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Analysis of wind-speed characteristics and energy potential across North Central Nigeria

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ABSTRACT

Unreliable conventional electricity supply constrains the processing and storage of agricultural produce in North Central Nigeria, contributing to food losses and insecurity. This study evaluates the region's wind-energy potential using 20 years (2001–2020) of daily wind-speed data from the Modern-Era Retrospective Analysis for Research and Applications, Version 2 (MERRA-2), produced by the National Aeronautics and Space Administration. Weibull, lognormal, and Gamma probability distribution functions were fitted to data from Abuja, Jos, Lafia, Lokoja, Makurdi, and Minna. Observed wind speeds ranged from 2.5 to 6.1 m/s, and mean wind-power densities ranged from 16.8 to 45.8 W/m^2, indicating potential mainly for off-grid electricity generation and other small-scale applications. Based on higher coefficients of determination and lower root mean square errors, the Weibull distribution generally provided the best fit. Average monthly wind-energy densities increased from 12.235 kWh/m^2 in Abuja to 33.010 kWh/m^2 in Jos, with intermediate values of 17.759, 20.254, 24.711, and 27.664 kWh/m^2 for Minna, Lokoja, Lafia, and Makurdi, respectively. These results indicate that wind energy could complement conventional supply in domestic, agricultural, and industrial facilities across the region.

1. INTRODUCTION

Nigeria's population is growing continuously. The country's population in 2026 is estimated at approximately 242 million according to the United Nations Department of Economic and Social Affairs data reported by Worldometer [1]; however, power generation, which has long been inadequate, has not grown proportionally. Ref. [2] projected that Nigeria's energy deficit would continue to increase until 2050, while a World Bank report estimated that unreliable electricity costs the Nigerian economy approximately US$26.2 billion (NGN 10.1 trillion) annually [3]. Alternative energy resources, including wind and solar energy, are therefore needed to help address the country's energy deficit. Wind energy can provide clean, renewable electricity for industries, businesses, and homes, but it remains largely untapped in Nigeria. Wind turbines consume no fuel during operation and produce no direct emissions or other air pollutants, unlike conventional electricity-generation systems [4]. Consequently, concerns about global warming have helped drive the development and adoption of wind power [5].

Numerous studies within and outside Nigeria have assessed wind-power potential using probability distribution functions (PDFs) [6–9]. Most employed the Weibull distribution [10–18];

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others used Weibull, Gamma, and lognormal distributions [19], Weibull and Rayleigh distributions [14], or Weibull, lognormal, Gamma, and Rayleigh distributions [20]. Ref. [21] statistically analyzed wind characteristics at five locations in North Central Nigeria: Bida, Minna, Makurdi, Ilorin, and Lokoja. The Weibull distribution was applied to 35 years (1971–2007) of wind-speed data obtained from the Nigerian Meteorological Agency (NiMet) at an elevation of 10 m. Monthly, annual, and seasonal variations were extrapolated from the 10-m monthly data to different hub heights using the wind power law. The results indicated that the five locations were suitable only for off-grid electricity generation and other mechanical applications because their mean annual wind speeds were 2.747, 4.289, 4.570, 4.386, and 3.158 m/s, and their mean annual wind-power densities were 16.569, 94.113, 76.399, 71.823, and 26.089 W/m^2 for Bida, Minna, Makurdi, Ilorin, and Lokoja, respectively. Similarly, Ref. [15] used the Weibull distribution to investigate wind-energy potential in Makurdi from 1961 to 2014 and obtained mean wind speeds of 3–4 m/s and a wind-power density of 86.85 W/m^2, indicating that wind in Makurdi could support off-grid electricity generation.

In a review of possible wind-energy grid integration in Nigeria, Ref. [22] reported that almost every state has some wind-power potential, at least for water pumping. This finding provides a basis for determining whether North Central Nigeria is suitable for stand-alone or grid-connected wind-power generation. Using Weibull, Gamma, and lognormal distributions to estimate the average wind speed in Bitlis, Türkiye, between 2012 and 2016, Ref. [19] reported that the Gamma distribution modeled the wind-speed data better than the other distributions, with the lowest Kolmogorov–Smirnov goodness-of-fit statistic and root mean square error (RMSE), 0.1053 and 0.0047, respectively, and the highest coefficient of determination, $R^2 = 0.9998$.

Despite these studies, additional assessments based on multiple PDFs are required because energy supply remains a major challenge in the region. Such assessments can help determine the viability of installing wind-power plants. The available studies for North Central Nigeria, including Ref. [21] for 1971–2007 and Ref. [15] for 1961–2014, used only the Weibull distribution and do not cover recent years. The present study therefore uses three PDFs—Weibull, lognormal, and Gamma—to reduce the limitations associated with relying on a single distribution. Unstable conventional electricity supply affects the processing and storage of agricultural produce in a region where much of the population depends on farming, which can contribute to food shortages and insecurity. Accordingly, this study statistically evaluates wind-energy potential for possible wind-power generation in North Central Nigeria. The specific objectives are to (i) determine daily mean wind-speed characteristics using different PDFs, (ii) determine the variation in monthly mean daily wind speed, (iii) determine monthly mean daily power and energy densities, and (iv) determine trends in annual mean wind-power density using PDFs. The findings may support policy formulation for wind-power development in the region.

1.1. DATA SOURCE

Table 1. Selected locations, geographical coordinates, and elevation above sea level.

S/No.	Location	Latitude (°N)	Longitude (°E)	Elevation (m)
1.	Makurdi	7.7411	8.5121	104
2.	Jos	9.9284	8.8921	1208
3.	Abuja	9.0578	7.4950	339
4.	Lokoja	7.8023	6.7430	55
5.	Lafia	8.4833	8.5166	290
6.	Minna	9.6138	6.5569	299

Source: [34, 35].

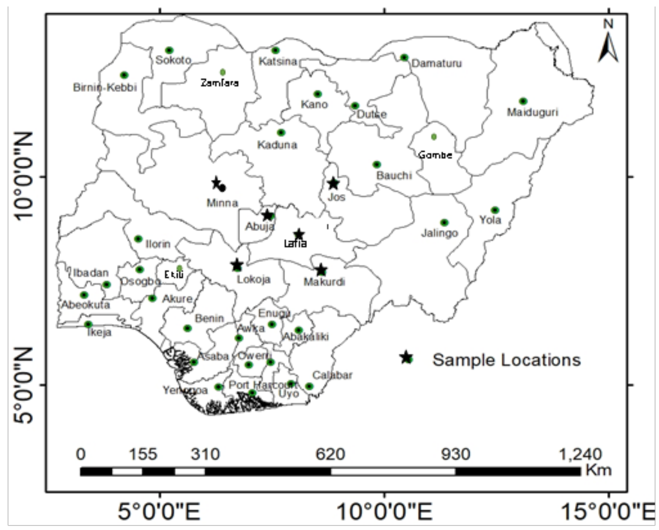

Figure 1. Map of Nigeria showing the six sampled locations.

Source: Generated by the authors.

1.2. THEORETICAL BACKGROUND OF PROBABILITY DENSITY FUNCTIONS

A major limitation of wind energy is its uneven geographical distribution. Statistical measurement and analysis are therefore required to identify locations and periods in which this resource can be harnessed. Probability distributions are used in wind-potential analysis to obtain weighted averages [23]. The three distributions used in this study are described below.

1.2.1. Weibull distribution

The Weibull distribution is a unimodal distribution that describes probabilities associated with a continuous data set [24]. Its probability density function is [25]

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

where $f_w(v)$ is the probability of measuring wind speed v, k is the dimensionless Weibull shape parameter, and c is the Weibull scale parameter, which has the same unit as wind speed. The shape parameter describes the geometry and skewness of the probability distribution and represents the gradient of a line on the probability plot. The values of k can be interpreted as follows [24]: $k < 1$, steadily increasing values; $k = 1$, a two-parameter exponential distribution; $1 < k < 1.26$, a right-skewed distribu-

Table 2. Daily mean wind speed characteristics from 2001–2020 using different probability distribution functions.

