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Research Article

Domestic Wind Energy Planning for Deprived Communities in the Tropics: A Case Study of Nigeria

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Abstract. Despite the notable inventions in solar energy, it is still too high for standalone users from developing countries. For example, it cost $2200 to provide power for a two-bedroom apartment while the average citizen lives below the country's poverty line of $381.75 per year. The use of fossil fuel generators remains cheaper, except there is an affordable energy option for the average populace. The objective of this study is to investigate the wind energy potential for domestic or standalone use in Nigeria. It is proposed that the domestic wind turbine will be relatively cheap for adoption. Hence, there is the need to wholistic examine the prospects of wind energy generation in Nigeria. Though previous studies had been carried out, none has been wholistic as presented in this research work. Forty years wind speed and wind direction dataset, i.e., 1980-2020, was obtained from the Modern-Era Retrospective analysis for Research and Applications (MERRA). The analysis of the wind energy potential across the research locations was considered using five sampling techniques, i.e., considering the general statistics of the forty years dataset; considering ten years in an evenly distributed pattern and accruable wind energy across the nation. It was observed that the early wet season (MAM) is the most unstable among the seasons. Also, sudden multi-directionality of the wind vectorization within forty years was observed. This event is ascribed to evidence of climate change to wind energy generation. Wind energy generation prospect was seen to be generally sustainable and reliable with SON, MAM, DJF and JJA having energy distribution of 325-950 kWh, 539-1700 kWh, 161-650 kWh and 761-3650 kWh respectively. Despite the variation of energy generation over the years within all seasons over Nigeria, it was found that it is predictable and can be optimized using various technological solutions.

Keywords: Wind energy, renewable energy, wind speed, wind direction, wind

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1. Introduction

Wind energy generation capacity in some countries of the world has reached the range of Giga-Watts of electricity (Omole and Ndambuki, 2014) some countries in Africa have started generating a few megawatts for national use while others, mainly West African countries, are yet to start (Ajayi, 2013). South Africa has the highest wind power capacity in Africa, with a generation capacity of 1053 MW as of the end of 2015 (GWEC, 2016). In a review of previous works on wind profile characteristics of Nigeria (Fagbenle, 1980; Ojosu, and Salawu, 1990a; Ojosu, and Salawu, 1990b), Ajayi *et al.,* (2014) reported that the North had twice mean wind speed recorded in the South and Sokoto, with its high latitude, had the highest mean speed with the possibility of generating power 97 MWh/yr. Okoro *et al.* (2007) recommended that wind power generating plants be installed at Plateau and Sokoto States sites, which have shown promising results in studies. For example, Heipany in Plateau state is reported to have a maximum power intensity of 14.23 W/m^2 of the available 24.00 W/m^2 that can be harnessed. A review of recent studies (Fadare, 2010; Fagbenle *et al*., 1980) has generated promising results of monthly mean wind speed of 0.9 to 13.1 m/s and 4.35 and 6.33 m/s in different places (Ajayi *et al*., 2014). Despite the existence of an energy policy in Nigeria, its implementation is moving at snail's speed. Currently, wind power projects that exist in Nigeria are a 10-kW power station at Danjawa village, a windmill for pumping water in Kaduna, a 5-kW aero-generator in Sayya, Gidan Gada Sokoto, a 10 MW wind farm in Katsina, and two 215 kW wind turbines being developed by the Usman Danfodio University, Sokoto (Fagbenle *et al.,* 2011). Oyedeji *et al.* (2018) reported a wind speed range of 6 m/s to 8m/s for southern Nigeria's northern and mountainous parts. Twelve states had wind speeds of between 2.5 m/s and 4.0 m/s, fifteen states had 4 m/s and above, and ten States had 6m/s wind speed. Some of the challenges hindering the development of wind energy in Nigeria are inadequate funding from the government, lack of training for technical personnel resulting in the absence of technical knowledge. As a result, private investors are discouraged from investing in wind energy generation.

