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COMPARATIVE ASSESSMENT OF NUMERICAL TECHNIQUES FOR WEIBULL PARAMETERS' ESTIMATION AND THE PERFORMANCE OF WIND ENERGY CONVERSION SYSTEMS IN NIGERIA

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ABSTRACT: The wind speed of a location is a critical parameter for analyzing wind energy conversion systems. Background knowledge has revealed that the two-parameter Weibull distribution is commonly used for fitting wind speed data because of its simplicity, flexibility and suitability. This research study examines wind speed data from five locations in Nigeria (Kano, Maiduguri, Jos, Abuja and Akure). It employs five numerical techniques, namely the maximum likelihood method, method of moment, power density method, empirical method and the logarithmic moment method, to estimate the Weibull parameters based on the locations' data. The goodness of fit test is used to determine which numerical method best fits the distribution. The paper also considers the techno-economic design of wind electricity of five 25 kW pitch-controlled wind turbines with dissimilar characteristics. The test result presents the method of moment and empirical method as the best methods for calculating the Weibull parameters. Results also show that wind turbine-3 has the least cost of energy and wind turbine-5 has the highest cost of energy.

ABSTRAK: Kelajuan angin sesuatu lokasi adalah parameter kritikal bagi menganalisa sistem penukaran tenaga angin. Latar belakang berkaitan telah mendedahkan 2-parameter taburan Weibull (Wbl) lazimnya digunakan bagi memadan data kelajuan angin berdasarkan kesederhanaan, fleksibiliti dan kesesuaian. Kajian penyelidikan ini adalah berkaitan ujian data kelajuan angin pada lima lokasi di Nigeria (Kano, Maiduguri, Jos, Abuja dan Akure). Ia menggunakan lima teknik berangka iaitu kaedah kemungkinan maksimum, kaedah momen, kaedah ketumpatan kuasa, kaedah empirikal dan kaedah momen logaritma bagi menganggar parameter Weibull berdasarkan lokasi data. Ujian kesesuaian digunakan bagi memastikan kaedah berangka adalah padanan paling sesuai bagi taburan. Kajian ini juga turut menimbang reka bentuk tekno-ekonomi elektrik angin bagi lima turbin angin 25 kW kawalan anggul dengan ciri berbeza. Dapatan kajian menunjukkan momen dan kaedah empirikal adalah kaedah terbaik bagi mengira parameter Weibull. Ini menunjukkan bahawa turbin angin-3 mempunyai kos tenaga paling rendah dan turbin angin-5 mempunyai kos tenaga tertinggi.

KEY WORDS: *Wind Speed, Numerical Method, Weibull Distribution, Energy Cost*

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1. INTRODUCTION

The term "energy" is considered one of the most crucial human needs and is also identified as one of the essential indicating factors for measuring a country's level of development and the human development index (HDI) [1]. Although conventional energy sources, i.e., fossil fuels, play a critical role in meeting the world's energy demand requirements, its utilization has continued to raise environmental concerns [2]. Therefore, the quest to reduce the usage of fossil fuels due to its negative environmental effects, depletion, unstable price and the issue of energy consumption growth has driven the need for cleaner alternative energy resources [3].

Despite the global cry for the energy transition to green energy, burning of fossil fuel still occupy the larger percentage of Nigeria's electricity generation both at the utility and the energy users' levels [4]. The present electricity generation capacity of the country is less than 5000 MW for all sources (thermal, gas and hydro) as at March 2022. This is inadequate considering the country's population of over 200 million. The gap in generation and the citizens' demand has resulted in energy poverty and low standard of living [5]. In order to address this problem, it is necessary to grow the country's energy mix by harnessing the available renewable energy (RE) sources, one of which is the wind energy resource.

Wind energy is naturally-occurring and can be deployed for on-grid and off-grid generation applications [6]. However, in order to utilize wind energy, the probability density function (PDF) related to wind speed must be well assessed or evaluated for the supply of reliable electricity at an affordable cost. Such parameter provides crucial information in wind energy planning and implementation and also helps to ascertain a location's wind power potential. Various PDFs have been proposed in the literature to describe the distribution of wind speed, but the 2-parameter Weibull (Wbl) distribution is widely employed because of its simplicity, flexibility and suitability for fitting recorded wind data [7]. In analyzing wind speed data, the distribution that fits the data statistically needs to be firstly determined, and then the estimations of the relevant parameters concerning this distribution can be calculated. Some studies have been presented on wind energy generation in Nigeria. Some of these scholarly works will be presented in this section for the purpose of laying useful background for this present study.

Oyedepo et al., [8] presented the wind characteristics and the potential for selected locations in Nigeria utilizing data that spans 24 to 27 years, measured at the height of 10 m. The central concern of the paper includes the determination of the annual output power and capacity factor (CFw). Adaramola et al., [9] presented wind turbines' performance for electricity production in seven different areas within the Niger-Delta region of Nigeria based on wind data that spans 9 to 37 years, using the 2-parameter Wbl distribution functions. Observation showed that 35 kW wind turbine discussed in their work has the highest CFw irrespective of the locations.

Ajayi et al., [10] presented a Techno-economic (TE) evaluation of wind turbines for electricity supply to 10 locations in Nigeria. The 2-parameter method WPD was used to assess the wind potential for the locations. The turbine matching results reveal that the cut-in and rated wind speeds range from 2.0 to 3.0 m/s, and 10 to 12.0 m/s, respectively. Sulaiman et al., [11] also discussed the assessment of the wind potential of 4 different locations in Nigeria, emphasizing wind power potentials and wind speed characteristics using the 2-parameter WDF technique. The paper used the CFw calculation to determine the most suitable turbine for the specified locations and reported monthly mean wind speed of 4.50, 3.72, 4.77 and 5.34 m/s with corresponding wind power densities of 67.74, 40.87, 79.52 and 107.49 Wm-2 for the sites.

Okakwu et al., [12] discussed the TE evaluation of wind resources for power generation in Nigeria. The study used a 2-parameter WDF for analyzing the wind potential of four different locations based on the average wind speeds/day measured at the anemometer positioned at 10 m over a period of 11 years. It employed the power density and the CFw to classify the sites and select the most suitable turbine for these locations. It also used the present-value cost to the COE by the WECS at various h/hs.

Mohammadi et al., [13] considered the TE analysis of large-scale wind electricity systems in Iran. The paper employed the 2-parameter WDF for analyzing the measured wind data between 2008 and 2009 at the height of 40 m height. However, the authors examined the TE analysis of four large-scale wind turbine systems at a height of 70 m height. Ajayi et al. [14] discussed the wind profile and turbine system performance assessment in Kano, Nigeria. The authors also presented the wind energy analysis using the 2-parameter WDF method based on the wind data that spans between 1987 and 2007 at 10 m. The study also employed wind rose to describe the direction of the wind energy in different seasons.

Alkhalidi et al., [15] evaluated wind potential at coastal and offshore locations in Kuwait. This work explores ten coastal and offshore locations for the analysis and then considered the potential at different heights of 50, 80, 100, and 120 m. The authors employed a 2-parameter Wbl distribution method to analyze the wind resource and calculate wind energy density. In addition, the study calculated the Wbl distribution parameters by using the maximum likelihood method. Mostafaeipour et al., [16] analyzed the wind potential and the WECSs cost for Zahedan, Iran using 5-year wind resource data. The wind power density and the energy output have also been determined by using the WDF. The study considered the comparative analyses of the 3 different PDF models such as Wbl, Rayleigh, and lognormal, to analyze the location's wind profile.

