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Research Paper

Evaluation of Wind Speed Probability Distribution Model and Sensitivity Analysis of Wind Energy Conversion System in Nigeria

I. K. Okakwu*, O. E. Olabode**, D. O. Akinyele*(C.A.), and T. O. Ajewole**

Abstract: This paper evaluates the wind potential of some specified locations in Nigeria, and then examines the response of wind energy conversion systems (WECSs) to this potential. The study employs eight probability distribution (PD) functions such as Weibull (Wbl), Rayleigh (Ryh), Lognormal (Lgl), Gamma (Gma), Inverse Gaussian (IG), Normal (Nl), Maxwell (Mwl) and Gumbel (Gbl) distributions to fit the wind data for nine locations in Nigeria viz. Kano, Maiduguri, Jos, Abuja, Akure, Abeokuta, Uyo, Warri and Ikeja. The paper then uses the maximum likelihood (ML) method to obtain the parameters of the distributions and then evaluates the goodness of fit for the PD models to characterize the locations' wind speeds using the minimum Root Mean Square Error (RMSE). The paper analyses the techno-economic aspect of the WECSs based on the daily average wind speed; it evaluates the performance of ten 25 kW pitch-controlled wind turbines (WT1 – WT10) with dissimilar characteristics for each location, including the cost/kWh of energy (COE) and the sensitivity analyses of the WECSs. Results reveal that Ryh distribution shows the best fit for Kano, Jos, Abeokuta, Uyo, Warri and Ikeja, while the Lgl distribution shows the best fit for Maiduguri, Abuja and Akure due to their minimum RMSE. WT7 achieves the least COE ranging from $0.0328 in Jos to $4.4922 in Uyo and WT5 has the highest COE ranging from $0.1380 in Ikeja to $53.371 in Uyo. The paper also details the sensitivity analysis for the technical and economic aspects.

Keywords: Wind Speed, Wind Turbine, Probability Density Function, Cost of Energy, Wind Resource.

1 Introduction

THE role of energy in determining the quality and standard of life and measuring a country's level of development cannot be over-emphasized [1].

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*The authors are with Department of Electrical and Electronics Engineering, Olabisi Onabanjo University, Ago-Iwoye, Nigeria.
E-mails: okakwu.ignatius@oouagoiwoye.edu.ng and akinyele.daniel@oouagoiwoye.edu.ng.
**The authors are with Department of Electrical and Electronic Engineering, Osun State University, Osogbo, Nigeria.
E-mails: 095082@gmail.com and titus.ajewole@uniosun.edu.ng.
Corresponding Author: Daniel Akinyele.
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It is well-established in the literature how the conventional energy sources (i.e., fossil fuels) have played a major role in meeting the world's energy demand [2]. However, such resources are carbon-intensive with negative effects on the environment and people's health. Hence, the quest for reducing the utilization of fossil fuels due to its environmental impact, depletion, unstable price, and the need to satisfy the increasing energy demand have motivated a growing interest in cleaner energy sources [3].

In recent times, the application of wind resources for electricity generation continues to be popular; this is because of the resource being natural, abundant, affordable, clean, and environmentally friendly. Also, WECSs have no complexity in their installation and they require little or no maintenance, which is why they are considered one of the widely utilized renewable energy (RE) source in different parts of the world [4]. In Nigeria, for instance, electricity is largely still being generated from hydro and fossil resources and the country's generation capacity resolves around 5,000 MW over the years [5, 6]. It is clear that the current capacity is inadequate for the need of over 200 million people in the country, and the huge gap between power generation and demand is a major cause of hampered development in different sectors, energy poverty and low standard of living, most especially in local areas [6]. Based on this premise, there is the need to grow the country's energy mix beyond the existing centralized hydro and thermal systems by harnessing the nation's huge renewable energy sources - solar, biomass, small hydro, including wind energy resources in different parts of the country.

Furthermore, WECSs can be utilized and configured both for on-grid and off-grid electricity applications [7]. However, in order to utilize a wind energy resource of a location, the probability density (PD) function associated with the wind speed must be properly assessed. This is done due to the quest for reliable and cost-effective electricity supply. Various PD functions have been examined in the literature to describe the wind distribution. The first step in analyzing wind data is the determination of distribution that fits the data, which is then followed by relevant parameters estimations. Quite a number of studies have been presented in the literature on wind power application using different PD functions. These studies are discussed in this section as an important background to this paper.

Oyedepo et al., [8] analyzed wind characteristics and potential for three selected locations in Nigeria based on data that spans between 24-27 years, measured at 10 m. Adaramola et al., [9] evaluated the performance of wind turbines (WTs) in Nigeria. Such analysis was based on the electricity generation application through the WECSs. Ayodele et al., [10] investigated the techno-economic (TE) aspect of WECSs for water pumping application in the southern part of Nigeria. Ohunakin et al., [11] discussed the cost estimation of WTs for electricity generation in six different areas in Nigeria. Ajayi et al., [12] assessed the TE aspect of WTs for energy production in ten locations in Nigeria. Sulaiman et al., [13] also presented the evaluation of wind potential of four selected locations in Nigeria. Okakwu et al., [14] investigated the TE viability of WECSs in Nigeria.

Swisher et al., [15] presented the competitiveness of a low-specific power, low cut-out WT speed wind using the North and Central Europe as focus points towards 2050. The authors' main focus was to investigate the cost-competitiveness of an exploratory 3.4 MW 100 Wm^{-2} low WT with a hub-height (h-h), rotor diameter and cut-out wind speed of 127.5 m, 208 m, and 13 ms^{-2}, respectively for the mentioned locations. El Khchine et al., [16] evaluated the performance of WTs for a coastal region in Morocco. The authors calculated the shape and scale parameters by using for different methods such as the ML, modified ML, energy pattern factor and the WAsP approach. Pishgar-Komleh et al., [17] presented wind resource and power density (PDn) analyses using Wbl and Ryh distributions for an area in Iran.

Sumair et al. [18] compared three PDs and the TE analysis of wind energy production for coastal belt of Pakistan. The work focuses on wind analysis based on the Wbl, Ryh, and Lgl methods. Dookie et al., [19] evaluated wind PD models using Trinidad and Tobago as case studies. The study presented detailed comparative analysis of the different distribution models. Bertrand et al. [20] discussed sustainable electricity production through wind resources and power density analyses using Ambam, South Region of Cameroon as a case study.

Khamees et al. [21] investigated different PD functions for wind speed modelling based on classical and metaheuristic methods. The authors based the study analysis the Wbl, Lgl, Gma, and the IG distribution techniques with detailed comparative assessments. Charabi and Abdul-Wahab [22] presented the design, simulation and analysis of WECSs for locations in Oman and also assess the systems' performance for energy cost minimization. The authors employed the HOMER micropower simulation tool to model the wind energy generation system. The paper focused on the TE aspect using the locations' wind data and also includes the emissions analysis. A study was also presented that focused on the modeling of wind resource distribution and power in Rwanda [23]. The paper employed the Wbl, Ryh, Lgl, Nl and Gma methods for the analysis.