	Weibull				Lognormal				Gamma			
Location	k	c	RMSE	R^2	μ	σ	RMSE	R^2	K	θ	RMSE	R^2
Makurdi	6.135	19.870	0.013	0.953	2.883	0.276	0.029	0.751	16.320	1.129	0.026	0.813
Jos	5.950	20.945	0.017	0.915	2.931	0.287	0.030	0.693	15.170	1.278	0.027	0.758
Lafia	6.181	20.474	0.016	0.934	2.912	0.289	0.032	0.699	15.382	1.236	0.028	0.770
Lokoja	6.211	19.570	0.014	0.950	2.871	0.265	0.029	0.763	17.423	1.043	0.026	0.817
Abuja	6.189	20.755	0.016	0.928	2.927	0.277	0.031	0.712	16.300	1.182	0.028	0.776
Minna	6.580	20.772	0.013	0.957	2.936	0.255	0.029	0.764	18.874	1.025	0.026	0.820

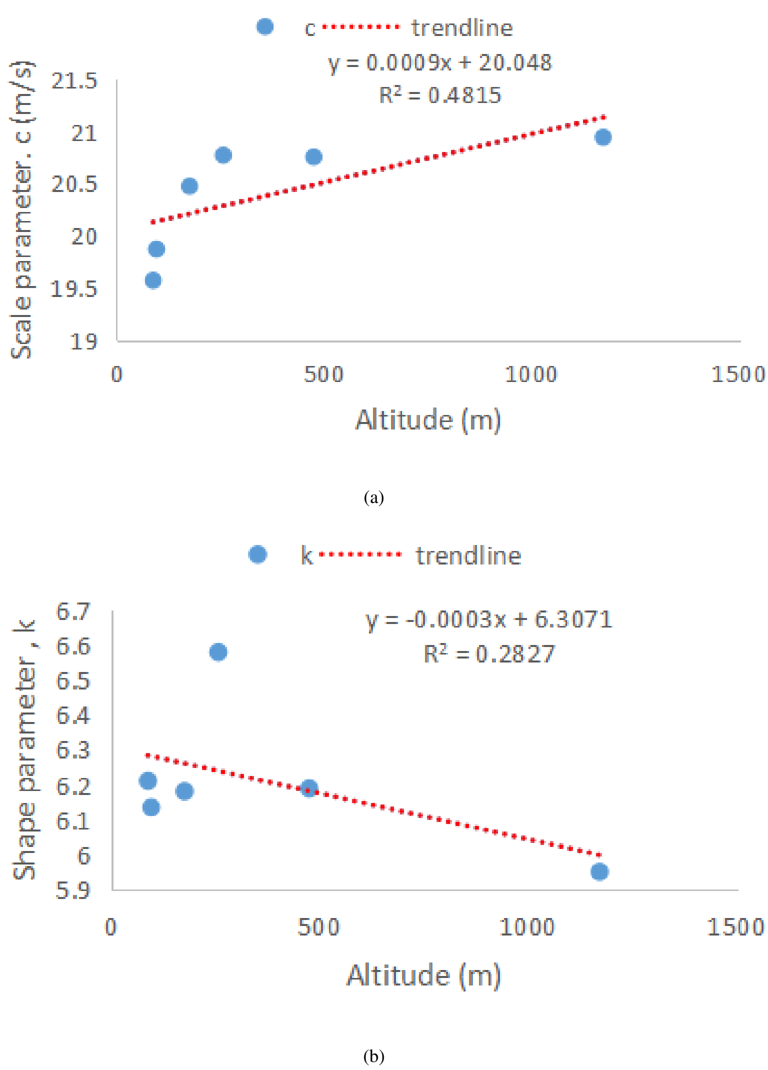

Figure 2. Variation of the Weibull scale parameter c and shape parameter k with location elevation: (a) scale parameter and (b) shape parameter.

tion; $k \approx 3$, a normal distribution; and $k > 3.7$, a left-skewed distribution.

The scale parameter c determines the variability of the probability distribution and represents its 62.3rd percentile. Increasing c stretches the distribution and decreases its height, whereas decreasing c shifts and contracts the distribution to the left and increases its height [24]. The corresponding cumulative probability function is [19]

$$F_w(v) = 1 - \exp\left[-\left(\frac{v}{c}\right)^k\right]. \tag{2}$$

The Weibull shape and scale parameters can be determined using several methods, depending on the complexity and size of the data set [26]. These methods include maximum likelihood

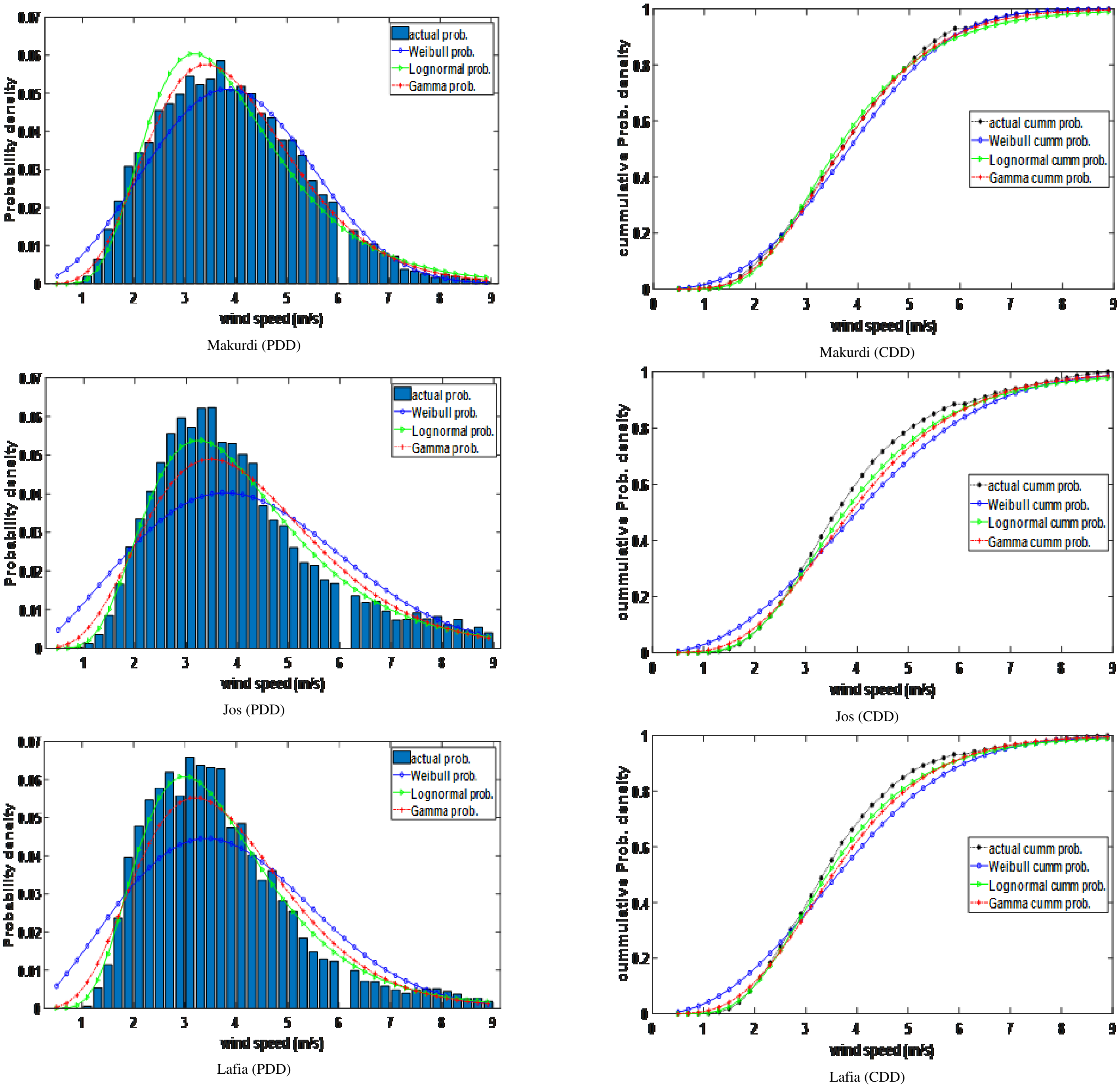

Figure 3. Probability density distributions (PDDs) and cumulative probability density distributions (CDDs) of mean daily wind speed for Makurdi, Jos, and Lafia using the Weibull, lognormal, and Gamma probability distribution functions.

estimation (MLE), the method of moments (MoM), the graphical method (GM), probability plots (PPs), standard-deviation plotting (SDP), and the power-density method (PDM) [27]. Although MLE is recommended for large samples ($n > 100$) because of its statistical reliability, the least-squares method (LSM), MoM, and GM are also used for smaller data sets and may exhibit greater bias [28]. MLE is a powerful method for estimating Weibull parameters, but its limitations include computational complexity, poor performance for small samples ($n < 100$), dependence on asymptotic normality for confidence-interval estimation, and an iterative solution that may fail to converge [27, 29]. Complementary or modified methods may therefore be required. In this study, the Weibull parameters were evaluated using the LSM [28] by fitting equation (2) to the observed discrete cumulative-frequency distribution. Taking the natural logarithm twice gives

$$\ln\{-\ln[1-F_w(v)]\} = k\ln(v) - k\ln(c). \tag{3}$$

Equation (3) has the form $y = mx + b$; thus, a plot of $\ln\{-\ln[1-F(v)]\}$ against $\ln(v)$ has slope k and intercept $-k\ln(c)$. Values of k typically range from 1.5 to 3.0 under common wind conditions