Souloukngа et al. [18] evaluated the cost of generating wind-generated electricity in Chad. The work used the Wbl distribution for assessing the wind resource data obtained at an anemometer height of 10 m. The work also determined the Wbl statistical parameters (k and c) at different heights of 10, 30, 50, and 70 m. Belabes et al., [19] evaluated the wind potential and the cost of electricity by the WECSs for 6 different areas of the north of Algeria. The data recorded for over 10 years were used; the authors also obtained the Wbl parameters k and c for all months at different heights of 30, 50 and 70 m by extrapolating the 10 m data at the locations.

The reviewed studies have contributed substantially to the body of knowledge in the research direction of wind potential and cost analysis for different locations, all of which are based on the 2-parameter WDF at the height of 10 m. It is also found that [15] used the maximum likelihood method, while some others used the empirical method to calculate Wbl distribution parameters. The work in [20] compared the Wbl, Rayleigh, and lognormal models to assess the locations' wind resources and profiles. The main focus of the aforementioned studies includes the identification of suitable locations and the selection of WTs and COE, which are useful background contributions for understanding wind potential analysis and WECS design and planning.

However, this present study will first identify the best fit for the probability density function (PDF) of wind speed data and then ascertain suitable sites for wind power generation. It will also calculate the impact of varying the h/hs on the COE to provide useful insights into decision-making for a sound investment model for wind energy production in Nigeria. Importantly, this study uses five different techniques, namely the maximum likelihood, method of moment, power density, empirical and logarithmic moment methods, to characterize the wind resource data of 5 different locations in Nigeria and then determine the respective Wbl parameters (i.e., k and c). The comparative analysis is employed to understand the performance of different numerical methods mentioned given the locations' resource data, which also takes this paper a step further than the analysis presented in some previous studies discussed earlier.

In addition, the research study examines the TE performances of five 25 kW pitch-controlled wind turbines (WT1 – WT5) from different manufacturers with dissimilar design characteristics at varying h/hs. The results of this paper are expected to demonstrate a detailed TE analysis, which may be useful for designing, planning and assessing WECSs for local energy and agricultural applications, e.g. water-pumping.

The remaining part of this research article is arranged as follows: section 2 is on materials and methods, section 3 focuses on the results and discussion, while section 4 presents the conclusion of the paper.

2. MATERIALS AND METHOD

2.1 Study Area

This study considered five locations in Nigeria, namely Kano, Maiduguri, Jos, Abuja and Akure, in the northern and southern parts of the country. The wind speed data used in this work was obtained from the Nigeria Meteorological Agency (NIMET), Lagos State, Nigeria. The wind resource was measured by NIMET at a h/h of 10 m by an anemometer cup-generator. Table 1 presents the case study areas.

Table 1: The case study areas [24]

Locations	Latitude (^{0}N)	Longitude (^{0}E)	Data Period
Kano	12.05	8.52	2002-2012
Maiduguri	11.85	13.08	2002-2012
Jos	9.64	8.88	2002-2012
Abuja	9.00	7.27	2002-2012
Akure	7.25	5.20	2002-2012

2.2 Simulation Software

The implementation of the proposed approaches in terms of modelling, simulation and analysis was achieved using MATLAB version (2013a) and Microsoft Excel software.

2.3 Numerical Approaches to Weibull Parameters' Estimation

Background knowledge of wind resources and systems modelling and analysis shows that several methods can be employed for calculating the Wbl parameters k and c. However, five different methods are employed in this paper to characterize the wind speed data under review.

2.3.1. Maximum Likelihood Approach

Using the maximum likelihood method (MLM), k and c parameters are calculated by Eqs. (1) and (2) [21-23]:

$$\mathrm{k} = \left[\frac{\sum_{i=1}^{n} V_i^k \ln V_i}{\sum_{i=1}^{n} V_i^k} - \frac{\sum_{i=1}^{n} \ln(V_i)}{n}\right]^{-1} \tag{1}$$

$$\mathrm{c} = \left[\frac{1}{n}\sum_{i=1}^{n} V_i^k\right]^{\frac{1}{k}} \tag{2}$$

where V_i and n are the wind speed in time step i, and the number of 'non-zero' wind speed data points. In the MLM, numerical iterations are required to determine the Wbl parameters.

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2.3.2. Method of Moment

In the method of moment (MOM), the k and c parameters are given by Eqs. (3) and (4) [21-23]:

$$\mathrm{k} = \left[\frac{0.9874}{\frac{\sigma}{\bar{V}}}\right]^{1.0983} \tag{3}$$

$$\mathrm{c} = \frac{\bar{V}}{\Gamma\left(1+\frac{1}{k}\right)} \tag{4}$$

where; σ and $\bar{V}$ in this case, are the standard deviation and the mean wind speed.

2.3.3. Power Density Method

In employing the power density method (PDM) for wind resource analysis, the value of k parameter is calculated by Eqs. (5) and (6) [21-23]:

$$\mathrm{k} = 1 + \frac{3.69}{E_{pf}^2} \tag{5}$$

The scale parameter (c) in the case of PDM is estimated using Eq. (4).

$$E_{pf} = \frac{\overline{V^3}}{\left(\bar{V}\right)^3} = \frac{\frac{1}{n}\sum_{i=1}^{n} V_i^3}{\left(\frac{1}{n}\sum_{i=1}^{n} V_i\right)^3} \tag{6}$$

2.3.4. Empirical Method

In the empirical method (EPM), the k parameter is estimated by Eq. (7), while c parameter is calculated by employing Eq. (4) [22-24]:

$$\mathrm{k} = \left[\frac{\sigma}{\bar{V}}\right]^{-1.086} \tag{7}$$

In which case σ and $\bar{V}$ represent the standard deviation and the mean wind speed, respectively.

2.3.5. Logarithmic Moment Method

In the logarithmic moment method (LMM), the values of k and c parameters are estimated by Eqs. (8) and (9) [21-23]:

$$\mathrm{k} = \left[\frac{1.645}{\sigma^2}\right]^{\frac{1}{2}} \tag{8}$$

$$\mathrm{c} = exp\left[\frac{k\bar{V}+0.5772}{k}\right] \tag{9}$$

2.4 Numerical Method Accuracy Assessments

In order to test the accuracy of the presented numerical methods for estimating the Wbl parameters, two different approaches are employed, which are the root mean square error (RMSE) and the coefficient of determination (R^2). The value of RMSE is given by Eq. (10) [21-23]:

$$RMSE = \left[\frac{1}{n}\sum_{i=1}^{n}(y_i - x_i)^2\right]^{\frac{1}{2}} \tag{10}$$

The coefficient of determination is then given by Eq. (11) [21-23]:

$$R^2 = \frac{\sum_{i=1}^{N}\left(f(V_i)-\overline{f(V)}\right)^2 - \sum_{i=1}^{N}\left(f(V_i)-\hat{f}(V_i)\right)^2}{\sum_{i=1}^{N}\left(f(V_i)-\overline{f(V)}\right)^2} \tag{11}$$

2.5 Wind Speed Analysis

The daily mean wind speed, $\overline{V}$ and the standard deviation, σ of the wind resource data can be calculated by Eqs. (12) and (13), respectively [12]:

$$\overline{V} = \frac{1}{n}\left(\sum_{i=1}^{n} V_i\right) \tag{12}$$

$$\sigma = \sqrt{\frac{1}{n}\ \sum_{i=1}^{n}\left(V_i - \overline{V}\right)} \tag{13}$$

where V_i and n represent the daily wind speed in time step of i and the number of wind speed data points.