Islam et al., [24] discussed the statistical distribution and energy assessment of the wind resource at a location in Bangladesh. The study used the normal distribution, Wbl distribution, Gma distribution, and Ryh distribution for the analysis. A comparison was made to determine the best distribution technique among the 4 approaches for the wind speed data. The authors also calculated the annual energy generation for WECSs in the study location. Serban et al., [25] assessed the wind potential for two locations in Romania based on Wbl and Ryh distribution models. The models were employed for the hourly wind data to evaluate the resource profile and potentials at WT height of 10 m. Bidaoui et al., [26] discussed wind speed data analysis using Wbl and Ryh distibution functions using five cities in Northern Morocco as case studies. The study was also extended to the possible electricity generation from WECSs in the locations.

Mostafaeipour et al., [27] analyzed the wind potential and economic aspect of WECSs in Zahedan, Iran. The authors used the Wbl density function to calculate the wind PDn and the possible electricity generation of the region under study. Belabes et al., [28] evaluated wind potential and the cost per unit energy produced by WECSs using the north of Algeria as a test case. The authors used the Wbl parameters and the power law coefficient in the paper considering different h-hs of 30, 50, and 70 m being extrapolated from the 10 m height for the locations. Alkhalidi et al., [29] discussed wind potential at coastal and offshore sites in Kuwait. The authors calculated the wind energy output at different h-hs of 50, 80, 100, and 120 m. The 2-parameter Wbl distribution approach was used, while the Wbl distribution parameters were calculated by using the ML method.

The mentioned studies have added value to knowledge in different aspects of wind potential and WECSs analyses. These research works have made efforts to identify suitable locations, select appropriate WTs and then evaluate the unit cost of energy produced by the WECSs, which stand as useful background to this current study. Some of the studies have also investigated the impact of the change in the hub-heights (h-hs) of the WECSs. However, this current study first identifies the best fit for the PD function of the wind speed data, and the suitable sites for wind electricity production. It then employs eight PD functions such as Wbl, Ryh, Lgl, Ga, IG, Nl, Mwl and Gbl distributions to fit the wind data for nine different locations in Nigeria namely Kano, Maiduguri, Jos, Abuja, Akure, Abeokuta, Uyo, Warri and Ikeja. The paper uses ML method to estimate the distributions' parameters and then evaluates the goodness of fit for the PD models to characterize the locations' wind by employing the minimum Root Mean Square Error (RMSE).

Furthermore, the contribution of the study is extended to the determination of some sensitivity analyses in terms of the effect of varying the cut-in speed (V_{ci}), rated speed (V_r), hub-height (h-h), inflation rate and discount rate of the WTs on the COE for all the locations. The general idea that such analysis brings is the useful economic insight that can aid decision-making for the uptake and development of WECSs in Nigeria. The paper presents the techno-economic (TE) analysis of the WECSs by using the specified locations' daily average wind speeds, and to realize this objective, the research work evaluates the performance of ten 25 kW pitch-controlled wind turbines (WT1-WT10) with dissimilar characteristics for each location. The results obtained from this study are expected to be useful for planning, design and better understanding of wind potential and WECSs.

2 Materials and Methods

2.1 Study Location

This paper considers nine locations in Nigeria. The daily wind data measured at the h-h of 10 m by an anemometer cup-generator were obtained from the Nigeria Meteorological Agency (NIMET), Oshodi, Lagos State, Nigeria. Table 1 presents the study locations of the paper.

Table 1 The study locations of the paper.

Locations	Latitude (^{0}N)	Longitude (^{0}E)	Data Period
Kano	12.05	8.52	10yrs
Maiduguri	11.85	13.08	10yrs
Jos	9.64	8.88	10yrs
Abuja	9.00	7.27	10yrs
Akure	7.25	5.20	10yrs
Abeokuta	7.14	3.33	10yrs
Uyo	5.04	7.91	10yrs
Warri	6.20	6.73	10yrs
Ikeja	6.35	3.20	10yrs

2.2 Probability Distribution Functions

One of the possible ways of assessing the wind energy of a site is by using the PD functions. In this paper, eight different methods are employed to characterize the wind data of the study locations.

2.2.1 Weibull Distribution

The Wbl PD function ($f_w(v)$) is given by Eq. (1) [30-35]:

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

where v, k and c are wind speed in m/s, shape parameter and scale parameter in m/s, respectively. The k and c parameters can be calculated by using the ML method given by Eqs. (2) and (3) [30-35]:

$$k = \left[\frac{\sum_{i=1}^{n} V_i^k \, ln\, V_i}{\sum_{i=1}^{n} V_i^k} - \frac{\sum_{i=1}^{n} ln(V_i)}{n}\right]^{-1} \quad (2)$$

$$c = \left[\frac{1}{n}\sum_{i=1}^{n} V_i^k\right]^{\frac{1}{k}} \quad (3)$$

V_i in this case represents the wind speed in time step i; n is the number of non-zero wind speed data points. In the MLM, numerical iterations are required to determine the Wbl parameters.

2.2.2 Rayleigh Distribution

The Ryh PD function $(f_r(v))$ is given by Eq. (4) [30-35]:

$$f_r(v) = \left(\frac{2V}{c^2}\right) exp\left[-\frac{v}{c}\right]^2 \quad (4)$$

This is a type of Wbl distribution whereby the value of k is taken as 2. The scale parameter (c) is given by Eq. (5) [30-35] in which the sharp parameter (k):

$$c = \frac{1}{n}\left(\sum_{i=1}^{n} V_i\right) \quad (5)$$

2.2.3 Lognormal Distribution

The Lgl PD function $(f_l(V))$ is given by Eq. (6) [30-35]:

$$f_l(V) = \frac{1}{V\beta\sqrt{2\pi}} \exp\left[-\frac{1}{2}\left(\frac{\ln V_i - \alpha}{\beta}\right)^2\right] \quad (6)$$

where the location parameter (α) and the scale parameter (β) are obtained by the MLM given by Eqs. (7) and (8) [30-35]:

$$\alpha = \frac{1}{n}\sum_{i}^{n} \ln V_i \quad (7)$$

$$\beta = \left[\frac{1}{n}\sum_{i=1}^{n}(\ln V_i - \alpha)^2\right]^{\frac{1}{2}} \quad (8)$$

2.2.4 Gamma Distribution

The Gma PD function $(f_g(V))$ is given by Eq. (9) [30-35]:

$$f_g(V) = \frac{{V_i}^{k-1}}{c^k \Gamma(k)} \exp\left[-\frac{V_i}{c}\right] \quad (9)$$

where Γ represent the gamma function. The values of k and c can be obtained by using the ML method given by Eqs. (10) and (11) [30-35]:

$$k = \frac{n\sum_{i=1}^{n} V_i}{n\sum_{i=1}^{n} V_i \ln(V_i) - \sum_{i=1}^{n}\ln(V_i)_i \sum_{i=1}^{n} V_i} \quad (10)$$

$$c = \frac{1}{n^2}\left[n\sum_{i=1}^{n} V_i \ln(V_i) - \sum_{i=1}^{n}\ln(V_i)_i \sum_{i=1}^{n} V_i\right] \quad (11)$$

2.2.5 Inverse Gaussian Distribution

The IG PD function $(f_{in}(V))$ is given by Eq. (12) [30-35]:

$$f_{in}(V) = \left[\frac{\beta}{2\pi V_i^3}\right]^{\frac{1}{2}} \exp\left[-\frac{\beta(V_i - \alpha)^2}{2V_i\alpha^2}\right] \quad (12)$$

