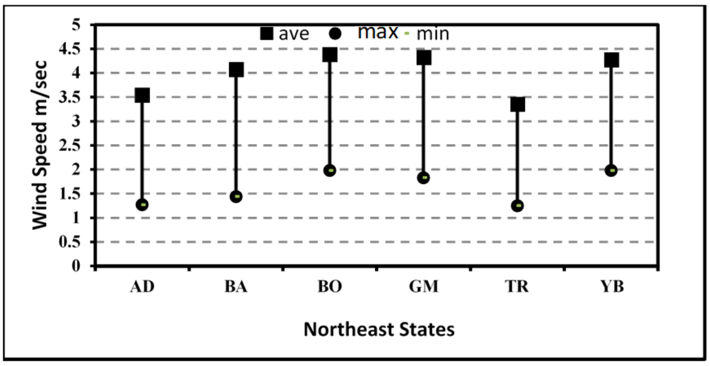


Figure 9: Min-Max Plot of Wind Speed for Six Northeast States Based on Ten-Year Wind Data

Table 2: Annual Mean Values and Standard Deviations of Wind Speed, 2009-2018

Year	Adamawa		Bauchi		Borno		Gombe		Taraba		Yobe	
	V_m m/s	S_D	V_m m/s	S_D	V_m m/s	S_D	V_m m/s	S_D	V_m m/s	S_D	V_m m/s	S_D
2009	3.64	0.423	4.04	0.449	4.88	0.725	4.49	0.452	3.67	0.266	4.97	0.679
2010	3.82	0.543	4.08	0.528	4.96	0.680	4.59	0.694	3.71	0.344	4.9	0.626
2011	3.83	0.367	4.17	0.646	5.05	0.742	4.61	0.628	3.78	0.454	5.06	0.728
2012	3.73	0.472	4.13	0.638	4.96	0.795	4.46	0.767	3.75	0.444	4.9	0.843
2013	3.75	0.470	4.02	0.426	4.72	0.694	4.34	0.603	3.78	0.398	4.77	0.667
2014	3.74	0.381	4.14	0.569	4.97	0.627	4.59	0.656	3.76	0.388	4.95	0.665
2015	3.83	0.396	4.29	0.730	5.13	0.830	4.68	0.698	3.77	0.593	5.15	0.771
2016	3.83	0.427	4.17	0.736	4.95	0.743	4.55	0.736	3.83	0.542	4.96	0.770
2017	3.75	0.331	4.2	0.718	5.19	0.642	4.52	0.722	3.61	0.353	5.16	0.725
2018	3.76	0.312	4.17	0.642	4.98	0.631	4.41	0.679	3.85	0.495	5.01	0.709

Table 3: 10-Year Maximum Mean Values of Wind Speed at 10m Height for Six States in NE

S/No	States	Monthly Mean Maximum Wind Speed for each State (m/sec)											
		Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
1	AD	4.44	4.59	5.40	5.55	4.94	4.57	4.44	3.94	3.15	3.05	3.58	4.30
2	BA	5.81	6.12	6.21	5.76	4.97	4.63	4.17	3.73	3.79	4.64	5.63	5.94
3	BO	6.36	6.80	6.79	6.33	5.91	5.61	4.95	4.08	3.55	3.83	5.34	6.17
4	GO	6.43	6.27	6.09	6.10	5.84	5.43	4.87	4.29	3.64	3.48	4.69	6.17
5	TA	5.00	4.57	4.77	4.57	3.84	3.80	4.08	3.93	3.11	2.69	3.03	4.67
6	YO	6.69	6.79	6.49	5.98	5.64	5.16	4.33	3.60	3.18	3.55	5.41	6.62

Table 4: Wind Energy Selected Model Parameters and Wind Power Densities for Adamawa State