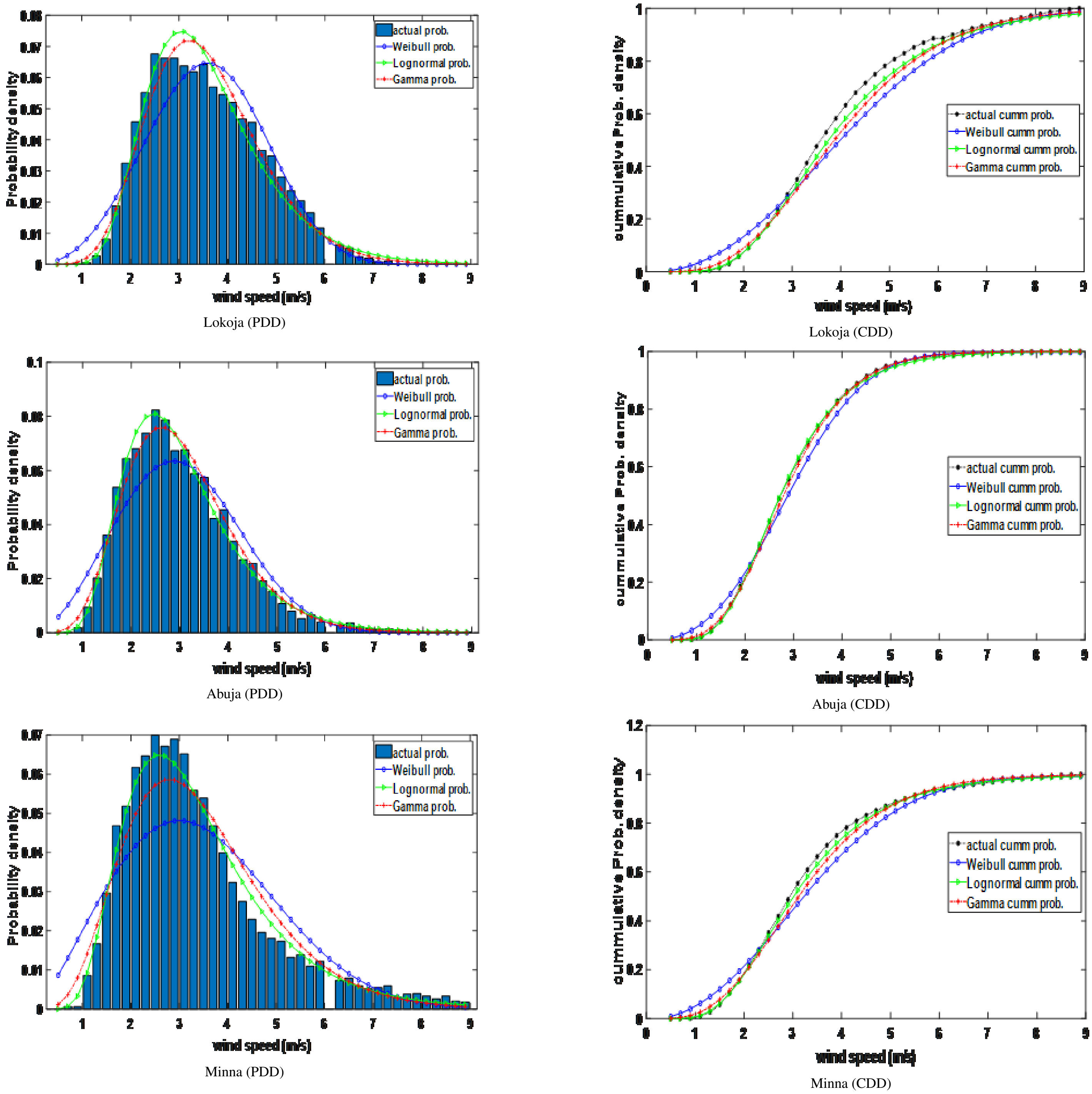

Figure 4. Probability density distributions (PDDs) and cumulative probability density distributions (CDDs) of mean daily wind speed for Lokoja, Abuja, and Minna using the Weibull, lognormal, and Gamma probability distribution functions.

[19]. The mean wind speed is

$$\bar{v}_w = c\,\Gamma\left(1+\frac{1}{k}\right), \tag{4}$$

where Γ is the Gamma function. The corresponding standard deviation is [19]

$$\sigma_w = \sqrt{c^2\left[\Gamma\left(1+\frac{2}{k}\right) - \left\{\Gamma\left(1+\frac{1}{k}\right)\right\}^2\right]}. \tag{5}$$

1.2.2. Lognormal distribution

The probability density and cumulative distribution functions for the lognormal distribution are [19]

$$f_l(v) = \exp\left[-\frac{1}{2}\left(\frac{\ln(v)-\mu}{\sigma}\right)^2\right] \times \frac{1}{\sigma v\sqrt{2\pi}}, \tag{6}$$

and

$$F_l(v) = \Phi\left(\frac{\ln(v)-\mu}{\sigma}\right), \tag{7}$$

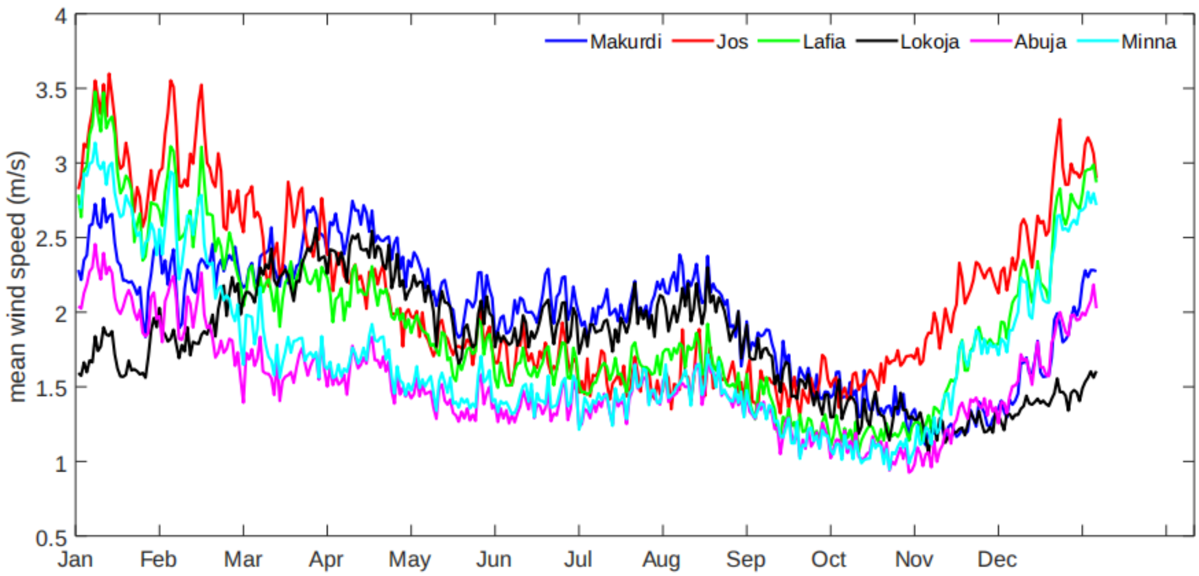

Figure 5. Variation of overall mean daily wind speed over Makurdi, Jos, Lafia, Lokoja, Abuja, and Minna.

Table 3. Monthly mean daily wind speed, power and energy densities for Makurdi.

Month	Weibull					Lognormal					Gamma				
	V_w (m/s)	Sd_w (m/s)	P_w (W)	PD_w (W/m^2)	ED_w (kWh/m^2 /month)	V_l (m/s)	Sd_l (m/s)	P_l (W)	PD_l (W/m^2)	ED_l (kWh/m^2 /month)	V_g (m/s)	Sd_g (m/s)	P_g (W)	PD_g (W/m^2)	ED_g (kWh/m^2 /month)
Jan	4.700	0.478	319,830.0	63.640	45.82	4.720	0.458	321,000.0	63.860	45.980	4.705	0.447	320,800.0	63.820	45.950
Feb	4.527	0.241	285,590.0	56.817	40.90	4.522	0.283	284,610.0	56.622	40.768	4.521	0.273	284,510.0	56.601	40.753
Mar	4.744	0.390	328,758.4	65.404	47.09	4.758	0.323	331,617.8	65.973	47.501	4.758	0.318	331,564.5	65.963	47.493
Apr	5.014	0.289	388,163.0	77.223	55.60	5.016	0.283	388,629.6	77.315	55.667	5.016	0.277	388,549.2	77.299	55.656
May	4.200	0.336	228,135.3	45.386	32.67	4.206	0.315	229,002.7	45.559	32.802	4.205	0.309	228,927.9	45.544	32.792
Jun	4.059	0.283	205,884.7	40.959	29.49	4.071	0.228	207,786.1	41.338	29.763	4.071	0.224	207,761.0	41.333	29.760
Jul	4.061	0.224	206,124.6	41.007	29.52	4.067	0.195	207,140.6	41.209	29.671	4.067	0.192	207,116.9	41.205	29.667
Aug	4.133	0.391	217,431.8	43.257	31.14	4.132	0.407	217,254.8	43.221	31.119	4.131	0.395	217,091.2	43.189	31.096
Sep	3.218	0.345	102,616.3	20.415	14.69	3.227	0.297	103,423.9	20.576	14.814	3.226	0.293	103,393.3	20.569	14.810
Oct	2.697	0.248	60,378.8	12.012	8.649	2.704	0.228	60,879.4	12.112	8.720	2.704	0.222	60,851.4	12.106	8.716
Nov	2.510	0.187	48,657.5	9.680	6.970	2.516	0.156	49,020.7	9.752	7.022	2.516	0.153	49,013.3	9.751	7.021
Dec	3.651	0.588	149,891.4	29.820	21.470	3.657	0.553	150,615.9	29.964	21.574	3.656	0.540	150,454.4	29.932	21.551
Overall	3.973	0.799	193132.6	38.422	27.664	3.969	0.915	192508.8	38.298	27.574	3.962	0.871	191620.9	38.121	27.447

$\bar{v}_w$, $\bar{v}_l$, and $\bar{v}_g$ are the mean wind speeds; σ_w, σ_l, and σ_g are the standard deviations; P_w, P_l, and P_g are the wind powers; p_w, p_l, and p_g are the wind-power densities; and ED_w, ED_l, and ED_g are the energy densities for the Weibull, lognormal, and Gamma distributions, respectively.

where σ and μ are the lognormal scale and location parameters, respectively. The scale parameter σ is the standard deviation of the natural logarithm of the data and controls the spread of the distribution. Increasing σ increases the skewness and variance, and vice versa. The location parameter μ represents the natural logarithm of the lognormal distribution. Increasing μ shifts the distribution to the right on the original scale but does not affect its skewness or spread [30].