The scale parameter (α) and shape parameter (β) can be obtained by using the ML method given by Eqs. (13) and (14) [30-35]:

$$\alpha = \frac{1}{n}\sum_{i}^{n} \ln V_i \quad (13)$$

$$\beta = \frac{\alpha^3}{\left[\frac{1}{n}\sum_{i=1}^{n}(\ln V_i - \alpha)^2\right]} \quad (14)$$

2.2.6 Normal Distribution

The Nl PD function $(f_n(V))$ is given by Eq. (15) [30-35]:

$$f_n(V) = \frac{1}{\sqrt{2\pi\sigma^2}} \exp\left[-\frac{1}{2}\left(\frac{V_i - \mu}{\sigma}\right)^2\right] \quad (15)$$

The mean (μ) and standard deviation (σ) for this distribution can be obtained by Eqs. (16) and (17) [30-35]:

$$\mu = \frac{1}{n}\sum_{i}^{n} \ln V_i \quad (16)$$

$$\sigma = \left[\frac{1}{n}\sum_{i}^{n}(V_i - \mu)^2\right]^{\frac{1}{2}} \quad (17)$$

2.2.7 Maxwell Distribution

The Mwl PD function $(f_m(V))$ is given by Eq. (18) [30-35]:

$$f_m(V) = \frac{V_i^2}{\alpha^3}\left[\frac{2}{\pi}\right]^{\frac{1}{2}} \exp\left[-\frac{V_i^2}{2\alpha^2}\right] \quad (18)$$

The scale parameter (α) of the Maxwell distribution can be obtained by using the MLM given by Eq. (19) [30-35]:

$$\alpha = \left[\frac{1}{3n}\sum_{i=1}^{n} V_i^2\right]^{\frac{1}{2}} \tag{19}$$

2.2.8 Gumbel Distribution

The Gbl PD function $(f_{gu}(V))$ is given by Eq. (20) [30-35]:

$$f_{gu}(V) = \frac{1}{\beta}\exp\left[-\exp\left(-\frac{V_i-\mu}{\beta}\right)\right]\exp\left(-\frac{V_i-\mu}{\beta}\right) \tag{20}$$

The location parameter (μ) and scale parameter (β) of this distribution can be obtained by solving the simultaneous Eqs. (22) and (23) [30-35]:

$$\overline{V} = \mu + 0.5772\beta \tag{21}$$

$$\sigma^2 = \frac{\pi^2}{6}\beta^2 \tag{22}$$

where $\overline{V}$ stands for the mean value.

2.3 Assessment of Numerical Method Accuracy

To test the accuracy of these numerical methods for estimating the Wbl parameters, two different methods are used, which include the RMSE and coefficient of determination (R^2). The RMSE value is given by Eq. (23) [32-34]:

$$RMSE = \left[\frac{1}{n}\sum_{i=1}^{n}(y_i - x_i)^2\right]^{\frac{1}{2}} \tag{23}$$

where y_i is the actual data frequency; x_i stands for the estimated PD function value, and n representing the number of intervals.

2.4 Wind Speed Analysis

The most probable wind speed (V_{mps}) and the wind speed associated with maximum energy (V_{emax}) are calculated by Eqs. (24) and (25) [14]:

$$V_{mps} = c\left(\frac{k-1}{k}\right)^{\frac{1}{k}} \tag{24}$$

$$V_{emax} = c\left(\frac{k+2}{k}\right)^{\frac{1}{k}} \tag{25}$$

At times, the wind speed is usually measured at a reference h-h (h_0) but needs to be adjusted to the relevant wind turbine h-h (h). By using relevant power law equation, the new wind speed (V_h), scale factor (c_h) and shape factor (k_h) are estimated by using Eqs. (26), (27), (28) and (29) [1]:

$$V_h = V_0\left(\frac{h}{h_0}\right)^{\propto} \tag{26}$$

$$c_h = c_0\left(\frac{h}{h_0}\right)^n \tag{27}$$

$$k_h = k_0\left\{\frac{\left[1-0.088\ln\frac{h_0}{10}\right]}{\left[1-0.088\ln\frac{h}{10}\right]}\right\} \tag{28}$$

$$n = \frac{[0.37-0.088\ln c_0]}{\left[1-0.088\ln\frac{h}{10}\right]} \tag{29}$$

where $\propto$ is the location's surface roughness coefficient, which is assumed to be 0.143 in this work [1].

2.5 Estimation of Wind Power Density

The wind power density is estimated by Eq. (30) [10]:

$$P_{WPD} = \frac{1}{2}\rho c^3\Gamma\left(1+\frac{3}{k}\right) \tag{30}$$

where ρ represents the air density (1.225 kg/m^3).

2.6 Estimation of WT Output Power and Capacity Factor

The wind turbine output power, i.e., power curve, is modeled 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 of the WT (P_r). For a pitch-controlled WT, the power curve model can be approximated by a parabolic law, given by Eq. (31) [14, 30]:

$$P = P_r\begin{cases}\frac{V_{ms}^2-V_{ci}^2}{V_r^2-V_{ci}^2} & V_{ci} \le V_{ms} \le V_r\\ 1 & V_r \le V_{ms} \le V_{co}\\ 0 & V_r \le V_{ci}\ and\ V_{ms} \ge V_{co}\end{cases} \tag{31}$$

The average power output (P_{ave}) of a WT is given by Eq. (32) [14, 30]:

$$P_{ave} = P_r\left[\frac{e^{-\left[\frac{V_{ci}}{c}\right]^k} - e^{-\left[\frac{V_r}{c}\right]^k}}{\left[\frac{V_r}{c}\right]^k - \left[\frac{V_{ci}}{c}\right]^k} - e^{-\left[\frac{V_{co}}{c}\right]^k}\right] \tag{32}$$

The capacity factor (CF_w) of a WT is essentially the ratio of average power to the WT rated power, and is given by Eq. (33) [14, 30, and 36]:

$$CF_w = \frac{P_{avr}}{P_r} = \left[\frac{e^{-\left[\frac{V_{ci}}{c}\right]^k} - e^{-\left[\frac{V_r}{c}\right]^k}}{\left[\frac{V_r}{c}\right]^k - \left[\frac{V_{ci}}{c}\right]^k} - e^{-\left[\frac{V_{co}}{c}\right]^k}\right] \tag{33}$$

The annual energy generated by the WT is calculated by Eq. (34):

$$E_{ae} = CF_w \times P_r \times t \quad (34)$$

where t represents the total hours in the year (i.e., 8760 hours).

2.7 Economic Cost Analysis

The life cycle cost of the WECSs system is calculated by Eq. (35) [11]:

$$C_{LCC} = C_{inv} + C_{opm}\left(\frac{1+i}{d-i}\right)\left(1-\left(\frac{1+i}{1+d}\right)^n\right) \quad (35)$$

where C_{opm} is assumed to be 0.1 % of the invest cost; i is the inflation rate, which is 8.4 %; d is the discount rate taken as 11 %, and n is the lifetime of the project which is 20 years.