Description	Variable Specification	Month											
		Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Wind Data	$V_m\ (m/s)$	3.64	3.73	4.45	4.57	4.08	3.74	3.65	3.23	2.54	2.45	2.89	3.5
Wind Data	$SD\ (\sigma)$	1.22	1.31	1.44	1.49	1.31	1.26	1.21	1.08	0.94	0.91	1.05	1.22
Wind PD	$PD\ (Wm^{-2})$	29.5	31.8	54	58.5	41.6	32.0	29.8	20.6	10.0	9.01	14.8	26.3
Weibull Model	k	3.28	3.12	3.41	3.38	3.43	3.26	3.32	3.29	2.94	2.93	3	3.14
Weibull Model	$C\ (m/s)$	4.06	4.17	4.96	5.09	4.55	4.18	4.07	3.61	2.85	2.75	3.24	3.92
Weibull Model	$V_{mp,W}\ (m/s)$	3.63	3.68	4.48	4.59	4.12	3.74	3.65	3.23	2.47	2.38	2.83	3.47
Weibull Model	$V_{max,E,W}(m/s)$	4.69	4.89	5.68	5.84	5.2	4.84	4.69	4.17	3.4	3.28	3.84	4.59
Weibull PD	$\partial_{V_{Weibull}}(Wm^{-2})$	39.6	43.7	71.4	77.3	55	43.3	39.8	27.8	14.3	12.9	20.8	36.2
Raleigh Model	k	2	2	2	2	2	2	2	2	2	2	2	2
Raleigh Model	$C\ (m/s)$	4.11	4.21	5.02	5.16	4.6	4.22	4.12	3.64	2.87	2.76	3.26	4.11
Raleigh Model	$V_{mp,R}\ (m/s)$	2.9	2.98	3.55	3.65	3.26	2.98	2.91	2.58	2.03	1.95	2.31	2.79
Raleigh Model	$V_{max,E,R}(m/s)$	5.81	5.95	7.1	7.29	6.51	5.97	5.82	5.15	4.05	3.91	4.61	5.59
Raleigh PD	$\partial_{V_{Raleigh}}(Wm^{-2})$	56.42	60.7	103.	112	79.	61.2	56.8 8	39.4 2	19.1 7	17.2	28.2	50.2

Table 5: Wind Energy Selected Model Parameters and Wind Power Densities for Bauchi State

Description	Variable Specification	Month											
		Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Wind Data	$V_m\ (m/s)$	4.81	4.95	4.92	4.49	3.88	3.62	3.28	2.95	2.97	3.6	4.43	4.93
Wind Data	$StD\ (\sigma)$	1.35	1.58	1.73	1.72	1.47	1.36	1.2	1.05	1.11	1.41	1.62	2.32
Wind PD	$PD\ (Wm^{-2})$	68.16	74.3	73.0	55.4 4	35.7 8	29.0 6	21.6 1	15.7 2	16.0 5	28.5 8	53.3	73.4
Weibull Model	k	3.97	3.46	3.11	2.84	2.87	2.9	2.98	3.07	2.91	2.77	2.98	2.27
Weibull Model	$C\ (m/s)$	5.32	5.51	5.51	5.04	4.36	4.06	3.68	3.3	3.33	4.05	4.97	5.57
Weibull Model	$V_{mp,W}\ (m/s)$	4.94	4.99	4.86	4.33	3.76	3.51	3.21	2.9	2.88	3.45	4.33	4.31
Weibull Model	$V_{max,E,W}(m/s)$	5.9	6.29	6.46	6.08	5.24	4.86	4.37	3.89	3.99	4.93	5.9	7.36
Weibull PD	$\partial_{V_{Weibull}}(Wm^{-2})$	84.88	97.4	101.	80.3 9	51.7 8	41.6 1	30.6 1	21.8	22.9 2	42.2 3	75.4	125.
Raleigh Model	k	2	2	2	2	2	2	2	2	2	2	2	2
Raleigh Model	$C\ (m/s)$	5.43	5.59	5.55	5.07	4.38	4.08	3.7	3.33	3.35	4.06	5	5.56
Raleigh Model	$V_{mp,R}\ (m/s)$	3.84	3.95	3.93	3.58	3.1	2.89	2.62	2.35	2.37	2.87	3.53	3.93
Raleigh Model	$V_{max,E,R}(m/s)$	7.68	7.9	7.85	7.17	6.19	5.78	5.23	4.71	4.74	5.74	7.07	7.87
Raleigh PD	$\partial_{V_{Raleigh}}(Wm^{-2})$	130.1 8	142.	139.	105. 9	68.3 3	55.4 9	41.2 8	30.0 3	30.6 5	54.5 8	102.	140.