Though wind energy is a clean energy source, some of its environmental impacts, such as its possible negative impact on the nearby animal population, noise, and visual impact, particularly for some individuals and groups, have raised onshore farms. Some individuals are against the harnessing of wind to generate energy due to claims that noises made by turbines can cause specific health issues such as cancer, which have been debunked by other reports (Chapman and George,

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2013; Crichton, 2014). Wind farms are usually located far from consumer markets; as a result, the distribution cost will invariably add to the unit cost of its energy price. Also, wind farms require multiple turbines to produce as much electricity as a single fossil fuel power plant. Another challenge to wind energy generation is intermittency, i.e., periods of irregular wind or absence of wind, reducing its generating capacity (Farris, 2019). This challenge of irregular winds has resulted in establishing offshore power plants as more robust and more uniform wind is usually experienced at sea (Leung and Yang, 2012). Also, more giant wind turbines can be used offshore, thereby reducing the operation and maintenance costs. Wind turbines require regular maintenance and repair procedures to ameliorate damage due to environmental conditions, manufacturing defects, and mechanical loads (Carrete *et al.,* 2012). Its maintenance requires specialized personnel and technology (Ciang, 2008).

The cost of installing and operating offshore wind turbines is relatively higher than onshore wind farms, but offshore wind farms tend to have higher capacity factors (IRENA, 2018). This idea is due to the evident need for additional operation and maintenance costs associated with obtaining customized vessels, transmission systems, weather monitoring (Adeoye, 2014; Li *et al.,* 2010; Bilgili, 2011), and foundation requirements for offshore wind turbines. The foundation types used for offshore wind farms include floating, multi-pile, gravity, or single-pile structures (Dicorato, 2011). As of 2010, the cost of installing an onshore wind farm typically ranges between USD1800/kW and USD2200/kW, while offshore farms range between USD4000/kW to USD4500/kW.

The stages for the establishment of offshore wind turbines, according to Effioma *et al.,* (2016), are predevelopment and consenting (P&C), procurement and acquisition (P&A), installation and commissioning (I&C), operation and maintenance (O&M) and decommissioning and disposal (D&D). For a 500MW offshore wind turbine farm in the coastal area around Calabar, Cross River State. Each stage estimated cost was USD316,905,112.5 for P&C, USD1,476,063,983 for P&A, USD471,089,968.4 for I&C, USD123,814,927.7 per year for O&M and USD316,202,607.3 for D&D (Lucena and Lucena, 2019).

Countries like Germany, the USA, and China that had hitherto depended on coal now rely on wind energy, becoming relatively cheaper than coal-generated energy and fossil fuel. Wind power frees local businesses from dependence on imports from potentially unstable regions and is excellent financial protection against future increases in energy prices (Okoro *et al.*, 2007). South Africa is currently ranked top in wind energy generation in the continent as its most tremendous wind energy potential lies in the coastal areas (Matha *et al*., 2014). According to Ajayi *et al.* (2014), Lagos has a very high potential for harvesting wind power. In Nigeria, the Atlantic Ocean is a good spot for offshore wind parks where wind energy can be generated to meet Lagos's high demand for energy due to industrialization and high population density. It will also provide jobs for the teeming population of unemployed graduates and technicians flooding Lagos who can be employed in the offshore wind industry and its value chain. Floating offshore wind turbines (FOWT) is a promising technology for electricity generation offshore (IRENA, 2012; Madariaga *et al*., 2012). Ajayi *et al.* (2014) reported that the cost of generating electricity from wind using turbine models in Lagos is estimated at €3,033,617.2 for Lagos Island, Ikeja, and Marina respectively. The highest average power per annum will be 2.1×106 kWh from the Lagos Island site.