The annualized life cycle cost (C_{ALCC}) is calculated by Eq. (36):

$$C_{ALCC} = C_{LCC} \times CRF \quad (36)$$

where CRF is the capital recovery factor being calculated by Eq. (37)[10]:

$$CRF = \frac{i\,(1+i)^n}{(1+i)^n - 1} \quad (37)$$

The unit cost of energy is calculated by Eq. (38) [14, 37, and 38]:

$$COE = \frac{C_{ALCC}}{8760 \times P_r \times CF_w} \quad (38)$$

In this study, ten different turbines from different manufacturers were considered and are represented by WT1-WT10 respectively, with their characteristics shown in Table 2.

3 Results and Discussion

3.1 Comparison of the Wind Speed Distribution Model

The estimated parameters of the PDs for different locations are shown in Table 3 below. The result reveals that for Wbl distribution, k ranges from 3.01 in Akure to 5.63 in Jos. The value of c ranges from 3.65 in Abeokuta to 12.41 in Jos. For Ryh distribution, c ranges from 3.28 in Abeokuta to 11.63 in Jos. For the Lgl distribution, the location parameter (α) ranges from 1.14 in Abeokuta to 2.44 in Jos, while the scale parameter (β) ranges from 0.22 in Kano to 1.12 in Akure. In the Gma distribution, the values of k and c parameter ranges from 7.14 in Akure to 28.86 in Jos and 0.17 in Abuja to 1.06 in Ikeja, respectively. For IG distribution, the scale parameter (α) ranges from 3.28 in Abeokuta to 11.63 in Jos, while the shape parameter (β) ranges from 26.88 in Akure to 367.64 in Jos, respectively. For Nl distribution, the mean (μ) parameter varies from 3.28 in Abeokuta to 11.63 in Jos, while the standard deviation (σ) parameter varies from 0.82 in Uyo to 3.12 in Ikeja. The scale parameter (α) of the Mwl distribution ranges from 1.98 in Abeokuta to 6.82 in Jos. For the Gbl distribution, the scale parameter (β) ranges from 0.64 in Uyo to 2.43 in Ikeja, while the location parameter (μ) ranges from 2.82 in Abeokuta to 10.70 in Jos.

Figures 1 to 9 show the comparison of the observed wind speed histogram with the estimated eight models of the probability density (PDn) functions of the locations.

Table 2 Characteristics of the WTs.

Characteristics	WT1	WT2	WT3	WT4	WT5	WT6	WT7	WT8	WT9	WT10
Rated power (kW)	25	25	25	25	25	25	25	25	25	25
Rotor diameter (m)	15	15	15	15	15	15	15.5	16	16.5	15
Cut-in wind speed (m/s)	2	2.5	3	3.5	4	2	2.5	3	3	2.5
Rated wind speed (m/s)	16	18	15	17	19	14	13	17	16	16
Cut-off wind speed (m/s)	25	27	23	28	30	25	25	25	25	25
Investment cost ($/kW)	1300	1300	1300	1300	1300	1300	1300	1300	1300	1300

Table 3 Estimated parameters of PD functions for different locations.

Location	Weibull		Rayleigh		Lognormal		Gamma		Inverse Gaussian		Normal		Maxwell	Gumbel	
	k	c	k	c	α	β	k	c	α	β	μ	σ	α	β	μ
Kano	4.62	10.12	2.00	9.39	2.22	0.22	22.02	0.43	9.39	205.68	9.39	2.01	5.55	1.57	8.49
Maiduguri	4.12	6.01	2.00	5.49	1.67	0.60	15.77	0.35	5.49	86.26	5.49	1.39	3.27	1.08	4.87
Jos	5.63	12.41	2.00	11.63	2.44	0.30	28.86	0.41	11.63	367.64	11.63	2.07	6.82	1.62	10.70
Abuja	4.76	5.23	2.00	4.87	1.57	0.68	28.57	0.17	4.87	130.18	4.87	0.94	2.87	0.74	4.45
Akure	3.01	3.86	2.00	3.47	1.17	1.12	7.14	0.49	3.47	26.88	3.47	1.25	2.13	0.97	2.91
Abeokuta	3.50	3.65	2.00	3.28	1.14	0.33	9.96	0.33	3.28	34.23	3.28	1.02	1.98	0.79	2.82
Uyo	4.99	4.38	2.00	4.04	1.38	0.32	24.36	0.17	4.04	97.47	4.04	0.82	2.38	0.64	3.67
Warri	4.53	4.13	2.00	3.77	1.29	0.31	14.96	0.25	3.77	59.86	3.77	0.95	2.24	0.74	3.34
Ikeja	3.62	10.95	2.00	9.96	2.24	0.34	9.44	1.06	9.96	101.74	9.96	3.12	6.03	2.43	8.56

The Ryh and Mwl PD functions are a one-parameter function, while the Wbl, Lgl, Gma, IG, Nl and Gbl are a two-parameter function. The justification for using the ML method is that it is more efficient than other estimation methods. The vertical axis of the diagram shows the probability function value, while the horizontal axis shows the wind speed range. As seen in the diagrams presented by Figs. 1 to 9, all distributions are skewed to the righthand side, which therefore, means that the mean wind speed is higher than both the median and the mode of the data. The results show that each PDn functions follow perfectly the form of the wind speed histogram. The peak of the probability function curves indicates the most frequent wind speed. From Figs. 1 to 9, Gumbel has the most peaked PDn curve in all the locations and Ryh has the least in Kano, Jos, Abeokuta, Uyo, Warri and Ikeja, while the Lgl method has the least for Maiduguri, Abuja and Akure, respectively.

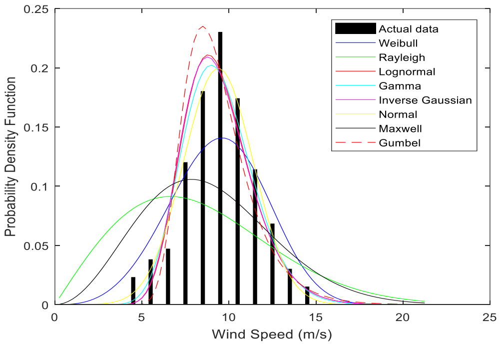

Fig. 1 Comparison of PDn functions for Kano.

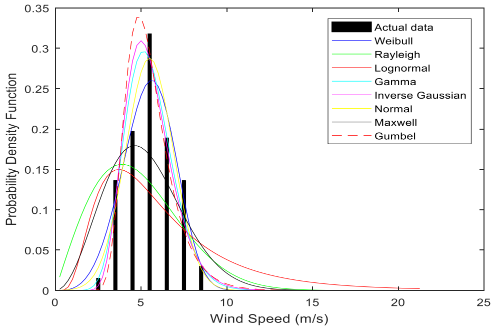

Fig. 2 Comparison of PDn functions for Maiduguri.

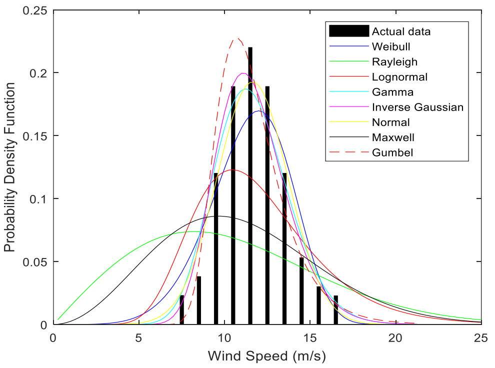

Fig. 3 Comparison of PDn functions for Jos.