Table 6: Wind Energy Selected Model Parameters and Wind Power Densities for Borno State

Description	Variable Specification	Month											
		Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Wind Data	$V_m\ (m/s)$	5.23	5.5 8	5.49	4.9	4.54	4.43	3.96	3.23	2.79	2.96	4.33	5.1
Wind Data	$StD\ (\sigma)$	1.35	1.4 7	1.56	1.71	1.65	1.42	1.19	1.02	0.89	1.04	1.22	1.2 8
Wind PD	$PD\ (Wm^{-2})$	87.62	106	101	72.0 6	57.3 2	53.2 5	38.0 4	20.6 4	13.3	15.8 8	49.7	81. 3
Weibull Model	k	4.35	4.2 6	3.92	3.14	3	3.44	3.69	3.5	3.46	3.11	3.96	4.4 9
Weibull Model	$C\ (m/s)$	5.75	6.1 4	6.07	5.48	5.09	4.93	4.39	3.59	3.11	3.31	4.79	5.6
Weibull Model	$V_{mp,W}\ (m/s)$	5.41	5.7 7	5.63	4.85	4.45	4.46	4.03	3.26	2.82	2.92	4.45	5.2 9
Weibull Model	$V_{max,E,W}(m/s)$	6.27	6.7 2	6.74	6.41	6.03	5.63	4.94	4.08	3.55	3.88	5.31	6.0 8
Weibull PD	$\partial_{V_{Weibull}}(Wm^{-2})$	105.5 8	129	126.	98.9 8	80.7 7	69.9 1	48.4 5	26.8 6	17.5 2	21.8 9	62	97. 1
Raleigh Model	k	2	2	2	2	2	2	2	2	2	2	2	2
Raleigh Model	$C\ (m/s)$	5.9	6.3	6.19	5.53	5.12	5	4.47	3.64	3.15	3.34	4.89	5.7 5
Raleigh Model	$V_{mp,R}\ (m/s)$	4.17	4.4 5	4.38	3.91	3.62	3.53	3.16	2.58	2.23	2.36	3.45	4.0 7
Raleigh Model	$V_{max,E,R}(m/s)$	8.35	8.9	8.76	7.82	7.24	7.07	6.32	5.15	4.45	4.72	6.91	8.1 4
Raleigh PD	$\partial_{V_{Raleigh}}(Wm^{-2}))$	167.3 4	203 .	194	137. 6	109. 4	101. 7	72.6 4	39.4 2	25.4 1	30.3 4	95	155

Table 7: Wind Energy Selected Model Parameters and Wind Power Densities for Gombe State

Description	Variable Specification	Month											
		Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Wind Data	$V_m\ (m/s)$	5.31	5.1 8	4.93	4.98	4.9	4.53	4	3.48	2.92	2.76	3.72	5.0 8
Wind Data	$StD\ (\sigma)$	1.55	1.5 2	1.61	1.55	1.32	1.25	1.21	1.13	0.99	1	1.35	1.5 2
Wind PD	$PD\ (Wm^{-2})$	91.7	85. 1	73.4	75.6 5	72.0 6	56.9 4	39.2	25.8 1	15.2 5	12.8 8	31.5	80. 3
Weibull Model	k	3.81	3.7 9	3.37	3.55	4.16	4.05	3.66	3.39	3.24	3.01	3.01	3.7 1
Weibull Model	$C\ (m/s)$	5.88	5.7 4	5.5	5.54	5.4	5	4.44	3.88	3.26	3.09	4.17	5.6 4
Weibull Model	$V_{mp,W}\ (m/s)$	5.43	5.2 9	4.95	5.05	5.05	4.66	4.07	3.5	2.91	2.7	3.65	5.1 8
Weibull Model	$V_{max,E,W}(m/s)$	6.57	6.4 2	6.32	6.28	5.93	5.52	5	4.45	3.78	3.66	4.94	6.3 4
Weibull PD	$\partial_{V_{Weibull}}(Wm^{-2})$	115.5 7	108	97.7	98.3 3	88.0 4	70.2 1	50.2 2	34.2 3	20.6	18.0 5	44.4	103
Raleigh Model	k	2	2	2	2	2	2	2	2	2	2	2	2
Raleigh Model	$C\ (m/s)$	5.99	5.8 5	5.56	5.62	5.53	5.11	4.51	3.93	3.29	3.11	4.2	5.7 3
Raleigh Model	$V_{mp,R}\ (m/s)$	4.24	4.1 3	3.93	3.97	3.91	3.61	3.19	2.78	2.33	2.2	2.97	4.0 5
Raleigh Model	$V_{max,E,R}(m/s)$	8.47	8.2 7	7.87	7.95	7.82	7.23	6.38	5.55	4.66	4.4	5.94	8.1 1
Raleigh PD	$\partial_{V_{Raleigh}}(Wm^{-2})$	175.1 4	163	140	144. 5	137. 6	108. 7	74.8 7	49.3	29.1 2	24.5 9	60.2	153