The WPD function $(f_w(v))$ and the cumulative distribution function $(f_w(V))$ are given by Eqs. (14) and (15) [20]:

$$f_w(v) = \left(\frac{k}{c}\right)\left(\frac{v}{c}\right)^{k-1} exp\left[-\frac{v}{c}\right]^k \tag{14}$$

$$f_w(V) = 1 - exp\left[-\frac{v}{c}\right]^k \tag{15}$$

where; v, k and c represent the wind speed (m/s), shape parameter (dimensionless) and the scale parameter (m/s), respectively. In addition, the most probable wind speed (V_{mps}) and the wind speed at the maximum energy (V_{emax}) are given by Eqs. (16) and (17) [24]:

$$\mathrm{V_{mps}} = \mathrm{c}\left(\frac{\mathrm{k}-1}{\mathrm{k}}\right)^{\frac{1}{\mathrm{k}}} \tag{16}$$

$$V_{emax} = c\left(\frac{k+2}{k}\right)^{\frac{1}{k}} \tag{17}$$

At times, wind speeds are measured at a reference h/h (h_0) but needs to be adjusted to the relevant wind turbine h/h (h). The new wind speed (V_h), scale factor (c_h) and shape factor (k_h) are given by Eqs. (18) to (20) by using a relevant power law equation, while Eq. (21) is employed to estimate the value of n [25]:

$$V_h = V_0\left(\frac{h}{h_0}\right)^{\propto} \tag{18}$$

$$c_h = c_0\left(\frac{h}{h_0}\right)^{n} \tag{19}$$

$$k_h = k_0\left\{\frac{\left[1-0.088\ln\frac{h_0}{10}\right]}{\left[1-0.088\ln\frac{h}{10}\right]}\right\} \tag{20}$$

$$n = \frac{[0.37-0.088\ln c_0]}{\left[1-0.088\ln\frac{h}{10}\right]} \tag{21}$$

where $\propto$ represents the site surface roughness coefficient and assumed in this work to be 0.143 [11].

2.6 Wind Power Estimation

The wind power density, P_{WPD} is a measure of the capacity of the wind resource of a particular location per unit swept area of the blades. Eq. (22a) is employed to estimate the wind power density, while the wind power capacity, P_{WPC} is estimated by Eq. (22b) [10]:

$$P_{WPD} = \frac{1}{2}\rho c^3 \Gamma\left(1 + \frac{3}{k}\right) \tag{22a}$$

$$P_{WPC} = \frac{1}{2} A\rho V_{ms}^3 \tag{22b}$$

where ρ and A stand for the air density (i.e., 1.225 kg/m^3) and the swept area of the rotor blades (m^2). The P_{WPD} and P_{WPC} parameters are measured in (W/m^2) and (W), respectively.

To extend the performance of the WECS further, in terms of the available power in the wind, this study considers the contribution made by Albert Betz (a German Physicist). This scientist made bold in 1919 as part of his contributions to knowledge that there is no wind turbine system that can convert above $\frac{16}{27}$ (i.e., 0.593) of the wind's kinetic energy to mechanical energy for turning the wind turbine rotor [26, 27]. In wind power system engineering, this factor 0.593 is referred to as the Betz limit. It is translated as the theoretical maximum power efficiency or (the aerodynamic efficiency of the rotor [28] of a wind turbine system design, i.e., 0.59), implying that not more than 59% of energy can be obtained from the wind by the WT system. It is then referred to as the power coefficient, $C_{p(max)}$ and is added to Eqs. (22b) leading to Eq. (22c) describes the maximum power obtainable from the WT:

$$P_{(WPC)max} = \frac{1}{2} A\rho C_{p(max)} V_{ms}^3 \tag{22c}$$

It is important to state that the value of the power coefficient in real life limit is practically lower than the Betz limit [26, 28]. Typical values of the Betz limit range from 0.35 to 0.45 even for best wind turbine systems; therefore, after making realistic design considerations for the gearbox, bearings, generator, etc., only around 0.1 to 0.3 fraction of the power of in the wind that is in reality converted into usable electrical energy [26].

2.7 Estimation of WECS' Output Power and Cf_w

The wind turbine output power is of a significant benefit, as it presents a good economic indicator compared to its rated capacity. The wind turbine output power, i.e., the power curve, is modelled via four parameters: the cut-in wind speed (V_{ci}), the cut-off wind speed (V_{co}), the rated wind speed (V_r) and the rated power capacity of the WT (P_r). For a pitch-controlled WT, the power curve model can be approximated by a parabolic law, given by Eq. (23) [11-12]:

$$P = P_r \begin{cases} \frac{V_{ms}^2 - V_{ci}^2}{V_r^2 - V_{ci}^2} & V_{ci} \le V_{ms} \le V_r \\ 1 & V_r \le V_{ms} \le V_{co} \\ 0 & V_r \le V_{ci} \text{ and } V_{ms} \ge V_{co} \end{cases} \tag{23}$$

The average power output (P_{ave}) of a WT is given by Eq. (24) [13-14]:

$$P_{ave} = P_r \left[\frac{e^{-\left[\frac{V_{ci}}{c}\right]^k} - e^{-\left[\frac{V_r}{c}\right]^k}}{\left[\frac{V_r}{c}\right]^k - \left[\frac{V_{ci}}{c}\right]^k} - e^{-\left[\frac{V_{co}}{c}\right]^k} \right] \tag{24}$$

Technically, CF_w of a WT is the ratio of P_{ave} to P_r and is given by Eq. (25) [11-12]:

$$CF_w = \frac{P_{avr}}{P_r} = \left[\frac{e^{-\left[\frac{V_{ci}}{c}\right]^k} - e^{-\left[\frac{V_r}{c}\right]^k}}{\left[\frac{V_r}{c}\right]^k - \left[\frac{V_{ci}}{c}\right]^k} - e^{-\left[\frac{V_{co}}{c}\right]^k} \right] \tag{25}$$

In addition, the yearly energy produced by the WT is given by Eq. (26):

$$E_{ae} = CF_w \times P_r \times t \tag{26}$$

where *t* represents the total hours in a year, i.e., 8760 hours.

2.8 Economic Cost Analysis

Estimating the unit cost of energy, COE, is a way of knowing the most viable wind turbine to select for this study. The economic aspect of this work focuses on calculating the cost of the individual components of the system, which include the investment, operation and maintenance (O and M) and the replacement costs. The WECSs life-cycle cost can be calculated by Eq. (27) [11]:

$$C_{LCC} = C_{inv} + C_{opm}\left(\frac{1+i_r}{d-i_r}\right)\left(1-\left(\frac{1+i_r}{1+d}\right)^p\right) \tag{27}$$

where; C_{opm}, i_r, d, *r* and p in this case represent the operation and maintenance cost, inflation rate, discount rate, interest rate and the project lifetime, respectively, and the corresponding values of these are assumed to be 0.1 % of investment cost C_{inv}, 8.4 %, 11%, 15% and 20 years.

The annualized life-cycle cost (C_{ALCC}) is given by Eq. (28):

$$C_{ALCC} = C_{LCC} \times CRF \tag{28}$$

where *CRF* is regarded as the capital recovery factor and is given by Eq. (29) [10]:

$$CRF = \frac{i_r\,(1+i_r)^n}{(1+i_r)^n-1} \tag{29}$$

The unit cost of energy is then given by Eq. (30) [33]:

$$COE = \frac{C_{ALCC}}{8760 \times P_r \times CF_w} \tag{30}$$

In this study, five different turbines from different manufacturers were considered and are represented by WT1, WT2, WT3, WT4 and WT5, respectively, with their characteristics shown in Table 2.