The lognormal parameters were determined using MLE. The likelihood function is [19]

$$L(\mu, \sigma^2 \mid V_i) = \left(\frac{1}{\sqrt{2\pi\sigma^2}} \right)^n \times \prod_{i=1}^{n} \left[\frac{1}{V_i} \exp\left\{ -\frac{[\ln(V_i) - \mu]^2}{2\sigma^2} \right\} \right]. \tag{8}$$

Table 4. Monthly mean daily wind speed, power and energy densities for Jos.

Month	Weibull					Lognormal					Gamma				
	V_w (m/s)	Sd_w (m/s)	P_w (W)	PD_w (W/m^2)	ED_w (kWh/m^2 /month)	V_l (m/s)	Sd_l (m/s)	P_l (W)	PD_l (W/m^2)	ED_l (kWh/m^2 /month)	V_g (m/s)	Sd_g (m/s)	P_g (W)	PD_g (W/m^2)	ED_g (kWh/m^2 /month)
Jan	6.089	0.642	695113.8	138.289	99.568	6.103	0.568	699870.8	139.235	100.249	6.102	0.558	699616.5	139.184	100.213
Feb	5.976	0.658	656985.0	130.703	94.106	5.993	0.570	662837.7	131.867	94.945	5.993	0.560	662575.7	131.815	94.907
Mar	5.087	0.419	405183.8	80.609	58.038	5.091	0.395	406155.0	80.802	58.177	5.090	0.387	406020.9	80.775	58.158
Apr	4.330	0.297	250016.6	49.739	35.812	4.328	0.311	249656.3	49.668	35.761	4.328	0.302	249559.7	49.648	35.747
May	3.616	0.248	145550.6	28.956	20.849	3.625	0.205	146675.4	29.180	21.010	3.625	0.202	146656.7	29.176	21.007
Jun	3.616	0.248	145550.6	28.956	20.849	3.625	0.205	146675.4	29.180	21.010	3.625	0.202	146656.7	29.176	21.007
Jul	3.090	0.217	90858.5	18.076	13.015	3.097	0.185	91496.0	18.203	13.106	3.097	0.182	91481.9	18.200	13.104
Aug	3.106	0.336	92256.8	18.354	13.215	3.123	0.260	93807.1	18.662	13.437	3.123	0.258	93790.8	18.659	13.435
Sep	2.966	0.232	80292.7	15.974	11.501	2.974	0.200	81009.1	16.116	11.604	2.974	0.196	80989.7	16.112	11.601
Oct	3.210	0.222	101869.2	20.266	14.592	3.213	0.212	102140.7	20.320	14.631	3.213	0.207	102114.7	20.315	14.627
Nov	4.227	0.326	232473.9	46.249	33.299	4.221	0.347	231520.9	46.060	33.163	4.220	0.338	231408.3	46.037	33.147
Dec	5.530	0.598	520593.7	103.569	74.570	5.532	0.583	521291.6	103.708	74.670	5.531	0.569	520946.9	103.639	74.620
Overall	4.214	1.2423	230455.5	45.847	33.010	4.210	1.157	229881.3	45.733	32.928	4.214	1.142	230428.5	45.842	33.006

Table 5. Monthly mean daily wind speed, power, and energy densities for Lafia.

Month	Weibull					Lognormal					Gamma				
	V_w (m/s)	Sd_w (m/s)	P_w (W)	PD_w (W/m^2)	ED_w (kWh/m^2 /month)	V_l (m/s)	Sd_l (m/s)	P_l (W)	PD_l (W/m^2)	ED_l (kWh/m^2 /month)	V_g (m/s)	Sd_g (m/s)	P_g (W)	PD_g (W/m^2)	ED_g (kWh/m^2 /month)
Jan	5.778	0.693	593949.7	118.163	85.077	5.788	0.639	597015.4	118.772	85.516	5.787	0.626	596663.5	118.702	85.466
Feb	5.196	0.593	431987.2	85.941	61.878	5.214	0.506	436469.5	86.833	62.520	5.214	0.498	436299.9	86.799	62.495
Mar	4.377	0.195	258213.5	51.370	36.986	4.377	0.202	258213.2	51.370	36.986	4.377	0.197	258174.6	51.362	36.981
Apr	4.138	0.272	218,206.7	43.411	31.256	4.148	0.234	219,731.9	43.714	31.474	4.148	0.230	219,697.2	43.707	31.469
May	3.514	0.266	133,610.7	26.581	19.138	3.516	0.258	133,844.3	26.627	19.172	3.516	0.252	133,799.1	26.618	19.165
Jun	3.243	0.216	104,971.6	20.883	15.036	3.248	0.188	105,524.4	20.993	15.115	3.248	0.185	105,508.0	20.990	15.113
Jul	3.213	0.213	102,073.1	20.307	14.621	3.218	0.187	102,635.8	20.419	14.701	3.218	0.184	102,618.7	20.415	14.699
Aug	3.236	0.325	104,367.9	20.763	14.950	3.238	0.329	104,486.4	20.787	14.967	3.237	0.320	104,405.3	20.771	14.955
Sep	2.552	0.290	51,190.2	10.184	7.332	2.565	0.230	51,958.8	10.337	7.443	2.565	0.227	51,948.7	10.335	7.441
Oct	2.382	0.107	41,590.3	8.274	5.957	2.382	0.105	41,585.8	8.273	5.957	2.381	0.103	41,581.1	8.272	5.956
Nov	3.323	0.404	112,984.9	22.478	16.184	3.315	0.457	112,182.3	22.318	16.069	3.313	0.440	111,981.1	22.278	16.040
Dec	4.989	0.661	382,207.8	76.038	54.747	4.986	0.653	381,731.4	75.943	54.679	4.985	0.637	381,377.5	75.873	54.628
Overall	3.823	1.148	172088.2	34.235	24.649	3.825	1.087	172422.1	34.302	24.697	3.826	1.062	172522.0	34.322	24.711

Taking the natural logarithm and denoting the result by LL gives

$$\begin{aligned} LL(\mu, \sigma^2 \mid V_i) = & -\frac{n}{2}(2\pi\sigma^2) \\ & - \sum_{i=1}^{n} \ln(V_i)\mu - \frac{\sum_{i=1}^{n}[\ln(V_i)]^2}{2\sigma^2} \\ & + \frac{\sum_{i=1}^{n} \ln(V_i)\mu}{\sigma^2} - \frac{n\mu^2}{2\sigma^2}. \end{aligned} \tag{9}$$

The LL function is maximized with respect to μ and σ to obtain

$$\begin{aligned} \frac{\partial LL}{\partial \mu} &= \frac{\sum_{i=1}^{n} \ln(V_i)}{\sigma^2} - \frac{2n\mu}{2\sigma^2} = 0, \\ \widehat{\mu} &= \frac{\sum_{i=1}^{n} \ln(V_i)}{n}, \end{aligned} \tag{10}$$

Table 6. Monthly mean daily wind speed, power, and energy densities for Lokoja.

Month	Weibull					Lognormal					Gamma				
	V_w (m/s)	Sd_w (m/s)	P_w (W)	PD_w (W/m^2)	ED_w (kWh/m^2 /month)	V_l (m/s)	Sd_l (m/s)	P_l (W)	PD_l (W/m^2)	ED_l (kWh/m^2 /month)	V_g (m/s)	Sd_g (m/s)	P_g (W)	PD_g (W/m^2)	ED_g (kWh/m^2 /month)
Jan	3.415	0.328	122,625.1	24.395	17.565	3.426	0.271	123,802.7	24.630	17.733	3.426	0.268	123,779.8	24.625	17.730
Feb	3.806	0.371	169,777.6	33.776	24.319	3.820	0.303	171,559.5	34.131	24.574	3.819	0.299	171,523.3	34.123	24.569
Mar	4.510	0.298	282,419.7	56.186	40.454	4.523	0.246	284,900.5	56.679	40.809	4.523	0.242	284,864.1	56.672	40.804
Apr	4.690	0.247	317,578.9	63.180	45.490	4.688	0.255	317,124.1	63.090	45.425	4.687	0.249	317,062.6	63.078	45.416
May	3.937	0.340	187,858.6	37.373	26.909	3.937	0.336	187,925.8	37.387	26.918	3.937	0.328	187,840.3	37.370	26.906
Jun	3.767	0.248	164,535.1	32.733	23.568	3.774	0.210	165,467.7	32.919	23.702	3.774	0.207	165,446.3	32.915	23.698
Jul	3.847	0.257	175,255.6	34.866	25.104	3.861	0.202	177,209.8	35.255	25.383	3.861	0.199	177,190.5	35.251	25.381
Aug	3.925	0.334	186,141.8	37.032	26.663	3.932	0.315	187,200.6	37.242	26.815	3.932	0.307	187,122.7	37.227	26.803
Sep	3.045	0.322	86,899.7	17.288	12.447	3.053	0.285	87,580.8	17.424	12.545	3.052	0.279	87,546.1	17.417	12.540
Oct	2.622	0.185	55,477.9	11.037	7.947	2.625	0.172	55,676.8	11.077	7.975	2.625	0.168	55,663.2	11.074	7.973
Nov	2.456	0.145	45,595.0	9.071	6.531	2.457	0.139	45,673.3	9.086	6.542	2.457	0.136	45,663.9	9.085	6.541
Dec	2.857	0.201	71,803.2	14.285	10.285	2.865	0.166	72,395.1	14.403	10.370	2.865	0.164	72,385.0	14.401	10.368
Overall	3.581	0.736	141399.9	28.130	20.254	3.580	0.758	141379.4	28.126	20.251	3.578	0.735	141111.5	28.073	20.212

Table 7. Monthly mean daily wind speed, power, and energy densities for Abuja.