From literature, the fastest way to solve the massive energy deficit in the third world is via a standalone route. Despite the massive innovation in solar energy device, it is still costly to purchase or maintain. For example, it costs $2200 to provide power for a two-bedroom apartment while the average citizen lives below the country's poverty line of $381.75 per year (World Bank, 2020). Since the average price of a domestic wind turbine is about $395 (Ebay, 2021), there is the need to re-examine the current wind energy potential using multiple reliable techniques. Past research had focused on industrial or large-scale wind generation (Torralba *et al.,* 2017; Rakhshani *et al.*, 2019; Haryanto *et al.,* 2021), but this research is mainly on small-scale wind generation to boost standalone based on cost and affordability. Running a small-scale wind energy generation scheme for the standalone user may be much complicated than the large-scale wind energy generation. Policy formulation that takes care of importation of new technology wind turbine for small scale energy generation; enabling laws that attract foreign and local investors; technical guidelines for small-scale wind turbine users; evaluation and monitoring activities; proficient urban planning so that users can maximally benefit the wind flow; commercialization of unused energy generated from standalone users. In this study, the objective is to establish domestic wind energy supply potentials to enlighten public and private investors and potential users on the prospect of small-scale wind energy generation.

2. Methodology

The methodology was divided into two main sections, i.e., data sampling and analytics techniques; and peculiarity of research location. This information is salient as it would guide why the specific statistical and logical decision was made in the discussion. Thirty-seven locations were considered across Nigeria.

2.1. Research Location

Thirty-seven locations across the provinces in Nigeria were considered. There are five climatic zones (i.e., coastal, Sahel, guinea savannah, Sudan, and tropical rain forest) across Nigeria, as presented in Figure 1. Nigeria has two main seasons, i.e., wet and dry seasons. In this study, the two seasons were further subdivided into four, i.e., early dry season (September, October, and November (SON)), late dry season (December, January, and February (DJF)), early wet season (March, April, and May (MAM)), and late wet season (June, July, and August (JJA)). Two migrating air masses drive all these types of seasons. The dry season is controlled by the dry tropical continental air mass of the northern high-pressure system, which gives rise to the dry, dusty, Harmattan winds which blow from the Sahara. The wet season is driven by the moisture-laden, tropical maritime or equatorial air mass, producing southwest winds. The effect of the air masses differs in all seasons. Hence, the thirty-seven locations were evenly distributed across the climatic zones to understand its implication to wind energy generation in Nigeria.

2.2. Data Sampling and Analytics Techniques

The wind speed and direction dataset were downloaded from Modern-Era Retrospective analysis for Research and Applications (MERRA). Wind speed and the wind direction were measured at 10 m above ground (0 means from North, 90 from East, 180 means from south, and 270 means from west). The height at which the wind speed was measured becomes necessary as the focus of the research was on domestic use. About 77% of domestic buildings in Nigeria are < 10 m, i.e., making this dataset appropriate for the study. Dataset on MERRA is obtained at 0.5° × 0.66° grid with 72 layers. MERRA dataset is the combination of the land surface (MERRA-Land) and atmospheric aerosols (MERRAero) (Rienecker *et al*., 2011).

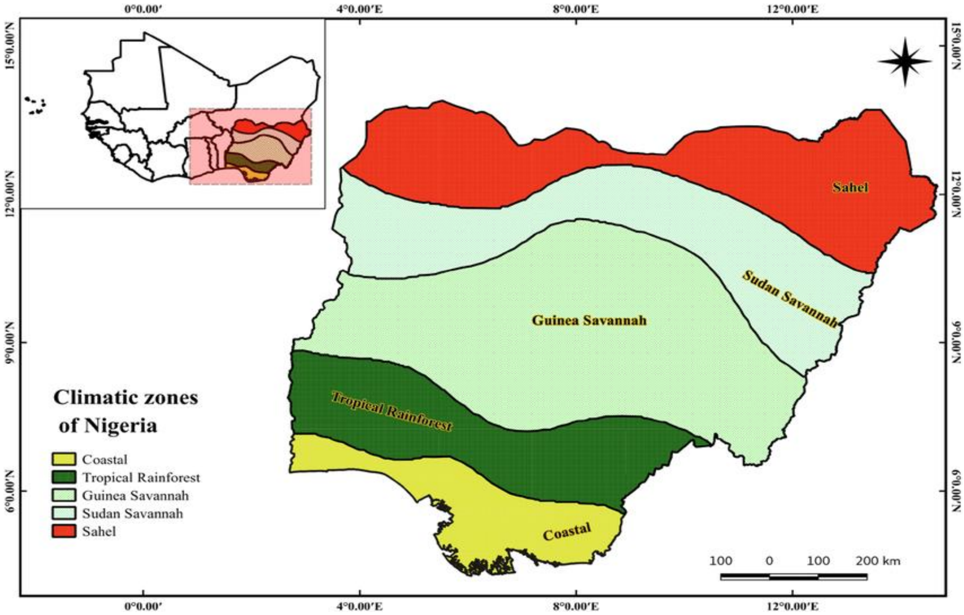

Fig 1. Climatic zones in Nigeria (Ragatoa et al., 2019)