Table 2: Characteristics of the selected WTs [16, 34]

Characteristics	WT1	WT2	WT3	WT4	WT5
Rated power P_r (kW)	25	25	25	25	25
Rotor diameter (m)	15	15	15	15	15
Cut-in wind speed V_{ci} (m/s)	2.0	2.5	3.0	3.5	4.0
Rated wind speed V_r (m/s)	16	18	15	17	19
Cut-off wind speed V_{co} (m/s)	25	27	23	28	30
Investment cost $\$/kW$	1300	1300	1300	1300	1300

3. RESULTS AND DISCUSSION

3.1 Comparison of Wind Speed Distributions of Estimated Wbl PDF

Figures 1 to 5 show the comparison of the wind speed histogram with the calculated Wbl PDFs for the five numerical approaches for the specified locations under study. The Wbl density function gets narrower and becomes peaked as k becomes larger, meaning that wind speeds tend to stay within a narrow range. The peak also moves in the higher wind speed direction as the value of c increases. For instance, in Kano, Maiduguri, Abuja and Akure, as shown in Figures 1, 2, 4 and 5, respectively, since the calculated value of k from the LMM is greater than those obtained from the other methods, the peaks of the probability density curves were larger compared to the others. However, in Jos as shown in Figure 3, the calculated k using MOM was greater than the value obtained using the other methods; hence, the peak of its probability density curve is observed to be larger. Therefore, Figures 1 to 5 demonstrates that lower shape parameters correspond to broader probability density curves (i.e., higher scale parameters), which implies that winds vary over a wide range of wind speeds.

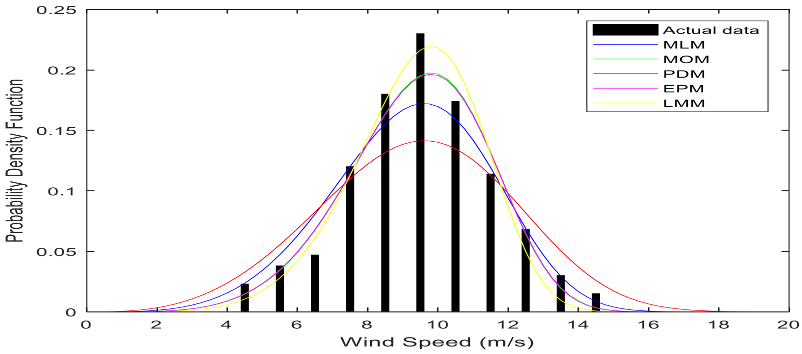

Fig. 1. Comparison of the PDFs for Kano

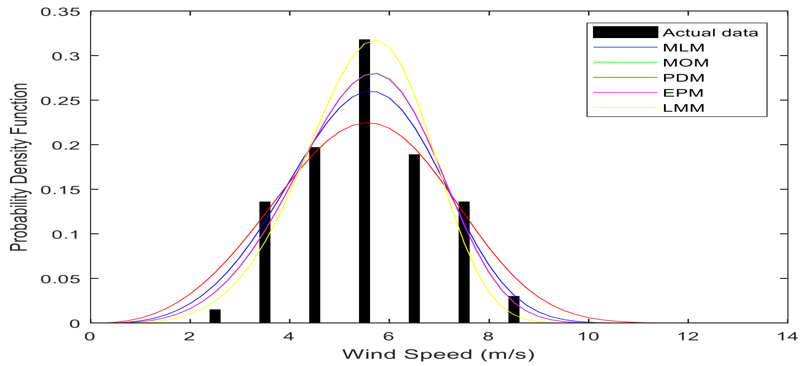

Fig. 2. Comparison of the PDFs for Maiduguri

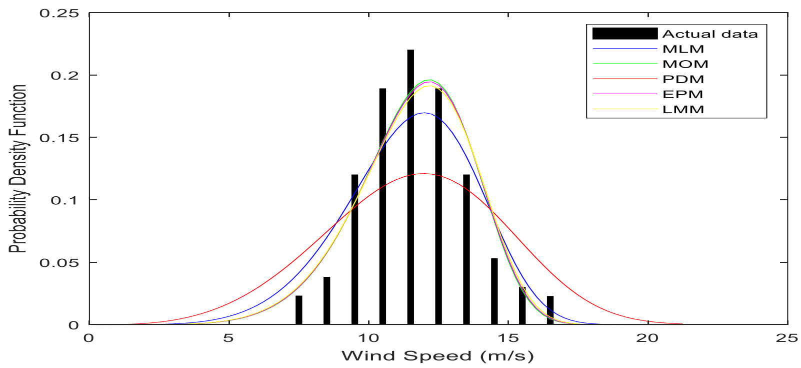

Fig. 3. Comparison of the PDFs for Jos

The Wbl parameters in the locations based on minimum $RMSE$ and maximum R^2 are presented in Tables 3 to 7, respectively. It is obvious from these results that the values of k range from 2.90 in Akure to 7.01 in Abuja, while those of c range from 3.86 in Akure to 12.82 in Jos. In the cases under study, $RMSE$ varies from 0.0584 to 0.1474, R^2 varies from 0.9611 to 0.9988. Therefore, Tables 3 to 7 summarize the fitness errors between the estimated PDFs and the histogram of the observed wind speed data at the height of 10 m. Results of calculated Weibull parameters from all the five NEMs (MLM, MOM, PDM, EPM and LMM) and two statistical methods (RMSE and R^2) for measuring the efficiency of these NEMs in all the five locations considered are presented in Table 3-7, respectively. For a robust comparison purpose of all NEMs, the statistical values for measuring efficiency have been listed up to 9 decimal points. From these tables, it is observed that out of the five NEMs of estimating Weibull parameters, MOM and EPM have estimated the same values for $k\ and\ c$ respectively in Kano (Table 7), hence, have the same efficiency of estimation. Each NEMs have been ranked against its performance on a scale from 1-5 (with 1 being the best efficient and 5 as the worst efficient). From Table 3, it is observed that MOM is the best and PDM is the worst with respect to RMSE and R^2 respectively. From Table 4, EPM has been found to be the most efficient and PDM the worst efficient with respect to RMSE and R^2 respectively. Furthermore, in Table 5, it is