Table 7: Wind Energy Selected Model Parameters and Wind Power Densities for Taraba State

Description	Variable Specification	Month											
		Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Wind Data	$V_m\ (m/s)$	4.25	3.83	3.99	3.85	3.22	3.17	3.37	3.22	2.54	2.22	2.52	3.97
Wind Data	$StD\ (\sigma)$	1.25	1.25	1.3	1.2	1.04	1.05	1.17	1.18	0.94	0.79	0.84	1.16
Wind PD	$PD\ (Wm^{-2})$	47.02	34.4	38.9	34.95	20.45	19.51	23.44	20.45	10.04	6.7	9.8	38.3
Weibull Model	k	3.78	3.37	3.38	3.55	3.41	3.32	3.15	2.97	2.94	3.07	3.3	3.8
Weibull Model	$C\ (m/s)$	4.71	4.27	4.45	4.28	3.59	3.54	3.77	3.61	2.85	2.49	2.81	4.4
Weibull Model	$V_{mp,W}\ (m/s)$	4.34	3.85	4.01	3.9	3.24	3.18	3.34	3.14	2.47	2.19	2.52	4.06
Weibull Model	$V_{max,E,W}(m/s)$	5.27	4.9	5.11	4.85	4.11	4.08	4.41	4.29	3.4	2.93	3.24	4.92
Weibull PD	$\partial_{V_{Weibull}}(Wm^{-2})$	59.5	45.7	51.7	45.34	27.06	26.17	32.19	28.94	14.3	9.37	13.1	48.5
Raleigh Model	k	2	2	2	2	2	2	2	2	2	2	2	2
Raleigh Model	$C\ (m/s)$	4.8	4.32	4.5	4.34	3.63	3.58	3.8	3.63	2.87	2.51	2.84	4.48
Raleigh Model	$V_{mp,R}\ (m/s)$	3.39	3.06	3.18	3.07	2.57	2.53	2.69	2.57	2.03	1.77	2.01	3.17
Raleigh Model	$V_{max,E,R}(m/s)$	6.78	6.11	6.37	6.14	5.14	5.06	5.38	5.14	4.05	3.54	4.02	6.34
Raleigh PD	$\partial_{V_{Raleigh}}(Wm^{-2})$	89.8	65.7	74.3	66.76	39.05	37.26	44.77	39.05	19.17	12.8	18.7	73.2

Table 8: Wind Energy Selected Model Parameters and Wind Power Densities for Yobe State