The dataset was measured at intervals of a minute; hence, the size of the dataset is about 19,699,200 cells each for the wind speed and wind direction parameters. The analysis of the wind energy potential across the research locations was considered using five sampling techniques, i.e., considering the general statistics of the forty years dataset; considering ten years in an evenly distributed pattern (1980, 1990, 2000, 2010, and 2020); considering seasonal changes across the selected years; considering the averages for a group of ten years were calculated e.g., 1980-1989, 1990-1999, 2000-2009, and 2010-2020; and considering statistics of hilly locations.

The normality and outliers of the datasets were statistically determined to ascertain two factors, i.e., the effect of climate change on the measured dataset; and the possibility of storm-prone areas as their data is expected to have spikes etc. More so, the normality of the data would aid the type of statistical treatment used to analyze the dataset. The general statistics include mean, mode, median, maximum, minimum, variance, standard deviation, skew, and kurtosis. The specialized statistical tools used include analysis of variance (ANOVA) with a posthoc of Least Significant Difference (LSD), Dunnett-C, and Games-Howell test as presented in equations (1-3) respectively. Equation 1 presents the formular for the Least Significant Difference (Glen, 2022):

$$LSD_{A,B} = t_{0.05/2DFW}\sqrt{MSW\left(\frac{1}{n_A}+\frac{1}{n_B}\right)} \quad (1)$$

Where t is the critical value from the t-distribution table, MSw is the mean square within, obtained from the results of your ANOVA test, and n is the number of scores used to calculate the means.
Equation 2 presents the formular for Dunnett-C (Zach, 2020):

$$D_C = t_d\sqrt{\frac{2MSW}{n}} \quad (2)$$

Where td is the value found in Dunnett's Table for a given alpha level, number of groups, and group sample sizes, MSW is the Mean Squares of the "Within Group" in the ANOVA output table, and n is the size of the group samples.

The Games-Howell test is defined as (Ruxton, G.D., and Beauchamp, 2008):

$$\bar{x}_i - \bar{x}_j > q_{\sigma,k,df} \quad (3)$$

Where σ is equal to standard error and it is defined as:

$$\sigma = \sqrt{\frac{1}{2}\left(\frac{s_i^2}{n_i}+\frac{s_j^2}{n_j}\right)} \quad (4)$$

Degrees of freedom is calculated using Welch's correction as shown:

$$\frac{\left(\frac{s_i^2}{n_i}+\frac{s_j^2}{n_j}\right)^2}{\frac{\left(\frac{s_i^2}{n_i}\right)^2}{n_i}+\frac{\left(\frac{s_j^2}{n_j}\right)^2}{n_j}} \quad (5)$$

The t-value is found with Welch's t-test:

$$t = \frac{\bar{x}_i-\bar{x}_j}{\sqrt{\frac{s_i^2}{n_i}+\frac{s_j^2}{n_j}}} \quad (6)$$

Thus, confidence intervals can be formed with:

$$\bar{x}_i - \bar{x}_j \pm t\sqrt{\frac{1}{2}\left(\frac{s_i^2}{n_i}+\frac{s_j^2}{n_j}\right)} \quad (7)$$

Lastly, p-values are calculated using Tukey's studentized range:

$$q_{t*\sqrt{2},k,df} \quad (8)$$

The function to perform the Games-Howell test takes two arguments, the group vector and the data vector.

Modern wind rubine could work with wind speed as low as 2 m/s (Zephyr Corpration, 2011) as presented in Figure 2.