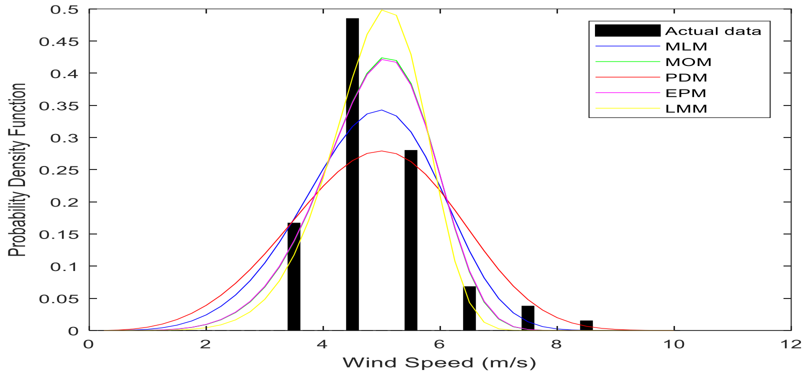

Fig. 4. Comparison of the PDFs for Abuja

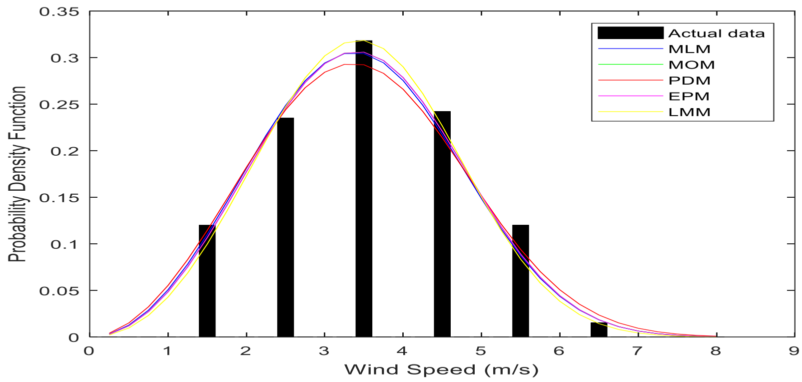

Fig. 5. Comparison of the PDFs for Akure

observed that MOM depicts the best performance and PDM still retains its worst efficient performance with respect to RMSE and R^2 respectively. In Table 6, EPM shows the best performance and PDM still shows the worst performance with respect to RMSE and R^2 respectively. However, in Table 7, MOM and EPM were found to be the most efficient, while PDM still retains its worst position. The results shown in Tables 3-7 demonstrate that the EPM and MOM are the best fit across all five locations due to their minimum $RMSE$ value and maximum R^2 value. The results also reveal that PDM was the worst-performing NEM across all five locations.

3.2 Wind Characteristics of Location

The wind speed characteristics of the locations are shown in Table 8. It can be seen that V_{ms} varies from 3.47m/s in Akure site to 11.63m/s in Jos; k varies from 2.90 in Akure to

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4.08 in Jos, while c varies from 3.89 m/s in Akure to 12.82 m/s in Jos. Also, V_{mps} varies from 3.36 m/s in Akure to 11.97 m/s in Jos; V_{emax} varies from 4.66 m/s in Akure to 14.14 m/s in Jos; P_{WPD} varies from 36 W/m^2 in Akure to 1182.12 W/m^2 in Jos, all at a h/h of 10 m. The results further show that Kano and Jos study locations are viable sites for grid integration because the wind power density at the h/h of 10 m is > 400 W/m^2. In addition, Abuja and Akure study locations are not viable for wind electricity production because the wind power density in these locations is < 100 W/m^2, while Maiduguri is only applicable for a stand-alone application because the wind power density is > 100 W/m^2 [11].

Table 3. Wbl parameters and goodness of fit estimation for Kano

	Numerical Methods	Wbl parameters		Statistical criteria		Rank
		k	c	RMSE	R^2	
Kano	MLM	4.62	10.12	0.022298950	0.999994120	4
	MOM	5.37	10.19	0.015769237	0.999997059	1
	PDM	3.83	10.39	0.035938398	0.999984726	5
	EPM	5.34	10.19	0.015880219	0.999997018	2
	LMM	5.95	10.12	0.015976125	0.999996982	3

Table 4. Wbl parameters and goodness of fit estimation for Maiduguri

	Numerical Methods	Wbl parameters		Statistical criteria		Rank
		k	c	RMSE	R^2	
Maiduguri	MLM	4.12	6.01	0.029812308	0.999968890	3
	MOM	4.47	6.02	0.029509497	0.999969519	2
	PDM	3.57	6.10	0.040316395	0.999943106	5
	EPM	4.46	6.02	0.029456943	0.999969628	1
	LMM	5.05	5.97	0.036872000	0.999952412	4

Table 5. Wbl parameters and goodness of fit estimation for Jos

	Numerical Methods	Wbl parameters		Statistical criteria		Rank
		k	c	RMSE	R^2	
Jos	MLM	5.63	12.41	0.029395252	0.999993500	4
	MOM	6.57	12.47	0.024726277	0.999995401	1
	PDM	4.08	12.82	0.052023787	0.999979641	5
	EPM	6.52	12.48	0.025154590	0.999995240	2
	LMM	6.42	12.50	0.026047047	0.999994896	3

Table 6. Wbl parameters and goodness of fit estimation for Abuja

	Numerical Methods	Wbl parameters		Statistical criteria		Rank
		k	c	RMSE	R^2	
Abuja	MLM	4.76	5.23	0.074049683	0.999751495	3
	MOM	5.99	5.25	0.071313582	0.999769520	2
	PDM	3.94	5.38	0.097370552	0.999570320	5
	EPM	5.95	5.25	0.071065282	0.999771122	1
	LMM	7.01	5.20	0.076836985	0.999732435	4

Table 7. Wbl parameters and goodness of fit estimation for Akure

	Numerical Methods	Wbl parameters		Statistical criteria		Rank
		k	c	RMSE	R^2	
Akure	MLM	3.01	3.86	0.019045125	0.999966622	3
	MOM	3.04	3.88	0.017679962	0.999971235	1
	PDM	2.90	3.89	0.019662755	0.999964422	4
	EPM	3.04	3.88	0.017679962	0.999971235	1
	LMM	3.17	3.87	0.018876644	0.999967210	2

Table 8. Wind speed characteristics of the locations

Location	V_{ms}	k	c	V_{mps}	V_{emax}	P_{WPD} (W/m^2)
Kano	9.39	3.83	10.39	9.60	11.59	636.84
Maiduguri	5.49	3.57	6.10	5.56	6.91	131.60
Jos	11.63	4.08	12.82	11.97	14.14	1182.12
Abuja	4.87	3.94	5.38	4.99	5.97	87.94
Akure	3.47	2.90	3.89	3.36	4.66	36.59

3.3 Estimation of CF_w of WTs

Although designing a wind turbine that will match a particular site's wind characteristics is the best practice; however, this can be time-consuming and frustrating [23], hence, the need to utilize available wind turbines in the market (W1 – W5). For this study, the CF_w method is used for the WT selection. Table 2 shows the characteristics of the WT used for this study. Wind turbines with a high value of CF_w is usually considered suitable for selection. Table 9 presents the results of CF_w of each turbine with respect to the specified locations. WT1, WT2, WT3, WT4 and WT5 have CF_w values of 0.0134 to 0.3705, 0.0083 to 0.2456, 0.0126 to 0.4471, 0.0067 to 0.3017, and 0.0034 to 0.1981, respectively.

Table 9. CF_w of the wind turbines in different locations

	CF_w				
Location	WT1	WT2	WT3	WT4	WT5
Kano	0.1901	0.1214	0.2393	0.1495	0.0968
Maiduguri	0.0314	0.0202	0.0373	0.0225	0.0139
Jos	0.3705	0.2456	0.4471	0.3017	0.1981
Abuja	0.0134	0.0082	0.0160	0.0090	0.0051
Akure	0.0144	0.0089	0.0126	0.0067	0.0034

Table 9 demonstrates that WT3 has the highest CF_w followed by WT1, WT4, WT2 and WT5, respectively. For uniformity of comparison, all the turbines considered have the same rated capacity of 25 kW. However, they have different cut-in and rated wind speeds as the machines are from different manufacturers.