Month	Weibull					Lognormal					Gamma				
	V_w (m/s)	Sd_w (m/s)	P_w (W)	PD_w (W/m^2)	ED_w (kWh/m^2 /month)	V_l (m/s)	Sd_l (m/s)	P_l (W)	PD_l (W/m^2)	ED_l (kWh/m^2 /month)	V_g (m/s)	Sd_g (m/s)	P_g (W)	PD_g (W/m^2)	ED_g (kWh/m^2 /month)
Jan	4.182	0.377	225,132.7	44.789	32.248	4.192	0.331	226,852.6	45.131	32.494	4.192	0.325	226,784.9	45.117	32.485
Feb	3.815	0.418	170,960.8	34.012	24.488	3.822	0.380	171,943.5	34.207	24.629	3.822	0.372	171,854.8	34.189	24.616
Mar	3.229	0.241	103,609.9	20.613	14.841	3.235	0.218	104,258.3	20.742	14.934	3.235	0.213	104,231.1	20.736	14.930
Apr	3.174	0.258	98,444.3	19.585	14.101	3.180	0.232	99,037.3	19.703	14.186	3.180	0.227	99,009.6	19.697	14.182
May	2.788	0.211	66,693.5	13.268	9.553	2.792	0.187	67,017.6	13.333	9.600	2.792	0.184	67,003.8	13.330	9.598
Jun	2.711	0.208	61,348.1	12.205	8.787	2.719	0.171	61,870.0	12.309	8.862	2.719	0.169	61,861.1	12.307	8.861
Jul	2.826	0.230	69,512.2	13.829	9.957	2.837	0.188	70,289.2	13.984	10.068	2.837	0.185	70,276.2	13.981	10.066
Aug	2.930	0.247	77,480.9	15.414	11.098	2.939	0.211	78,141.9	15.546	11.193	2.939	0.208	78,123.9	15.542	11.190
Sep	2.379	0.236	41,470.6	8.250	5.940	2.385	0.207	41,785.6	8.313	5.985	2.385	0.203	41,771.3	8.310	5.983
Oct	2.101	0.166	28,534.8	5.677	4.087	2.106	0.143	28,759.8	5.722	4.120	2.106	0.141	28,753.5	5.720	4.119
Nov	2.562	0.241	51,782.0	10.302	7.417	2.554	0.292	51,281.6	10.202	7.346	2.553	0.280	51,212.7	10.188	7.336
Dec	3.606	0.407	144,315.4	28.711	20.672	3.607	0.399	144,446.2	28.737	20.690	3.606	0.390	144,341.0	28.716	20.675
Overall	3.017	0.697	84593.7	16.829	12.117	3.027	0.632	85409.1	16.991	12.233	3.027	0.624	85420.9	16.993	12.235

and

$$\frac{\partial LL}{\partial \sigma} = -\frac{n}{2\sigma^2} + \frac{\sum_{i=1}^{n}[\ln(V_i) - \mu]^2}{2\sigma^4} = 0, \qquad \widehat{\sigma} = \sqrt{\frac{\sum_{i=1}^{n}[\ln(V_i) - \mu]^2}{n}}. \tag{11}$$

The mean wind speed of the lognormal distribution is

$$v_l = \exp\left(\mu + \frac{\sigma^2}{2}\right), \tag{12}$$

and the standard deviation is

$$\sigma_l = \left(\exp(2\mu + \sigma^2)\left(\exp(\sigma^2) - 1\right)\right). \tag{13}$$

1.2.3. Gamma distribution

The Gamma distribution can also be applied to randomly varying data because of its flexibility. Its probability density and cumulative distribution functions are given by Ref. [31] as

$$f_g(v) = \frac{v^{k-1}\exp(-v/\theta)}{\theta^k\,\Gamma(k)}, \tag{14}$$

Table 8. Monthly mean daily wind speed, power, and energy densities for Minna.

Month	Weibull					Lognormal					Gamma				
	V_w (m/s)	Sd_w (m/s)	P_w (W)	PD_w (W/m^2)	ED_w (kWh/m^2 /month)	V_l (m/s)	Sd_l (m/s)	P_l (W)	PD_l (W/m^2)	ED_l (kWh/m^2 /month)	V_g (m/s)	Sd_g (m/s)	P_g (W)	PD_g (W/m^2)	ED_g (kWh/m^2 /month)
Jan	5.441	0.472	496,052.0	98.686	71.054	5.446	0.440	497,421.9	98.959	71.250	5.446	0.431	497,255.2	98.926	71.227
Feb	4.745	0.660	328,824.5	65.418	47.101	4.751	0.630	330,224.0	65.696	47.301	4.750	0.613	329,868.8	65.625	47.250
Mar	3.506	0.353	132,698.0	26.399	19.008	3.528	0.267	135,195.9	26.896	19.365	3.528	0.264	135,174.1	26.892	19.362
Apr	3.307	0.280	111,394.6	22.161	15.956	3.314	0.250	112,060.5	22.294	16.051	3.314	0.245	112,028.2	22.287	16.047
May	2.949	0.228	78,951.8	15.707	11.309	2.956	0.197	79,520.9	15.820	11.391	2.956	0.194	79,505.2	15.817	11.388
Jun	2.820	0.206	69,048.5	13.737	9.890	2.825	0.183	69,416.4	13.810	9.943	2.825	0.180	69,401.1	13.807	9.941
Jul	2.874	0.234	73,050.6	14.533	10.464	2.885	0.189	73,921.7	14.706	10.589	2.885	0.186	73,908.0	14.704	10.587
Aug	2.970	0.249	80,684.3	16.052	11.557	2.977	0.220	81,226.7	16.160	11.635	2.977	0.216	81,205.1	16.155	11.632
Sep	2.389	0.236	41,987.4	8.353	6.014	2.395	0.206	42,297.2	8.415	6.059	2.395	0.203	42,283.7	8.412	6.057
Oct	2.147	0.168	30,488.4	6.065	4.367	2.155	0.140	30,796.0	6.127	4.411	2.154	0.137	30,790.2	6.126	4.410
Nov	3.231	0.408	103,815.9	20.654	14.871	3.218	0.507	102,562.9	20.404	14.691	3.215	0.482	102,262.4	20.344	14.648
Dec	4.763	0.587	332,577.0	66.164	47.638	4.756	0.610	331,146.1	65.879	47.433	4.754	0.593	330,777.9	65.806	47.380
Overall	3.424	1.101	123658.2	24.601	17.712	3.422	0.991	123474.9	24.564	17.686	3.427	0.982	123987.5	24.666	17.759

and

$$F_g(v) = \frac{[(\Gamma\, v/\theta)]^k}{\Gamma(k)}, \int_0^v t^{k-1} \exp^{-\frac{t}{g}} dt \tag{15}$$

Here, θ and k are the scale and shape parameters, respectively. The scale parameter represents the mean time between events and stretches the distribution along the horizontal axis; a larger θ increases the spread or variance. The shape parameter k represents the number of events or occurrences modeled. Increasing k increases the peak and decreases the skewness [31].