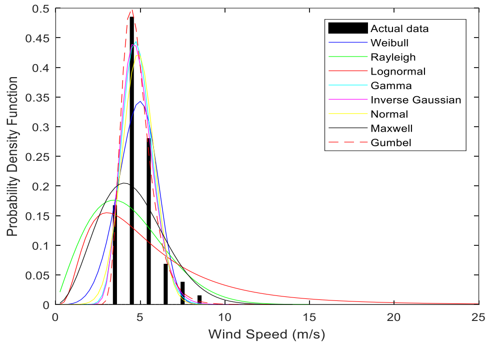

Fig. 4 Comparison of PDn functions for Abuja.

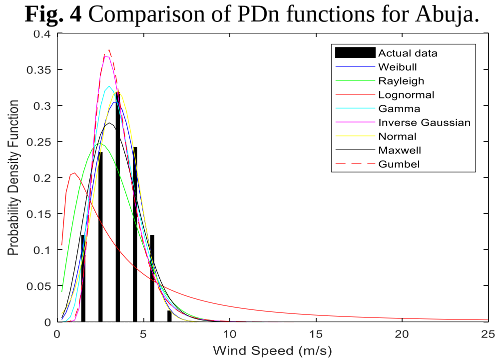

Fig. 5 Comparison of PDn functions for Akure.

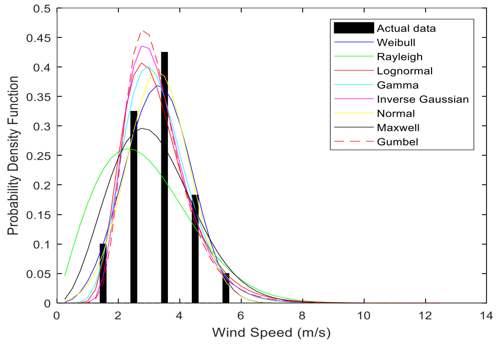

Fig. 6 Comparison of PDn functions for Abeokuta.

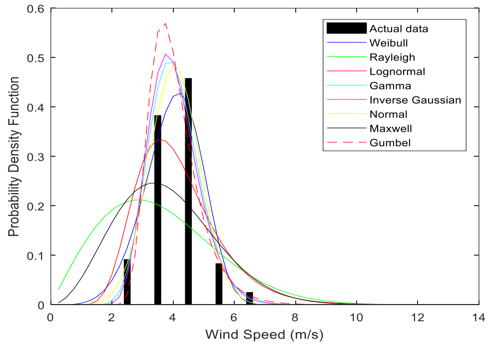

Fig. 7 Comparison of PDn functions for Uyo.

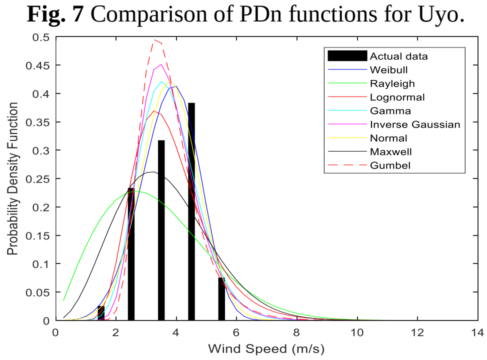

Fig. 8 Comparison of PDn functions for Warri.

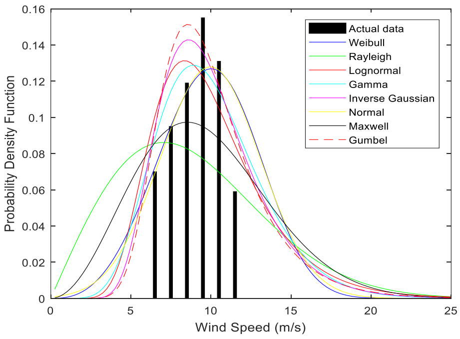

Fig. 9 Comparison of PDn functions for Ikeja.

The goodness of fit for the different PD models was evaluated to characterize the wind speed distribution in the locations based on minimum RMSE. Table 3 to 12 presents the statistical RMSE values and precise rank for the PD models. These indicators are also represented graphically in Fig. 10. For the nine locations considered in this work, the suitable distribution is the one with the least RMSE. From the results, the Ryh distribution shows the best fit for Kano, Jos, Abeokuta, Uyo, Warri and Ikeja and Lgl distribution shows the best fit for Maiduguri, Abuja and Akure due to their minimum RMSE. In general, the statistical analysis shows a good fit for all the distributions because the RMSE is very small. Also, as seen in Tables 3 to 12, one cannot conclude that Wbl distribution is always the best for all locations without first verifying. The results show that Ryh and Lgl distributions are the most effective for all nine study locations in this paper.

Table 4 Estimated parameters and goodness of fit estimation for Kano.

PD function	Estimated parameters		RMSE	Rank
Wbl	k = 4.62	c = 10.12	0.06123	3rd
Rayleigh	k = 2	c = 9.39	0.05597	1st
Lognormal	α = 2.22	β = 0.22	0.07266	7th
Gamma	k = 22.02	c = 0.43	0.07133	5th
Inverse Gaussian	α = 9.39	β = 205.68	0.07249	6th
Normal	μ = 9.39	σ = 2.01	0.07072	4th
Maxwell	α = 5.55	-	0.05671	2nd
Gumbel	β = 1.57	μ = 8.49	0.07612	8th

Table 5 Estimated parameters and goodness of fit estimation for Maiduguri.

PD function	Estimated parameters		RMSE	Rank
Wbl	k = 4.12	c = 6.01	0.08164	4th
Rayleigh	k = 2	c = 5.49	0.06987	2nd
Lognormal	α = 1.67	β = 0.60	0.06541	1st
Gamma	k = 15.77	c = 0.35	0.08646	6th
Inverse Gaussian	α = 5.49	β = 86.26	0.08814	7th
Normal	μ = 5.49	σ = 1.39	0.08511	5th
Maxwell	α = 3.27	-	0.07103	3rd
Gumbel	β = 1.08	μ = 4.87	0.09176	8th

Table 6 Estimated parameters and goodness of fit estimation for Jos.

PD function	Estimated parameters		RMSE	Rank
Wbl	k = 5.63	c = 12.41	0.06084	4th
Rayleigh	k = 2	c = 11.63	0.04969	1st
Lognormal	α = 2.44	β = 0.30	0.05362	3rd
Gamma	k = 28.86	c = 0.41	0.06332	5th
Inverse Gaussian	α = 11.63	β = 367.64	0.06513	7th
Normal	μ = 11.63	σ = 2.07	0.06416	6th
Maxwell	α = 6.82	-	0.05015	2nd
Gumbel	β = 1.62	μ = 10.70	0.06864	8th

Table 7 Estimated parameters and goodness of fit estimation for Abuja.

PD function	Estimated parameters		RMSE	Rank
Weibull	k = 4.76	c = 5.23	0.08772	4th
Rayleigh	k = 2	c = 4.87	0.07459	2nd
Lognormal	α = 1.57	β = 0.68	0.06965	1st
Gamma	k = 28.57	c = 0.17	0.09725	7th
Inverse Gaussian	α = 4.87	β = 130.18	0.09662	6th
Normal	μ = 4.87	σ = 0.94	0.09555	5th
Maxwell	α = 2.87	-	0.07532	3rd
Gumbel	β = 0.74	μ = 4.45	0.10129	8th

Table 8 Estimated parameters and goodness of fit estimation for Akure.