3.4 Estimation of COE

Table 10 presents the COE for the selected WTs at a h/h of 10 m. WT3 has the least cost performance for all the locations considered in this study. The values of COE for WT3 range from \$ 0.041/kWh in Jos to \$ 1.457/kWh in Akure. However, WT5 has the highest cost performance of all the systems. Its *COE* values range from \$ 0.093/kWh in Jos to \$5.331/kWh in Akure. In Nigeria, electricity tariff in the country for residential "Band A" customers with daily minimum of 20 hours of electricity availability is \$ 0.13. This translates to ₦ 52 at an official exchange rate of \$1 to ₦ 400. Hence, generation of electricity using wind turbines, WT1 – WT5 is suitable for Jos and WT1 – WT4 is suitable for Kano, while other locations are not economically viable for wind power generation compared with the national grid supply.

Table 10. COE of the WECSs

	COE (\$/kWh)				
Location	WT1	WT2	WT3	WT4	WT5
Kano	0.096	0.151	0.077	0.123	0.189
Maiduguri	0.584	0.909	0.491	0.814	1.316
Jos	0.049	0.075	0.041	0.061	0.093
Abuja	1.370	2.243	1.149	2.046	3.601
Akure	1.278	2.050	1.457	2.728	5.331

3.5 Sensitivity Analysis Cases

The sensitivity analysis introduced in this study showcases the dependency of the WECSs variable on certain defined input variables. In this study, the variable considered is the effect of change in the h/hs on the probability density curve and the values of k, c, P_{WPD}, CF_w and *COE*. The results are shown in Figures 6 to 11.

The results in Figures 6 and 7 show that the Wbl parameters are directly proportional to the h/h; this is because the air mass flow appears to be smoother at a higher height. This is as a result of less impact of land topography obstructions to the flow of moving air. As shown in Figures 6 and 7, increasing h/h will lead to an increase in k and c. Also, an increase in k and c will make the shape of the PDF narrower (i.e., peaked) and broader by the right side of the graph (i.e., higher wind speeds). This peaked shape is not noticeable because of the little increase in the value of k as a result of higher h/hs, while an increase in the value of c will make the PDF move to the direction of higher wind speeds as can be seen in Figure 8. Figure 8 presents the effect of increasing h/hs on the probability density curve.

The values of k for Kano, Maiduguri, Jos, Abuja and Akure range from 3.83 to 5.09, 3.57 to 4.75, 4.08 to 5.43, 3.94 to 5.24 and 2.90 to 3.86, respectively, for corresponding h/hs of 10 to 50 m. Similarly, the values of c for these locations range from 10.39 to 14.13, 6.10 to 9.06, 12.82 to 16.84, 3.89 to 8.16 and 3.89 to 6.22, respectively, for the h/hs ranging from 10 to 50 m.

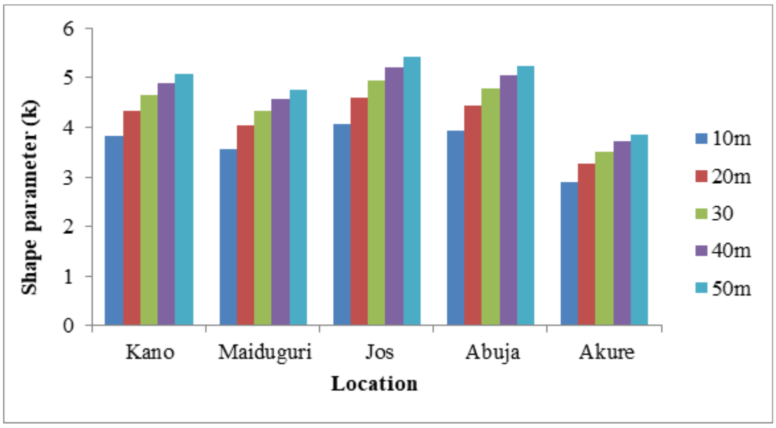

Fig. 6. Sensitivity analysis relating k with h/h

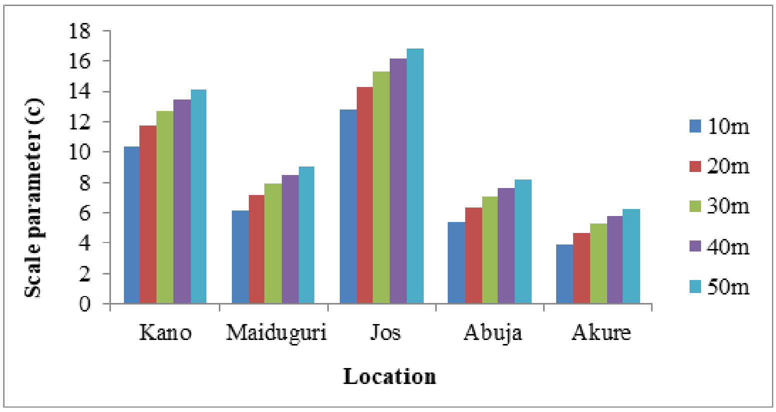

Fig. 7. Sensitivity analysis relating c with h/h

Fig. 9 shows the impact of varying h/h on the wind power density of the locations. Increasing h/hs leads to an increase in wind power density. The values of P_{WPD} for Kano, Maiduguri, Jos, Abuja and Akure range from 636.84 to 1541.34 W, 131.06 to 408.81 W, 1182.13 to 2600.36 W, 87.94 to 296.52 W and 36.59 to 136.41 W, respectively, for corresponding h/hs of 10 to 50 m.

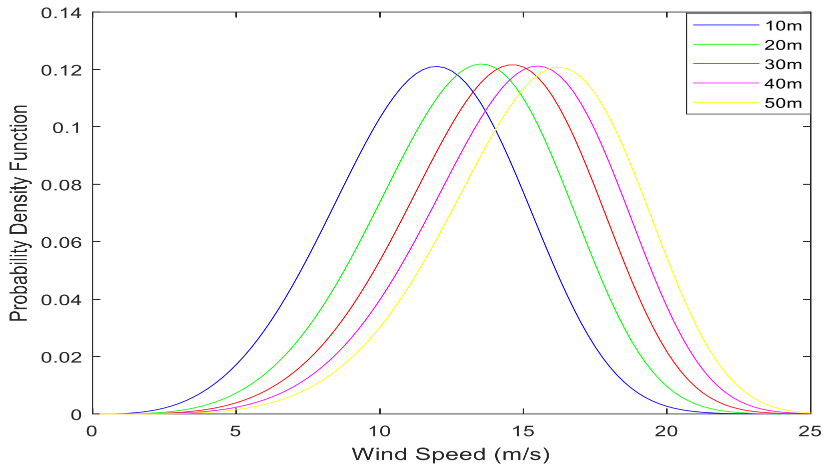

Fig. 8. Sensitivity analysis relating PDFs with h/hs

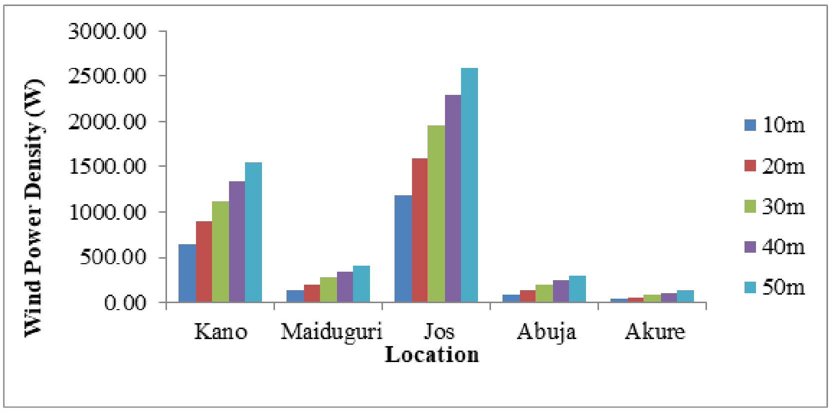

Fig. 9. Sensitivity analysis relating wind power density with h/h

Table 9 presents the results of the CF_w for the WTs in the specified locations. The results show that the CF_w of the WTs range from 0.0968 to 0.2393, 0.0139 to 0.0373, 0.1981 to 0.4471, 0.0051 to 0.0160 and 0.0034 to 0.0126 for Kano, Maiduguri, Jos, Abuja and Akure, respectively. It is also obvious from Table 9 that the value of CF_w of $WT3$ is the highest in all the five locations, and this is selected for utilization for all the locations under consideration as the most suitable turbine. According to [30], WTs with a value of $CF_w \leq 0.25$ is not suitable for grid integration applications. However, those with higher CF_w in excess of 0.25 are considered the best option any given location.