The parameters were computed using maximum log-likelihood estimation. The likelihood function for the Gamma distribution is given in the source manuscript as

$$L(k,\theta \mid V_i) = \left[\frac{\theta^k}{\Gamma(k)}\right]^n \prod_{i=1}^{n}(V_i)^{k-1} \times \exp\left[-\theta \sum_{i=1}^{n} V_i\right]. \tag{16}$$

Taking the natural logarithm gives

$$LL(k,\theta \mid V_i) = n[k\ln(\theta) - \ln\Gamma(k)] + (k-1)\sum_{i=1}^{n}\ln(V_i) - \theta\sum_{i=1}^{n}V_i. \tag{17}$$

The LL function is maximized with respect to k and θ:

$$\frac{\partial LL}{\partial k} = n\left[\ln(\theta) - \frac{\partial}{\partial k}\Gamma(k)\right] + \sum_{i=1}^{n}\ln(V_i) = 0, \tag{18}$$

$$\frac{\partial LL}{\partial \theta} = n\frac{k}{\theta} - \sum_{i=1}^{n}V_i = 0, \tag{19}$$

and

$$\frac{k}{\theta} = \frac{1}{n}\sum_{i=1}^{n}V_i = \mu. \tag{20}$$

Substituting the expression for θ from equation (20) into equation (18) gives

$$n\left[\ln(k) - \ln(\mu) - \frac{\partial}{\partial k}\ln\Gamma(k) + \frac{1}{n}\sum_{i=1}^{n}\ln(V_i)\right] = 0. \tag{21}$$

Here, $\frac{\partial}{\partial k}\ln\Gamma(k)$ is the digamma function. Equation (21) is solved graphically by plotting its bracketed expression against k; the zero crossing gives the optimal value of k. The mean wind speed for the Gamma distribution is [19]

$$v_g = k\theta, \tag{22}$$

and its standard deviation is given in the source manuscript as

$$\sigma_g = k\theta^2. \tag{23}$$

The actual wind power P_a of wind flowing at mean speed v through a rotor with swept area A, and the corresponding wind-power density, are

$$P_a(v) = \frac{1}{2}\rho A v^3 C_p, \tag{24}$$

$$PD_a(v) = \frac{P_a(v)}{A}. \tag{25}$$

The monthly wind-energy density is [15]

$$ED_a = \frac{P_a(v)}{A}T, \tag{26}$$

where $\rho = 1.225$ kg/m^3 is the sea-level air density, $A = \pi r^2$ is the swept area of the model turbine rotor, $r = 40$ m is the blade radius, v is the mean wind speed at the location, and C_p is the power coefficient. The Betz limit has a maximum value of 0.593; for practical three-bladed turbines, the value generally ranges from 0.35 to 0.45 because of blade drag, tip losses, gearbox losses, and related effects [32]. In this study, $C_p = 0.4$, and T is one 30-day month (720 h).

The proposed model-turbine height is 50 m above ground. Wind speeds were converted to this height using [25]

$$\frac{v_2}{v_1} = \left(\frac{h_2}{h_1}\right)^{\alpha}, \tag{27}$$

where v_1 and v_2 are wind speeds at heights h_1 and h_2, respectively, and α is the friction coefficient. For neutral and stable conditions, $\alpha = 0.1423$. For the MERRA-2 data, $h_1 = 10$ m and $h_2 = 50$ m. Thus, v_1 is the wind speed measured at 10 m, and v_2 is the wind speed estimated at 50 m using equation (27). r is the model turbine rotor radius and it is set as 40 m, while A is the swept area and is given by $A = \pi r^2 = 5026.55m^2$.

The wind powers for the Weibull, lognormal, and Gamma distributions at their respective mean wind speeds are [19]

$$P_w(v) = \frac{1}{2}\rho A v_w^3 = \frac{1}{2}\rho A c^3 \Gamma\left(1 + \frac{3}{k}\right), \tag{28}$$

$$P_l(v) = \frac{1}{2}\rho A v_l^3 = \frac{1}{2}\rho A \exp\left[3\left(\mu + \frac{\sigma^2}{2}\right)\right], \tag{29}$$

and

$$P_g(v) = \frac{1}{2}\rho A v_g^3 = \frac{1}{2}\rho A k^3 \theta^3. \tag{30}$$

The corresponding wind-power densities are [19]

$$p_w(v) = \frac{1}{2}\rho c^3 \Gamma\left(1 + \frac{3}{k}\right), \tag{31}$$

$$p_l(v) = \frac{1}{2}\rho \exp\left[3\left(\mu + \frac{\sigma^2}{2}\right)\right], \tag{32}$$

and

$$p_g(v) = \frac{1}{2}\rho k^3 \theta^3. \tag{33}$$

1.3. GOODNESS OF FIT AND MODEL-VALIDATION CRITERIA

The goodness of fit and predictive accuracy of the PDFs were evaluated using the coefficient of determination, R^2, and RMSE. A lower RMSE indicates a more accurate fitted-model output [33]. The R^2 and RMSE expressions used in the source manuscript are [10]

$$R^2 = \frac{\sum_{i=1}^{N}(F_i - \bar{v})^2 - \sum_{i=1}^{N}(F_i - F_d)^2}{\sum_{i=1}^{N}(F_i - \bar{v})^2}, \tag{34}$$

and

$$RMSE = \left[\frac{1}{N}\sum_{i=1}^{N}(F_i - F_d)^2\right]^{1/2}, \tag{35}$$

where $\bar{v}$ is the mean value of the observed parameter, F_i is the cumulative probability of the observed wind speed, F_d is the cumulative probability predicted by the Weibull, lognormal, or Gamma distribution, and N is the time-series length.

2. STUDY AREA AND DATA SOURCE

2.1. STUDY AREA

The study area is North Central Nigeria, and the sampled cities are Makurdi, Lokoja, Abuja, Jos, Lafia, and Minna. The region lies between latitudes $7°00'$ and $11°30'$N and longitudes $4°00'$ and $11°00'$E. Its climate is characterized by wet and dry seasons: the rainy season occurs from April to October, and the dry season occurs from November to March. Farming and fishing are important livelihoods because the Niger and Benue rivers and their tributaries traverse the region. Table 1 lists the sampled locations, geographical coordinates, and elevations obtained from online location services [34, 35], and Figure 1 shows their positions in Nigeria.

The meteorological data comprise daily average wind speeds obtained from the Modern-Era Retrospective Analysis for Research and Applications, Version 2 (MERRA-2), produced by the National Aeronautics and Space Administration (NASA) [36]. The spatial resolution is $0.25° \times 0.25°$. The data cover 20 years, from 2001 to 2020, and the source contained no missing observations.

3. RESULTS AND DISCUSSION

3.1. DAILY MEAN WIND-SPEED CHARACTERISTICS USING DIFFERENT PDFS

Table 2 presents the daily mean wind-speed characteristics obtained using the Weibull (k, c), lognormal (μ, σ), and Gamma (K, θ) distributions. Across the sampled locations, k, c, μ, σ, K, and θ range from 5.950 to 6.580, 19.570 to 20.945, 2.871 to 2.936, 0.255 to 0.289, 15.170 to 18.874, and 1.025 to 1.278, respectively. The large Weibull k and c values indicate left-skewed distributions with broad spreads and lower peaks. The values also indicate relatively uniform wind speeds and windy conditions in the study area [15]. These characteristics suggest that the region has potential for wind-power generation.

Table 2 further indicates that the Weibull scale parameter generally increases with altitude, as wind speed also increases from Lokoja to Jos, in accordance with the wind power law (Figure 2a). Conversely, the shape parameter generally decreases with altitude (Figure 2b). These relationships are weak and may be affected by local topography and infrastructure, which influence wind turbulence and friction [37]. The observed patterns indicate that topography and elevation influence wind-speed characteristics and energy potential. One possible explanation for the variation in k and c with altitude is the wind-extrapolation law in equation (27). Mean wind speed increases with altitude as surface roughness and obstruction by trees, buildings, and terrain decrease. Its variability or dispersion, represented by c, also increases because the flow is less obstructed. Conversely, skewness, represented by k, may decrease because turbulence is reduced and atmospheric-layer stability increases [25].

Based on higher R^2 and lower RMSE values, the Weibull distribution performed best, followed by the Gamma and lognormal distributions. Thus, the Weibull distribution is the most suitable of the three models for wind-speed data from North Central Nigeria. Similar variation patterns occur in the probability density distributions and cumulative probability density distributions of monthly mean wind speed for the study areas (Figures 3 and 4). The superior performance of the Weibull distribution con-