PD function	Estimated parameters		RMSE	Rank
Wbl	k = 3.01	c = 3.86	0.08169	4th
Rayleigh	k = 2	c = 3.47	0.07624	2nd
Lognormal	$\alpha = 1.17$	$\beta = 1.12$	0.06673	1st
Gamma	k = 7.14	c = 0.49	0.08361	6th
Inverse Gaussian	$\alpha = 3.47$	$\beta = 26.88$	0.08870	7th
Normal	$\mu = 3.47$	$\sigma = 1.25$	0.08257	5th
Maxwell	$\alpha = 2.13$	-	0.07788	3rd
Gumbel	$\beta = 0.97$	$\mu = 2.91$	0.08914	8th

Table 9 Estimated parameters and goodness of fit estimation for Abeokuta.

PD function	Estimated parameters		RMSE	Rank
Wbl	k = 3.50	c = 3.65	0.12688	3rd
Rayleigh	k = 2	c = 3.28	0.11423	1st
Lognormal	$\alpha = 1.14$	$\beta = 0.33$	0.13080	6th
Gamma	k = 9.96	c = 0.33	0.13075	5th
Inverse Gaussian	$\alpha = 3.28$	$\beta = 34.23$	0.13592	7th
Normal	$\mu = 3.28$	$\sigma = 1.02$	0.12945	4th
Maxwell	$\alpha = 1.98$	-	0.11621	2nd
Gumbel	$\beta = 0.79$	$\mu = 2.82$	0.13881	8th

Table 10 Estimated parameters and goodness of fit estimation for Uyo.

PD function	Estimated parameters		RMSE	Rank
Wbl	k = 4.99	c = 4.38	0.12845	4th
Rayleigh	k = 2	c = 4.04	0.10631	1st
Lognormal	$\alpha = 1.38$	$\beta = 0.32$	0.11551	3rd
Gamma	k = 24.36	c = 0.17	0.13748	6th
Inverse Gaussian	$\alpha = 4.04$	$\beta = 97.47$	0.13906	7th
Normal	$\mu = 4.04$	$\sigma = 0.82$	0.13574	5th
Maxwell	$\alpha = 2.38$	-	0.10763	2nd
Gumbel	$\beta = 0.64$	$\mu = 3.67$	0.14591	8th

Table 11 Estimated parameters and goodness of fit estimation for Warri.

PD function	Estimated parameters		RMSE	Rank
Wbl	k = 4.53	c = 4.13	0.13142	4th
Rayleigh	k = 2	c = 3.77	0.10703	1st
Lognormal	$\alpha = 1.29$	$\beta = 0.31$	0.12360	3rd
Gamma	k = 14.96	c = 0.25	0.13282	6th
Inverse Gaussian	$\alpha = 3.77$	$\beta = 59.86$	0.13782	7th
Normal	$\mu = 3.77$	$\sigma = 0.95$	0.13244	5th
Maxwell	$\alpha = 2.24$	-	0.10929	2nd
Gumbel	$\beta = 0.74$	$\mu = 3.34$	0.14430	8th

Table 12 Estimated parameters and goodness of fit estimation for Ikeja.

PD function	Estimated parameters		RMSE	Rank
Wbl	k = 3.62	c = 10.95	0.05460	6th
Rayleigh	k = 2	c = 9.96	0.04770	1st
Lognormal	$\alpha = 2.24$	$\beta = 0.34$	0.05382	3rd
Gamma	k = 9.44	c = 1.06	0.05394	4th
Inverse Gaussian	$\alpha = 9.96$	$\beta = 101.74$	0.05603	7th
Normal	$\mu = 9.96$	$\sigma = 3.12$	0.05425	5th
Maxwell	$\alpha = 6.03$	-	0.04888	2nd
Gumbel	$\beta = 2.43$	$\mu = 8.56$	0.05696	8th

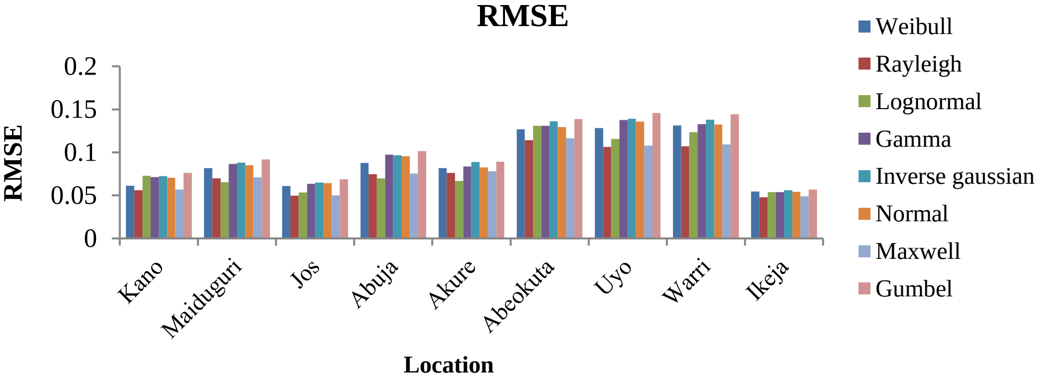

Fig. 10 RMSE of each PDn functions for various locations.

3.2 Wind Characteristic of Location

The wind speed characteristics and Wbl parameters of the study locations were determined and the results are shown in Table 13.

From Table 13, the average wind speed (V_{ms}) varies from 3.28 m/s in Abeokuta to 11.63 m/s in Jos, k varies from 3.01 in Akure to 5.63 in Jos, while c varies from 3.65 m/s in Abeokuta to 12.41 m/s in Jos. The most probable wind speed (V_{mps}) varies from 3.32 m/s in Abeokuta to 11.99 m/s in Jos, the wind speed with maximum energy (V_{emax}) varies from 4.15 m/s in Abeokuta to 13.10 m/s in Jos. P_{WPD} varies from 28 W/m^2 in Abeokuta to 1040 W/m^2 in Jos, all at a h-h of 10 m. The result presented in Table 13 clearly shows that Jos, Kano and Ikeja are viable locations for grid integration because P_{WPD} at a h-h of 10 m is $> 400\, W/m^2$, while Abuja, Akure, Abeokuta, Uyo and Warri locations are not viable for a wind power application because the P_{WPD} obtained for them is $< 100\, W/m^2$; however, Maiduguri is only viable for a standalone application because the P_{WPD} is $> 100\, W/m^2$ [14].

3.3 Estimation of Capacity Factor of WTs

Although designing a wind turbine that will match a particular site wind characteristics is the best, however, this can be time-consuming and frustrating [24], hence, the need to utilize available wind turbines in the market (W1 – W10). For this study, the capacity factor method is employed in turbine selection. Table 14 depicts the wind turbine characteristics considered for this study. Wind turbine with high value of capacity factor is usually encouraged for selection. For uniformity of comparison, each turbine considered were $25\ kW$ ratings with a different cut-in and rated wind speed. According to [10], any wind turbine with ≤ 0.25 CF is not suitable for grid integration and wind turbine with the highest CF in excess of 0.25 is the best for any given location. The response of the WTs with respect to the location based on capacity factor is presented in Table 14.