The response of CF_w of the WTs with respect to different h/hs of 10 to 50 m is shown in Figure 10. The results show that the h/h is directly proportional to CF_w, hence, the need to operate wind turbines at a reasonable height in order to achieve a value of CF_w that is ≥ 0.25. From Figure 10, Jos is suitable for grid integration at all the h/hs; Kano is suitable for grid integration at a h/h of $\geq 20m$; while Maiduguri, Abuja and Akure are not suitable for grid integration at these hub-heights.

Figure 11 shows the relationship between the COE and the turbine h/h. The results clearly demonstrate that COE decreases with increasing h/hs; this is because the wind turbine harness more energy at a higher height due to an increase in wind speed. Therefore, the values of COE obtained for Kano, Maiduguri, Jos, Abuja and Akure were reduced from0.077 to 0.033, 0.491 to 0.202,0.041 to 0.024, 1.149 to 0.449 and 1.457 to 0.579, respectively, for the specified heights of 10 to 50 m.

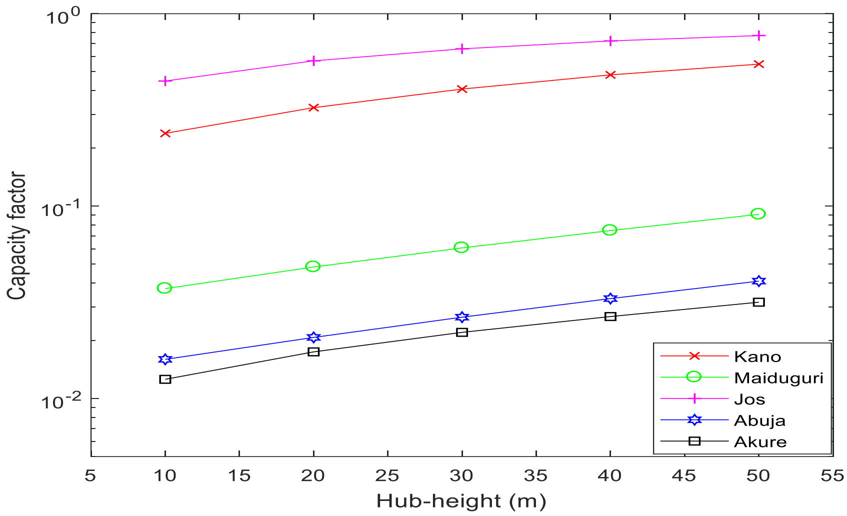

Fig. 10. Sensitivity analysis relating CF_w with h/h

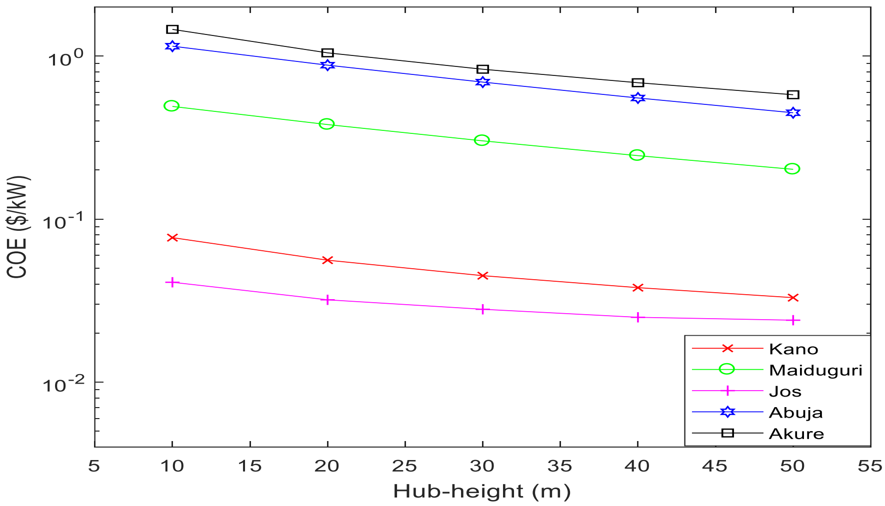

Fig. 11. Sensitivity analysis relating COE with h/h

3.6 Environmental analysis

Wind energy systems are renewable energy-based power generation technology. The environmental performance of the WECSs in the specified locations is realized by quantifying the amount of carbon emissions saved by utilizing the WECSs in the specified locations - Kano, Maiduguri, Jos, Abuja and Akure, using the emission factor approach. An emission factor of 1.27 x 10^3 kg CO_2 per MWh of electricity generated by a diesel generator [30, 31] is used to estimate the amount of CO_2 avoided by the wind energy generating systems in the five locations.

The environmental aspect, as presented in this study, is a function of the technical performance of the wind power system, which is based on wind energy resources of the locations. It is on this basis that the emission factor is multiplied by Eq. (26) to obtained the amount of emissions saved suppose that WECSs are employed as alternatives to fossil fuel system (i.e., diesel power systems) in the locations.

The values of the annual energy generated by the wind power systems, E_{ae}, are presented in Figure 12 for different heights - 10 to 50 m considered. The energy delivered at these heights for Kano, Maiduguri, Jos, Abuja and Akure range from 52,341 to 119,793 kWh/yr; 8,168.7 to 19,863.3 kWh/yr; 97,893 to 168,630 kWh/yr; 3,504 to 8,935.2 kWh/yr, and 2,759.4 to 6,942.3 kWh/yr, respectively. The results clearly ranks the WECSs in Jos, Kano, Maiduguri, Abuja and Akure as 1st, 2nd, 3rd, 4th and 5th positions, respectively, in terms of the amount of electricity they generate in a year, or simply the wind energy potential. These align with the results presented in Figure 13, which demonstrate that the wind speed determines the wind power as presented by Eqs. (22b) and (22c). Therefore, the wind speed of a location is a critical parameter that determines what the wind power and the energy output will be.