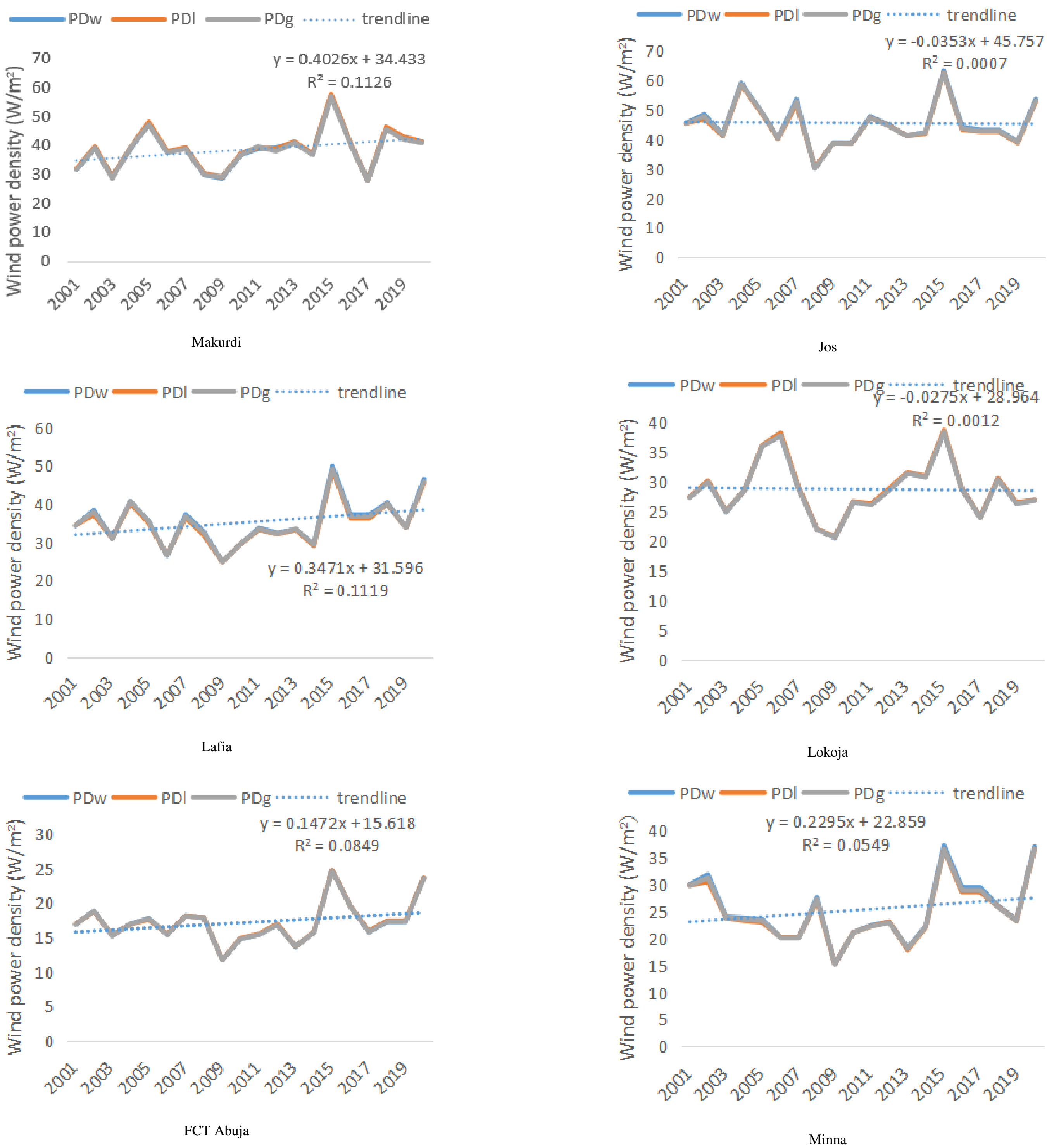

Figure 6. Annual mean wind-power density in Makurdi, Jos, Lafia, Lokoja, Abuja, and Minna using the three probability distribution functions.

trasts with the Gamma distribution recommended for Bitlis on the basis of R^2, RMSE, and the Kolmogorov–Smirnov test [19], indicating that the most suitable PDF may vary among study areas. Weibull, lognormal, and Gamma PDFs are widely used in wind-speed modeling; among them, the Weibull distribution has frequently been preferred [16–18, 37].

3.2. VARIATION IN MONTHLY MEAN DAILY WIND SPEED

Figure 5 shows that Lokoja and Makurdi have similar monthly wind patterns, with two clear peaks in April and August. Mean wind speed reaches 5.0 m/s in Makurdi and 4.7 m/s in Lokoja in April, and 4.1 and 3.9 m/s, respectively, in August. Both locations have their lowest mean wind speed in November, at approximately 2.5 m/s. The similarity may be associated with the proximity of the stations to the Benue and Niger rivers, although

Makurdi has a higher wind regime than Lokoja. Lafia, Abuja, and Minna also show similar wind patterns, with their highest mean wind speeds near the beginning and end of the year. In January, the mean wind speeds reach 5.8, 4.2, and 5.5 m/s, respectively. The values generally decrease during the year, with a small peak in August at 3.2, 3.0, and 3.0 m/s, respectively.

Lafia, Abuja, and Minna are relatively close and have broadly similar rocky topography. By contrast, the monthly pattern for Jos is approximately parabolic, with the highest mean wind speed, 6.1 m/s, in January and the lowest, 3.0 m/s, in September. This distinctive pattern may be associated with the high elevation of Jos relative to the other locations. Overall, monthly wind-speed patterns differ among stations, potentially because of water bodies, elevation, geographical location, and topography.

The mean wind speeds in Makurdi, Jos, Lafia, Lokoja, Abuja, and Minna are 3.963 ± 0.830, 4.214 ± 1.182, 3.826 ± 1.089, 3.578 ± 0.722, 3.027 ± 0.634, and 3.427 ± 1.036 m/s, respectively. Thus, the mean wind speed decreases in the order Jos, Makurdi, Lafia, Lokoja, Minna, and Abuja. Wind speeds in the region range from 2.5 to 6.1 m/s. The minimum wind speed required for effective wind-turbine operation is generally 3.0–4.0 m/s [15]; therefore, much of the observed range indicates potential for wind-energy use. Reported wind speeds for southern, southwestern, and northern Nigeria are 3.0–3.5, 2.9–5.8, and 4.0–7.5 m/s, respectively [14], confirming regional variation across the country.

3.3. MONTHLY MEAN DAILY POWER AND ENERGY DENSITIES

The PDF estimates in Tables 3–8 give average monthly energy densities of 27.664, 27.574, and 27.447 kWh/m^2/month for Makurdi; 33.010, 32.928, and 33.006 kWh/m^2/month for Jos; 24.649, 24.697, and 24.711 kWh/m^2/month for Lafia; 20.254, 20.251, and 20.212 kWh/m^2/month for Lokoja; 12.117, 12.233, and 12.235 kWh/m^2/month for Abuja; and 17.712, 17.686, and 17.759 kWh/m^2/month for Minna, as obtained from the Weibull, lognormal, and Gamma distributions, respectively. The Weibull distribution gives the highest average energy density for Makurdi, Jos, and Lokoja, whereas the Gamma distribution gives slightly higher values for Lafia, Abuja, and Minna. The lognormal distribution gives the lowest value for most of the locations. These differences indicate that model performance varies among study areas.

The observed average energy densities support the viability of wind energy as an alternative source in the region. In increasing order, the values are 12.235, 17.759, 20.254, 24.711, 27.664, and 33.010 kWh/m^2/month for Abuja, Minna, Lokoja, Lafia, Makurdi, and Jos, respectively. Deploying wind energy for processing and storing agricultural produce could help reduce food losses and insecurity. Policies supporting appropriate wind-power installations in the region are therefore recommended. Such development could contribute to economic growth and reduce food wastage. Further studies in other regions of Nigeria are recommended to provide a more comprehensive national assessment.

3.4. TREND IN ANNUAL MEAN WIND-POWER DENSITY

The annual mean wind-power density is relatively stable across the study area, with weak increasing trends at most locations. Jos and Lokoja show weak decreasing trends; however, all trends are statistically weak, with R^2 values close to zero (Figure 6). The variation reflects the stochastic nature of wind and may also be influenced by climatic variability [38].

4. CONCLUSION

The principal conclusions are as follows:

1. Based on higher R^2 and lower RMSE values, the PDFs rank from best to worst as Weibull, Gamma, and lognormal.
2. The PDF that most effectively models wind-energy potential may vary among study areas.
3. Wind-speed variation in the region may be influenced by water bodies, including the Niger and Benue rivers, as well as elevation, location, and topography.
4. The monthly mean daily wind-speed range of 2.5–6.1 m/s and the observed wind-speed characteristics indicate wind-energy potential in the region.
5. The average monthly energy densities indicate that wind energy could provide an alternative energy source.
6. Wind-energy potential increases in the order Abuja, Minna, Lokoja, Lafia, Makurdi, and Jos.
7. An exponential rather than a linear model is recommended for determining the Weibull scale and shape parameters to improve the fit.

DATA AVAILABILITY

The data supporting the findings of this study are available from the corresponding author upon reasonable request.

DECLARATION OF COMPETING INTEREST

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this manuscript.

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References

[1] Worldometer, "Nigeria Population (Live)", (2026). https://www.worldometers.info/world-population/nigeria-population.

[2] M. C. Ndukwu, D. I. Onwude, L. Bennamoun, F. I. Abam, M. Simo-Tagne, I. T. Horsfall & T. A. Briggs, "Nigeria's energy deficit: The challenges and eco-friendly approach in reducing the energy gap", International Journal of Sustainable Engineering **14** (2021) 442. https://doi.org/10.1080/19397038.2020.1842546.

[3] World Bank, "Nigeria to improve electricity access and services to citizens", 5 February 2021. Available online: https://www.worldbank.org/en/news/press-release/2021/02/05/nigeria-to-improve-electricity-access-and-services-to-citizens.

[4] M. A. Alsaad, "Wind energy potential in selected areas in Jordan", Energy Conversion and Management **65** (2013) 704. https://doi.org/10.1016/j.enconman.2011.12.037.

[5] J. G. Leishman, *Principles of Helicopter Aerodynamics*, Cambridge University Press, New York, USA, 2006, pp. 17–25.

[6] S. O. Amadi & S. O. Udo, "Analysis of trends and variations of monthly mean wind speed data in Nigeria", Journal of Applied Physics (IOSR-JAP) **7** (2015) 31. https://doi.org/10.9790/4862-07413141.

[7] A. Allouhi, O. Zamzoum, M. R. Islam, R. Saidur, T. Kousksou, A. Jamil & A. Derouich, "Evaluation of wind energy potential in Morocco's coastal regions", Renewable and Sustainable Energy Reviews **72** (2017) 311. https://doi.org/10.1016/j.rser.2017.01.047.