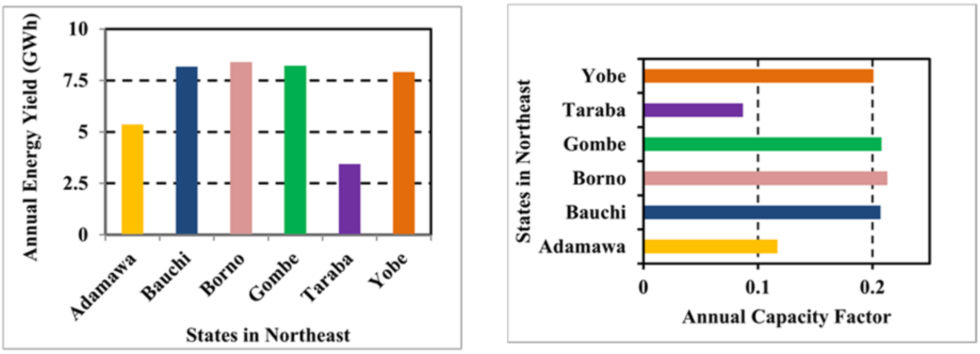
Description	Variable Specification	Month											
		Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Wind Data	$V_m\ (m/s)$	5.51	5.6	5.23	4.68	4.44	4.19	3.53	2.88	2.55	2.79	4.36	5.46
Wind Data	$StD\ (\sigma)$	1.45	1.47	1.54	1.6	1.47	1.19	0.99	0.88	0.77	0.93	1.3	1.42
Wind PD	$PD\ (Wm^{-2})$	102.46	108	87.6	62.78	53.61	45.06	26.94	14.63	10.16	13.3	50.8	99.7
Weibull Model	k	4.26	4.27	3.77	3.21	3.32	3.92	3.98	3.62	3.67	3.3	3.72	4.32
Weibull Model	$C\ (m/s)$	6.07	6.16	5.8	5.23	4.95	4.63	3.9	3.2	2.83	3.11	4.84	6
Weibull Model	$V_{mp,W}\ (m/s)$	5.7	5.79	5.34	4.66	4.44	4.29	3.63	2.93	2.6	2.79	4.45	5.65
Weibull Model	$V_{max,E,W}(m/s)$	6.64	6.74	6.49	6.08	5.71	5.14	4.32	3.61	3.19	3.59	5.43	6.55
Weibull PD	$\partial_{V_{Weibull}}(Wm^{-2})$	124.58	130	111	85.35	71.54	56.09	33.42	18.85	13	17.78	64.8	120
Raleigh Model	k	2	2	2	2	2	2	2	2	2	2	2	2
Raleigh Model	$C\ (m/s)$	6.22	6.32	5.9	5.28	5.01	4.73	3.98	3.25	2.88	3.15	4.92	6.16
Raleigh Model	$V_{mp,R}\ (m/s)$	4.4	4.47	4.17	3.73	3.54	3.34	2.82	2.3	2.03	2.23	3.48	4.36
Raleigh Model	$V_{max,E,R}(m/s)$	8.79	8.94	8.35	7.47	7.09	6.69	5.63	4.6	4.07	4.45	6.96	8.71
Raleigh PD	$\partial_{V_{Raleigh}}(Wm^{-2})$	195.69	205	167	119.9	102.4	86.05	51.46	27.94	19.4	25.41	97	190

Table 9: Comparison of Mean Wind Speed Model Parameters for NE States at 10m Height

Description		States of Northeast Sub-region					
Specifications	Variables	Adamawa	Bauchi	Borno	Gombe	Taraba	Yobe
Wind Data	$V_m\ (m/s)$	3.54	4.07	4.38	4.32	3.35	4.27
Wind Data	$StD\ (\sigma)$	1.2	1.49	1.32	1.33	1.1	1.25
Wind PD	$PD\ (Wm^{-2})$	29.83	45.36	58.07	54.99	25.33	56.22
Weibull Model	k	3.21	3.01	3.69	3.56	3.34	3.78
Weibull Model	$C\ (m/s)$	3.95	4.56	4.85	4.8	3.73	4.73
Weibull Model	$V_{mp,W}\ (m/s)$	3.52	3.96	4.45	4.37	3.35	4.36
Weibull Model	$V_{max,E,W}(m/s)$	4.59	5.44	5.47	5.43	4.29	5.29
Weibull PD	$\partial_{V_{Weibull}}(Wm^{-2})$	40.19	64.6	73.7	70.63	33.48	70.57
Raleigh Model	k	2	2	2	2	2	2
Raleigh Model	$C\ (m/s)$	3.99	4.59	4.94	4.87	3.78	4.82
Raleigh Model	$V_{mp,R}\ (m/s)$	2.82	3.25	3.49	3.44	2.67	3.41
Raleigh Model	$V_{max,E,R}(m/s)$	5.65	6.49	6.99	6.89	5.34	6.81
Raleigh PD	$\partial_{V_{Raleigh}}(Wm^{-2})$	56.96	86.63	110.91	105.02	48.38	107.37