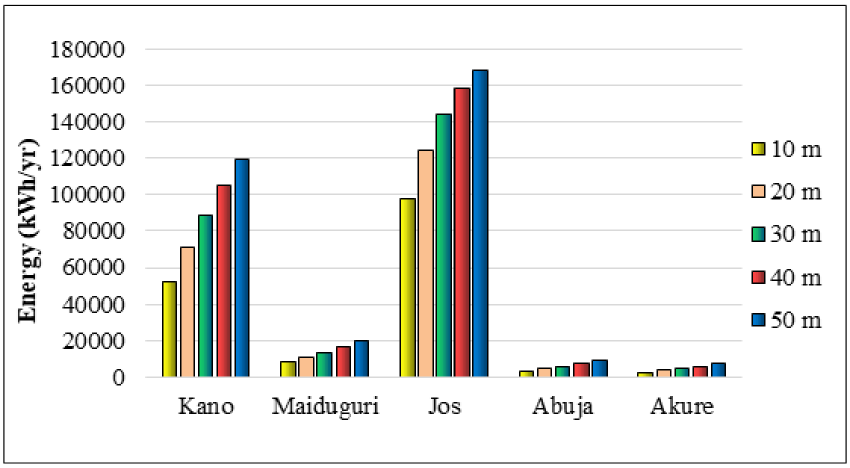

Fig. 12. The annual energy produced by the WECSs in the locations

Figure 14 presents the amount of carbon dioxide emissions assumed to be avoided when the wind energy systems are used in the location instead of diesel generating systems at hub heights of 10 to 50 m. The CO_2 emissions at the specified heights for Kano, Maiduguri, Jos, Abuja and Akure range from 66,473 to 152,137 kg/yr; 10,374 to 25,226 kg/yr; 124,324 to 214,160 kg/yr; 4,450 to 11,348 kg/yr, and 3,504 to 8,817 kg/yr, respectively. Again, the results show a similar trend with those presented in Figure 12 and Figure 13. This is so because the higher the wind speed, the higher the power and the energy produced and the higher the quantity of emissions saved by the WECSs.

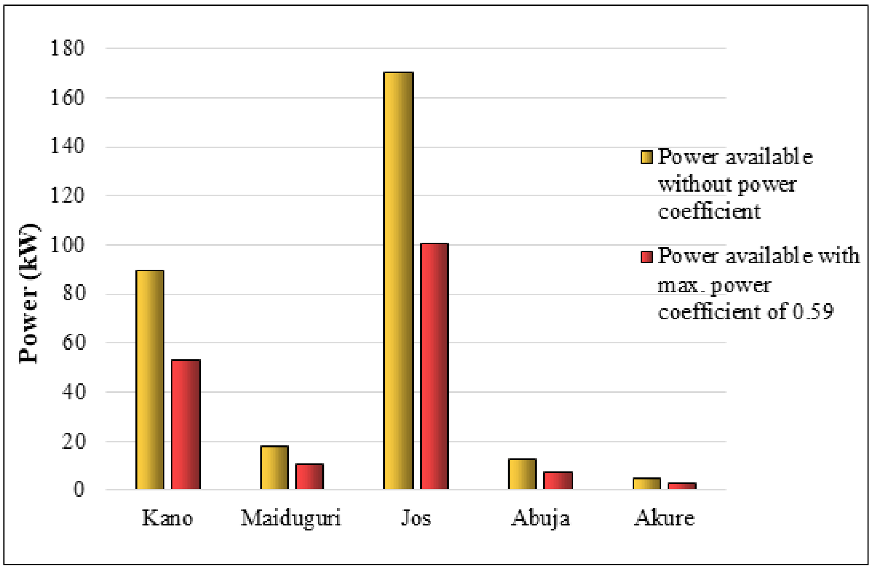

Fig. 13. Power available in the wind at the locations

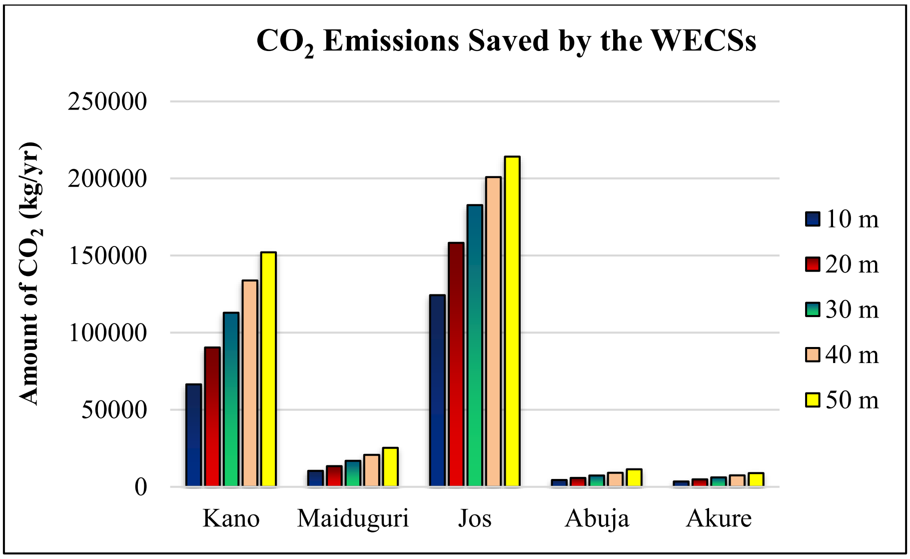

Fig. 14. Quantity of CO_2 emissions saved by the WECSs

4. CONCLUSIONS

This study has presented a detailed comparative evaluation of numerical methods for estimating Wbl parameters. It then discussed the TE analysis of wind electricity production in five different locations in Nigeria, such as Kano. Maiduguri, Jos, Abuja and Akure. The study utilized average daily wind speeds for 10 years, which have been obtained from Nigerian Meteorological Agency (NIMET). The paper examined five different numerical approaches for assessing the Wbl parameters and employed wind turbines of the same rating of 25kW for WECSs in those locations. The study reveals the following as useful conclusions to this paper:

i. The study reveals MOM as suitable for Kano and Jos, while EPM is suitable for Maiduguri and Abuja. With both NEMs suitable for Akure.
ii. The study also shows that PDM was the worst numerical approach for assessing the Wbl parameters.

iii. WECSs in Jos and Kano are viable for grid integration of wind energy, with Jos being the most viable for wind energy generation applications.
iv. WT3 has the highest CF_w in all the locations, which is a major determinant in selecting turbines.
v. WT3 has the least COE in all the selected locations, hence, it was selected among other wind turbines.
vi. WT5 has the highest COE in all the locations considered.
vii. It is more efficient to utilize WTs at a suitable h/h in order to maximize the location's wind resources. This is demonstrated in the study that COE decreases with increasing turbine hub-heights.
viii. The WECSs have the potential to avoid significant carbon footprints when implemented as an alternative to fossil fuel systems.

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Nomenclature Table

COE: Cost of energy	E_{pf} = Energy pattern factor
EPM: Empirical method	$\overline{V^3}$ = Average of wind speed cubes
HDI: Human development index	$(\overline{V})^3$ = Cube of average wind speed
MLM: Maximum likelihood method	y_i = actual data frequency;
MOM: Method of moment,	x_i = frequency of Wbl parameter;
NIMET: Nigeria Meteorological Agency	N = number of intervals;
PDM: Power density method	$f(V_i)$ = observed PDF value at bin i;
TE: Techno-economic	$\overline{f(V)}$ = observed average PDF value
Wbl: Weibull	$\hat{f}(V_i)$ = estimated PDF value of the computed Wbl method at the same bin.
WECSs: Wind energy conversion systems	C_{opm}= operation and maintenance cost
k = Shape Parameter	i_r= inflation rate
c = Scale Parameter (m/s)	$d = discount\ rate$,
V_i = Wind speed in time step i	r= Interest rate
n= number of non-zero	p = project lifetime
σ = standard deviation	
$\overline{V}$ = mean wind speed	