From Table 14, WT2, WT4, WT5 and WT8 are not suitable for any location because there CF is ≤ 0.25. WT1, WT3 and WT6 are suitable for locations in Jos and Ikeja, respectively. WT9 and WT10 are suitable for only Ikeja location. WT7 is suitable for locations in Kano, Jos and Ikeja respectively. The result further reveals that WT7 is the best turbine because it has the highest CF in all the nine locations considered in this study.

3.4 Cost Estimation of Energy

Table 15 presents the unit cost of energy for various WTs at a h-h of 10 m. This cost is used as criteria for deciding which WT is to be selected for power generation application.

Table 13 Wind speed characteristics of study locations.

Location	V_{ms}	k	c	V_{mps}	V_{emax}	P_{WPD}
Kano	9.39	4.62	10.12	9.60	10.94	571
Maiduguri	5.49	4.12	6.01	5.62	6.62	122
Jos	11.63	5.63	12.41	11.99	13.10	1040
Abuja	4.87	4.76	5.23	4.98	5.63	79
Akure	3.47	3.01	3.86	3.38	4.57	35
Abeokuta	3.28	3.50	3.65	3.32	4.15	28
Uyo	4.04	4.99	4.38	4.19	4.69	46
Warri	3.78	4.53	4.13	3.91	4.48	39
Ikeja	9.96	3.62	10.95	10.01	12.36	756

Table 14 CFw of WTs.

Location	CF_w									
	WT1	WT2	WT3	WT4	WT5	WT6	WT7	WT8	WT9	WT10
Kano	0.12	0.07	0.16	0.09	0.05	0.22	0.30	0.09	0.12	0.12
Maiduguri	0.02	0.01	0.02	0.01	0.01	0.03	0.04	0.01	0.02	0.02
Jos	0.25	0.12	0.33	0.17	0.09	0.44	0.56	0.17	0.24	0.24
Abuja	0.00	0.00	0.01	0.00	0.00	0.01	0.02	0.00	0.01	0.01
Akure	0.01	0.01	0.01	0.01	0.00	0.02	0.03	0.01	0.01	0.01
Abeokuta	0.01	0.00	0.01	0.00	0.00	0.01	0.02	0.00	0.00	0.00
Uyo	0.00	0.00	0.00	0.00	0.00	0.00	0.01	0.00	0.00	0.00
Warri	0.00	0.00	0.00	0.00	0.00	0.00	0.01	0.00	0.00	0.00
Ikeja	0.26	0.17	0.30	0.20	0.13	0.38	0.45	0.20	0.25	0.25

Table 15 COE.

Location	COE ($/kWh)									
	WT1	WT2	WT3	WT4	WT5	WT6	WT7	WT8	WT9	WT10
Kano	0.1523	0.2626	0.1135	0.2027	0.3410	0.0831	0.0609	0.2020	0.1527	0.1524
Maiduguri	1.0467	1.7281	0.8395	1.4787	2.5303	0.6037	0.4518	1.4067	1.0955	1.0635
Jos	0.0778	0.1488	0.0564	0.1082	0.2020	0.0420	0.0328	0.1082	0.0779	0.0778
Abuja	3.7952	6.7791	2.9647	5.8085	11.2453	2.0099	1.4398	5.3804	4.0313	3.8695
Akure	1.5177	2.4678	1.7281	3.3184	6.6998	1.0144	0.9226	2.5250	2.1016	1.7292
Abeokuta	3.6494	6.3638	4.2518	9.4405	23.2969	2.2860	2.0330	6.5975	5.3332	4.2117
Uyo	12.1499	22.7921	10.0521	22.4102	53.3706	6.2399	4.4922	18.7744	13.8726	12.6624
Warri	8.7877	15.9956	7.9881	17.8547	43.7570	4.7989	3.6609	14.0867	10.7026	9.3808
Ikeja	0.0739	0.1115	0.0603	0.0920	0.1380	0.0490	0.0405	0.0915	0.0743	0.0741

Table 16 Sensitivity analysis showing relationship between COE and V_{ci}.

Location	COE ($/kWh) for different values of V_{ci}				
	1.5 m/s	3 m/s	4.5 m/s	6 m/s	7.5 m/s
Kano	0.0608	0.0610	0.0619	0.0649	0.0729
Maiduguri	0.4417	0.4650	0.5889	1.1394	4.7608
Jos	0.0327	0.0328	0.0328	0.0331	0.0339
Abuja	1.4017	1.4995	2.2649	9.3202	337
Akure	0.7502	1.1185	3.3226	28	923
Abeokuta	1.6335	2.5706	12.2138	434	335726
Uyo	4.2452	4.9203	13.3746	535	10670330
Warri	3.3384	4.1749	14.3255	731	9134947
Ikeja	0.0404	0.0406	0.0415	0.0435	0.0475

Table 17 Sensitivity analysis showing relationship between COE and V_r.

Location	COE ($/kWh) for different values of V_r				
	8 m/s	10 m/s	12 m/s	14 m/s	16 m/s
Kano	0.0216	0.0284	0.0454	0.0832	0.1524
Maiduguri	0.0632	0.1530	0.3247	0.6133	1.0635
Jos	0.0191	0.0212	0.0270	0.0420	0.0778
Abuja	0.1423	0.4126	0.9835	2.0491	3.8695
Akure	0.2090	0.4153	0.7237	1.1547	1.7292
Abeokuta	0.3665	0.8078	1.5347	2.6369	4.2117
Uyo	0.3973	1.2122	3.0126	6.5027	12.6624
Warri	0.4040	1.1139	2.5469	5.1222	9.3808
Ikeja	0.0215	0.0258	0.0341	0.0491	0.0741

Table 18 Sensitivity analysis showing relationship between COE and h-h.

Location	COE ($/kWh) for different values of h-hs				
	10 m	20 m	30 m	40 m	50 m
Kano	0.0609	0.0406	0.0325	0.0283	0.0257
Maiduguri	0.4518	0.2750	0.1917	0.1427	0.1107
Jos	0.0328	0.0253	0.0226	0.0212	0.0204
Abuja	1.4398	0.8082	0.5303	0.3750	0.2776
Akure	0.9226	0.5662	0.4108	0.3195	0.2584
Abeokuta	2.0330	1.1613	0.8052	0.6039	0.4732
Uyo	4.4922	2.3642	1.5024	1.0355	0.7498
Warri	3.6609	2.0066	1.3150	0.9322	0.6925
Ikeja	0.0405	0.0319	0.0280	0.0257	0.0242

WT7 shows the best cost (least cost) for all the locations considered in this study. For WT7, COE ranges from $ 0.0328/kWh in Jos to $\$ 4.4922/$kWh in Uyo. WT5 shows the worst performance (highest cost) with COE ranging from $ 0.1380/kWh in Ikeja to $\$ 53.371/kWh$ in Uyo. In Nigeria, electricity tariff in the country for residential "Band A" customers with daily minimum of 20 hrs of electricity availability is $\$ 0.12$ at an official exchange rate of $ 1 to N 500. Hence, generation of electricity using WT3, WT6 and WT7 is suitable for Kano, Jos and Ikeja, respectively. WT1, WT4, WT8, WT9 and WT10 are suitable for Jos and Ikeja, respectively. WT2 is only suitable in Ikeja, while WT5 is not economically viable for wind power generation in all locations compared with utility grid supply.