Table 11: Monthly Wind Energy Harvestable per State from 1km^2 Wind Farm

Month	Monthly Wind Energy Available per State in (GWh)					
	Adamawa	Bauchi	Borno	Gombe	Taraba	Yobe
Jan	0.441	0.81	0.991	1.186	0.534	1.226
Feb	0.473	0.941	1.15	0.995	0.397	1.162
Mar	0.871	1.119	1.293	1.055	0.507	1.156
Apr	0.93	0.91	1.066	1.008	0.39	0.917
May	0.633	0.598	0.927	0.813	0.208	0.763
Jun	0.48	0.445	0.699	0.598	0.202	0.452
Jul	0.434	0.306	0.417	0.443	0.302	0.212
Aug	0.27	0.181	0.195	0.296	0.282	0.104
Sept	0.117	0.208	0.101	0.146	0.101	0.049
Oct	0.102	0.487	0.181	0.141	0.044	0.114
Nov	0.2	0.842	0.514	0.462	0.068	0.592
Dec	0.41	1.324	0.863	1.068	0.4	1.162



a) Annual Energy Yield of Wind Farm per State b) Annual Capacity Factor of each State Wind Farm

Figure 10: Annual Energy Yield and Capacity Factor of Wind Farms in Northeastern States

Table 12: Summary of Min-Max Benchmark Data of Green Energy Potential and Per Capita/Energy Density Range Estimates for Each State in Northeast Sub-region

S/No	Green Energy Classification/ Demographic Assessment	BENCHMARK DATA SPECIFICATIONS FOR STATES OF NORTHEAST SUB-REGION					
		Adamawa	Bauchi	Borno	Gombe	Taraba	Yobe
1	10-Year Running Average of Min- Max Wind Speed (m/s)	1.22-4.33	1.44-5.12	1.98-5.48	1.83-5.27	1,25-4.0	1.98-5.29
2	10-Year Running Average of wind power density (W/m^2)	22.4-37.3	34.0-56.7	43.6-72.6	41.2-68.7	19.0-31.7	42.2-70.3
3	Electrical Energy Potential from $1km^2$ of landmass per State as Wind farm (GWh/yr)	4.0-6.7	6.1-10.2	6.3-12.5	6.2-10.5	2.6-4.9	5.9-11.5
4	Per Capita Electrical Energy from Wind Farm (kWh/yr/person)	107-1.79	1.31-2.19	1.52-3.01	2.63-4.46	1.03-1.93	2.19-4.28

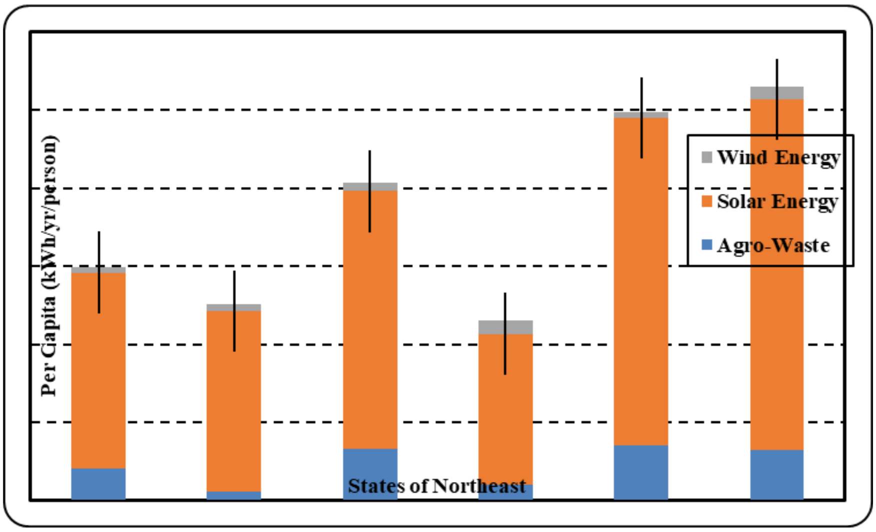


Figure 11: Comparison of Per Capita Electrical Energy Contributions for Six NE States from Three Major Green Energy Sources (Agro-Wastes, Solar & Wind Energy)