[8] Z. H. Hulio, W. Jiang & S. Rehman, "Technical and economic assessment of wind power potential of Nooriabad, Pakistan", Energy, Sustainability and Society **7** (2017) 35. https://doi.org/10.1186/s13705-017-0137-9.

[9] O. M. Kam, S. Noel, H. Ramenah, P. Kasser & C. Tanougast, "Comparative Weibull distribution methods for reliable global solar irradiance assessment in France areas", Renewable Energy **165** (2021) 194. https://doi.org/10.1016/j.renene.2020.10.151.

[10] D. A. Fadare, "Statistical analysis of wind energy potential in Ibadan, Nigeria, based on Weibull distribution function", Pacific Journal of Science and Technology **9** (2008) 110. Available online: https://repository.ui.edu.ng/bitstreams/5a9d0189-507b-45f7-a0ae-4b43c7b8d656/download.

[11] F. C. Odo & G. U. Akubue, "Comparative assessment of three models for estimating Weibull parameters for wind energy applications in a Nigerian location", International Journal of Energy Science **2** (2012) 22. Available online: www.ijesci.org.https://www.airitilibrary.com/Article/Detail?DocID=P20150611015-201508210018-201508210018-22-25.

[12] E. C. Odo, S. U. Offiah & P. E. Ugwoke, "Weibull distribution-based model for prediction of wind potential in Enugu, Nigeria", Advances in Applied Sciences Research **3** (2012) 1202. Available online: https://www.pelagiaresearchlibrary.com.https://www.academia.edu/67789646/Weibull_distribution_based_model_for_prediction_of_wind_potential_in_Enugu_Nigeria.

[13] F. Fazelpour, N. Soltani & M. A. Rosen, "Wind resource assessment and wind power potential for the city of Ardabil, Iran", International Journal of Energy and Environmental Engineering **6** (2015) 431. https://doi.org/10.1007/s40095-014-0139-8.

[14] N. A. Udo, A. I. Oluleye & K. A. Ishola, "Investigation of wind power potential over some selected coastal cities in Nigeria", Innovative Energy & Research **6** (2017) 156. https://www.researchgate.net/publication/319153731_Investigation_of_Wind_Power_Potential_over_Some_Selected_Coastal_Cities_in_Nigeria.

[15] M. O. Audu, A. S. Terwase & B. C. Isikwue, "Investigation of wind speed characteristics and its energy potential in Makurdi, North Central Nigeria", SN Applied Sciences **1** (2019) 178. https://doi.org/10.1007/s42452-019-0189-x.

[16] E. Dokur & M. Kurban, "Wind speed potential analysis based on Weibull distribution", Balkan Journal of Electrical and Computer Engineering **3** (2015) 231. https://dergipark.org.tr/tr/download/article-file/458542.

[17] U. M. Nubwa, D. T. Ogbaka & J. K. Julius, "Analysis of wind speed based on Weibull model and solar radiation potential for electricity generation in Mubi, Nigeria", International Journal of Research and Scientific Innovation **7** (2020) 10. Available online: https://www.rsisinternational.org.

[18] U. C. Ben, A. E. Akpan, C. C. Mbonu & C. H. Ufuafuonye, "Integrated technical analysis of wind speed data for wind energy potential assessment in parts of southern and central Nigeria", Cleaner Engineering and Technology **2** (2021) 100049. https://doi.org/10.1016/j.clet.2021.100049.

[19] H. E. Akyuz & H. Gamgam, "Statistical analysis of wind speed data with Weibull, lognormal and Gamma distributions", Cumhuriyet Science Journal **38** (2017) 68. https://doi.org/10.17776/csj.358773.

[20] A. J. Saavedra Montes, P. A. Amaya Martínez & E. I. Arango Zuluaga, "A statistical analysis of wind speed distribution models in the Aburrá Valley, Colombia (Weibull, lognormal, Gamma and Rayleigh distributions)", CT&F – Ciencia, Tecnología y Futuro **5** (2014) 121. https://doi.org/10.29047/01225383.36.

[21] S. O. Olayinka, "Assessment of wind energy resources for electricity generation using WECS in North-Central region, Nigeria", Renewable and Sustainable Energy Reviews **15** (2011) 1968. https://doi.org/10.1016/j.rser.2011.01.001.

[22] G. S. Alabi & P. K. H. Olulupe, "Review of wind energy potentials and the possibility of wind energy grid integration in Nigeria", International Journal of Latest Research in Engineering and Technology **4** (2018) 59. Available online: http://www.ijlret.com/Papers/Vol-04-issue-05/10.B2018060.pdf.

[23] C. M. Grinstead & J. L. Snell, *Conditional probability-discrete conditional probability*, in Introduction to Probability (2nd ed.), American Mathematical Society (2003). p. 133.

[24] E.A. Nketiah, L. Chenlong, J. Yingchuan, B. Dwumah, "Parameter estimation of the Weibull Distribution, Comparison of the Least-Squares Method and the Maximum Likelihood estimation", International Journal of Advanced Engineering Research and Science (IJAERS) **8** (2021) 210. https://dx.doi.org/10.22161/ijaers.89.21.

[25] S. M. Lawan, W. A. Abidin, T. Masri, W. Y. Chai & A. Baharun, "Wind power generation via ground wind station and topographical feed-forward neural network (T-FFNN) model for small-scale applications", Journal of Cleaner Production **143** (2017) 1246. https://doi.org/10.1016/j.jclepro.2016.11.157.

[26] H. Jiang, J. Wang, Y. Wong & H. Lu, "Comprehensive assessment of wind resources and the low-carbon economy: An empirical study in the Alxa and Xilin Gol leagues of Inner Mongolia, China", Renewable and Sustainable Energy Reviews **50** (2015) 1304. https://doi.org/10.1016/j.rser.2015.05.082.

[27] E. A. Nketiah, L. Chenlong, J. Yingchuan & B. Dwumah, "Parameter estimation of the Weibull distribution: Comparison of the least-squares method and the maximum likelihood estimation", International Journal of Advanced Engineering Research and Science **8** (2021) 210. https://doi.org/10.22161/ijaers.89.21.

[28] N. Aras, U. Erisoglu & H. D. Yıldızay, "Optimum method for determining Weibull distribution parameters used in wind energy estimation", Pakistan Journal of Statistics and Operation Research **16** (2020) 635. https://doi.org/10.18187/pjsor.v16i4.3456.

[29] S. Kang, A. Khanjari, S. You & J.-H. Lee, "Comparison of different statistical methods used to estimate Weibull parameters for wind speed contribution in nearby and offshore sites, Republic of Korea", Energy Reports **7** (2021) 7358. https://doi.org/10.1016/j.egyr.2021.10.078.

[30] J. Moral de la Rubia, "Lognormal distribution for social researchers: A probability classic", International Journal of Psychology and Counselling **16** (2024) 10. https://journal-backups.lon1.digitaloceanspaces.com/uploads/main/article/29e9de572216.pdf.

[31] U. Eric, M.O. Oti, C.E. Francis, "A Study of Properties and Applications of Gamma Distribution", African Journal of Mathematics and Statistics Studies **4** (2021) 52. https://doi.org/10.52589/AJMSSMR0DQ1DG.

[32] P. N. Lecanu, J. Bréard, D. Mouazé. "Theoretical calculation of wind (Or water) turbine considering kinetic and potential energy to exceed the Betz limit", HAL Open Science (2023). https://hal.science/hal-01982516v12.

[33] S. H. Shami, J. Ahmad, R. Zafar, M. Haris & S. Bashir, "Evaluating wind energy potential in Pakistan's three provinces, with proposal for integration into national power grid", Renewable and Sustainable Energy Reviews **53** (2016) 408. https://doi.org/10.1016/j.rser.2015.08.052.

[34] Latitudelongitude.org, "Online latitude and longitude finder" (2024). Available online: https://latitudelongitude.org/.

[35] Altitude-maps.com, "Get your altitude, longitude and latitude with Google Maps" (2024). Available online: https://www.altitude-maps.com/.

[36] R. Gelaro, W. McCarty, M. J. Suarez, R. Todling, A. Molod, L. Takacs, C. Randles, A. Darmenov, M. G. Bosilovich, R. Reichle, K. Wargan, L. Coy, R. Cullather, C. Draper, S. Akella, V. Buchard, A. Conaty, A. da Silva, W. Gu, G. K. Kim, R. Koster, R. Lucchesi, D. Merkova, J. E. Nielsen, G. Partyka, S. Pawson, W. Putman, M. Rienecker, S. D. Schubert, M. Sienkiewicz & B. Zhao, "The modern-era retrospective analysis for research and applications, version 2 (MERRA-2)", J. Clim. **30** (2017) 5419. https://doi.org/10.1175/JCLI-D-16-0758.1.

[37] S. Tiwari & N. Gupta, "Weibull parameter estimate for wind energy at different elevations using graphical method", International Journal of Scientific & Technology Research **8** (2019) 2921. Available online: https://www.researchgate.net/publication/373658439_Weibull_parameter_estimate_for_Wind_Energy_at_Different_elevations_using_Graphical_Method.

[38] X. Zeng, Chaos Theory and Its Application in the Atmosphere, Paper 504, Department of Atmospheric Science, Colorado State University, Fort Collins, USA, 1992, p. 5. Available online: https://mountainscholar.org/items/5c08ac0f-160b-468f-a3f7-588f9ef93632.