3.5 Sensitivity Analysis

Sensitivity analysis, as considered in this study, showcases the dependency of a given system variable on some defined input variables. In this study, the variables considered are the effect of varying V_{ci}, V_r, h-h, inflation rate and discount rate of WT7 on COE for all the locations. The results as shown in Tables 16 to 20 reveal that for each sensitivity variable, the COE was either increasing or decreasing. Table 16 shows the relationship between V_{ci} and COE.

Table 19 Sensitivity analysis relating COE to inflation rate (%).

Location	COE ($/kWh) for different values of inflation rate				
	2 (%)	4 (%)	6 (%)	8 (%)	10 (%)
Kano	0.0338	0.0412	0.0496	0.0589	0.0693
Maiduguri	0.2509	0.3058	0.3677	0.4371	0.5140
Jos	0.0182	0.0222	0.0267	0.0317	0.0373
Abuja	0.7997	0.9747	1.1719	1.3929	1.6381
Akure	0.5124	0.6245	0.7509	0.8925	1.0496
Abeokuta	1.1292	1.3763	1.6548	1.9667	2.3130
Uyo	2.4950	3.0410	3.6564	4.3456	5.1109
Warri	2.0333	2.4783	2.9798	3.5414	4.1651
Ikeja	0.0225	0.0274	0.0330	0.0392	0.0461

Table 20 Sensitivity analysis relating COE to discount rate.

Location	COE ($/kWh) for different values of discount rate				
	10 (%)	12 (%)	14 (%)	16 (%)	18 (%)
Kano	0.0615	0.0604	0.0594	0.0587	0.0580
Maiduguri	0.4562	0.4479	0.4409	0.4351	0.4303
Jos	0.0331	0.0325	0.0320	0.0315	0.0312
Abuja	1.4538	1.4273	1.4050	1.3868	1.3713
Akure	0.9315	0.9145	0.9003	0.8886	0.8787
Abeokuta	2.0528	2.0153	1.9839	1.9581	1.9363
Uyo	4.5358	4.4530	4.3837	4.3266	4.2785
Warri	3.6965	3.6290	3.5725	3.5259	3.4867
Ikeja	0.0409	0.0402	0.0396	0.0390	0.0386

The COE is directly proportional to V_{ci}, this means that WTs with minimum V_{ci} should be selected because at lower wind speed they will start to generate power. A WT that has a V_{ci} almost equal to or higher than a location's average wind speed should never be selected for the location as can be seen in Table 16. Table 17 presents the result of sensitivity between V_r and COE. The result reveals that V_r has a linear relationship with COE. In selecting WTs, V_r should be as low as possible but must match the location's wind regime for optimal utilization of the wind energy. If the selected V_r is lower than the location's mean wind speed, it means that the wind energy of that location is under-utilized. Table 18 shows the relationship between the COE and the WT h-h. The results clearly demonstrate that COE decreases with increasing h-hs; this is because the WT harnesses more energy at a higher height due to increase in the wind speed. Table 19 reveals that COE increases as inflation rate increases, while Table 20 shows that COE decreases as the discount rate increases. Hence, low inflation rate and high discount rate are favorable to COE.

4 Conclusions

This study has presented a detailed comparative study of eight probability distribution functions, namely Weibull (Wbl) distribution, Rayleigh (Ryh) distribution, Lognormal (Lgl) distribution, Gamma (Gma) distribution, Inverse Gaussian (IG), Normal (Nl) distribution, Maxwell (Mwl) distribution and Gumbel (Gbl) distribution. It has considered the techno-economic and sensitivity analyses of wind energy conversion systems (WECSs) in some selected locations in Nigeria. The study utilized average daily wind speeds for 10 yrs obtained from the Nigerian Meteorological Agency (NIMET). The paper used ten wind turbines of the same rating (25 kW) for analyzing the WECSs for nine different locations in Nigeria such as Kano, Maiduguri, Jos, Abuja, Akure, Abeokuta, Uyo, Warri and Ikeja. The study revealed the following findings:

i. That Ryh distribution shows the best fit for six locations (Kano, Jos, Abeokuta, Uyo, Warri and Ikeja) and Lgl distribution shows the best fit for the other three locations (Maiduguri, Abuja and Akure) due to their minimum $RMSE$.
ii. That Jos, Ikeja and Kano are viable for grid integration of wind energy, with Jos being the most viable followed by Ikeja and then Kano for wind energy generation..
iii. WT7 has the highest CF_w in all the locations, which is a major determinant in turbine selection.
iv. WT7 has the least COE in all the selected locations, hence, was selected among other wind turbines.
v. WT5 has the highest COE (worst economic performance) in all the locations considered.
vi. Technical parameters considered for sensitivity showed that it is more economical to operate wind turbines at a lower V_{ci}, moderate V_r that matches with the location's wind regime and optimal hub-height in order to maximize the location's wind speed.

vii. Economic parameters considered for sensitivity showed that it is more economical to operate wind turbines at a lower inflation rate and higher discount rate.

Intellectual Property

The authors confirm that they have given due consideration to the protection of intellectual property associated with this work and that there are no impediments to publication, including the timing to publication, with respect to intellectual property.

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Declaration of Competing Interest

The authors hereby confirm that the submitted manuscript is an original work and has not been published so far, is not under consideration for publication by any other journal and will not be submitted to any other journal until the decision will be made by this journal. All authors have approved the manuscript and agree with its submission to "Iranian Journal of Electrical and Electronic Engineering".

Reference

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Ignatius Okakwu holds a Ph.D. in Electrical Engineering from the University of Benin, Nigeria. He is a Lecturer and the acting Head of Department of Electrical and Electronics Engineering, Olabisi Onabanjo University, Ago-Iwoye, Nigeria. He is registered by the Council for the Regulation of Engineering in Nigeria (COREN). His research interests include electrical power systems, electrical machines, reliability analysis, and renewable energy.

Elijah Olabode holds a Ph.D. in Electrical Engineering from Osun State University, Osogbo, Nigeria. He is registered by the Council for the Regulation of Engineering in Nigeria (COREN). His research interests include electrical power systems, electrical machines and renewable energy.

Daniel Akinyele holds a Ph.D. in Engineering with emphasis on Renewable Energy from Victoria University of Wellington, New Zealand. He had a one-year Postdoctoral Fellowship at the Andrew and Erna Viterbi Faculty of Electrical Engineering, Technion-Israel Institute of Technology, Haifa, Israel. He is a Lecturer at the Department of Electrical and Electronics Engineering, Olabisi Onabanjo University, Ago-Iwoye, Nigeria. He is registered by the Council for the Regulation of Engineering in Nigeria (COREN). His research interests include renewable energy systems analysis, microgrid design and planning, energy efficiency analysis, life-cycle impact analysis, sustainability and energy policy.

Titus Ajewole holds a Ph.D. in Electrical Engineering from Obafemi Awolowo University, Ife, Nigeria. He is an Associate Professor at the Department of Electrical and Electronics Engineering, Osun State University, Osogbo, Nigeria. He is registered by the Council for the Regulation of Engineering in Nigeria (COREN). His research interests include power systems, microgrids, smart grid and renewable energy.