IV. Discussion

Statistical analyses carried out for the ten-year wind speed data analysis for the six states in northeast. The graphical plots monthly minimum mean wind speed profiles for the six NE states of Fig. 5 for two selected years (2009 & 2017) clearly connote low wind speed regime classifications as all wind speeds for the states are within the range of 0.5-3.7m/sec. The statistical analysis of monthly mean maximum wind speed profiles, using 10-year (2009-2018) wind data for the six NE states as plotted in Fig. 6, reveal higher mean wind speeds during the harmattan season than the dry and rainy seasons. It can be observed from Figs 7 and 8 that Adamawa and Taraba states have the least wind speed of between 0.5 and 2.5m/sec as further collaborated by annual mean wind speed of Fig. 9 based on the acquired 10-year wind speed data. Consulting long-term average wind speed contour lines (see Fig.5), it is established that the northern most fringes of the northeast sub-region have average wind speeds in the range of 2.27m/s to 5.58m/s whilst the southern most states typically have much lower average wind speeds of 3.3m/s to 4.5m/s. The prevailing wind speed patterns in the Northeast sub-region can only support wind farms in topographically induced rich wind localities but offer more prospects for distributed micro applications such as wind turbine driven rural water pumping schemes, battery charging systems, etc as earlier observed.

The wind farm (WF) design entertained is primarily based on modified data of existing commercially available wind turbine specifications as documented in Appendix C leading to design parameters summarized in Table 26. In particular, the cut-in speed, rated speed, cut-out speed and WT spacing specifications ensured maximum extraction of energies from sub-region dominated by low wind speed regime. For generic WT utilized bearing hub height of 30m and cut-in speed of 2m/sec and relying on its Weibull wind model, offered operational availabilities of greater than 90% for sites in Yobe, Bornu, Gombe and Bauchi States while its operational availabilities for sites in Taraba and Adamawa are in the neighborhood of 84%. Due to wind speeds variation with height necessitated extrapolations of wind speeds at 30m WT hub height given wind speed data at 10m height. The extrapolation techniques outlined in (Oyedepo *et al*, 2017) have been utilized as reproduced in Appendix C for the sake of convenience.

According to Table 27, being results of harvestable wind energy from consideration of scalable 1km^2 WF area per state, reveal that Bornu, Yobe, Gombe and Bauchi States have average monthly energy yield of between 0.66 and 0.7GWh while Adamawa and Taraba States have average monthly energy yield of 0.45GWh and 0.29GWh, respectively. The aforementioned results are further corroborated by Fig. 31(a) which returned Bornu State with highest aggregate annual wind energy yield of 8.34GWh whilst Taraba State returned the least aggregate annual wind energy yield of 3.44GWh. The corresponding computed annual capacity factors (See Fig. 31(b)) for WFs in Bornu, Yobe, Gombe and Bauchi are greater than 0.2 whilst that of Adamawa and Taraba States are lower than 0.12.

V. Conclusion

Table 28 constitutes novel benchmark data constructed to consolidate green energy potentials for economic sustainability and attainment of core Sustainable Development goal agenda. Some critical indices developed ought to guide potential energy investors on the comparative advantages of northeast states green energy development. The wind energy potential of this sub-region was also investigated with wind speeds falling between 1.25m/sec and 5.48m/sec and average power densities ranging from 0.019kW/m^2 to 0.085kW/m^2. Conclusively, the wind energy potential of this sub-region can be classified as low regime which largely offers prospects for distributed micro applications such as wind turbine driven rural water pumping schemes, battery chargers, etc. However, in the northern fringes of the study area, characterized by higher mean wind speeds greater than3.72m/sec and less than 10% calm periods, scalable wind farms are proposed for electrical power generation with estimated capacity of 2.5 MW achievable per km^2 wind farm area.

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