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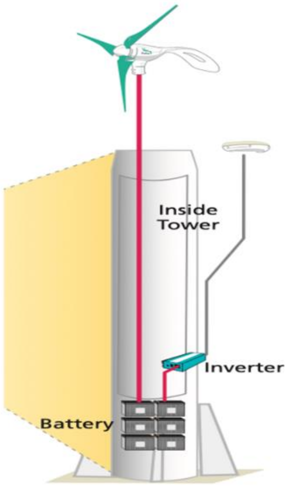

S/N	Type	Cut-in Wind Speed (m/s)	Rated Power (kW)
1	Airdolphin Mark-Zero/Pro	2.5	0.674
2	Enercon E70/2300	2	2300
3	Aeolos Wind Energy	2	12
4	AVATAR-I	2	1

Fig 2. Wind turbine for domestic application

The energy from the wind resource was calculated using equation 8. In practical terms, the Airdolphin Mark-Zero/Pro wind turbine is used for the study. It has a weight of 17.5 kg and rotor diameter of 1.8.

$$Energy = \frac{1}{2}\rho A v^3 t \quad (9)$$

Where ρ is the density of the air in kg/m^3, A is the cross-sectional area of the wind in m^2, v is the velocity of the wind in m/s, t is the time.

Spatial analysis of the seasonal and yearly analysis was carried to show the pictorial distribution of the dataset. The wind rose analysis was also carried out using the wind speed and wind direction parameters to determine the vectorized representation of wind energy potential in the research area. The contour representations were used for local analysis of wind potential in selected hilly locations. Like spatial analysis, it shows the turning effect and variability of vectorized wind potential.

3. Results and Discussion

The forty years dataset revealed that the magnitude of the wind speed in SON is < 2 m/s at 10 m above the ground. The maximum wind speed in SON was observed to be generally low. As a transitional season, it has a low influence on oceanic properties. Hence, despite the global increase in wind speed over the oceans, its magnitude in SON is slightly affected. This result is the reason few tropical cyclones occur during this period (Torralba *et al*., 2017). Using the statistical approach, it was observed that the interval between the lower and upper bound of the 95% confidence interval for mean is less than 0.5. Due to the influence of the oceanic properties in the December, January, and February (DJF) seasons, it was observed that the wind speed had the most significant variance and standard deviation throughout the four seasons.

3.1 Rayleigh and Weibull probability distribution function Analysis

The Rayleigh and Weibull probability distribution function (PDF) and the cumulative probability distribution (CDF)are presented in Figures 3a-d. The seasonal analysis for a group ten years within forty years is presented in Figure 3a-d. Figure 3a clearly shows that the wind resources for SON varies with the most active within 1980-1989. It was observed that alternate group had similarity. For example, the Rayleigh and Weibull CDF did not have point of intersection for 1990-1999 and 2010-2019. This illustration could also be corroborated based on the magnitudes presented. Figure 3b shows the wind resources for JJA. It was observed that there was no point of intersection in the CDF for all the years. This may be an evidence of climate change in the wind energy resources which in this case is positive for domestic wind energy generation. The shapes of both PDF and CDF are evidence that the wind system is compatible with any wind turbine listed in the methodology. More so, it proves that wind energy generation is sustainable in both SON and JJA as observed. However, the significant variation of wind resources between 1990-1999 is worth noting.

Figure 3c presents the wind resources in MAM. The shapes of the CDF and PDF are further evidence that wind energy generation would be sustainable for domestic use. Like JJA, it was clearly observed that Weibull and Rayleigh CDF did not intercept throughout the year. The PDF reveals that there may be a wind resources reversal into the 1980-1989 wind pattern for MAM.

The feature seen in JJA and MAM may be due to the significant of rain pattern in the tropics.This result further corroborates the hypothesis that more wind speed is noticeable in the tropical Pacific than in other basins (Ragatoa et al., 2019). In other words, the wind farm operation in the tropics' during DJF is expected to be most productive. It was observed that June, July, and August (JJA) had the lowest skewness, hence having the possibility of high wind speed stability for wind farms. It was observed that MAM season had the highest wind speed across the tropical rain forest as the tropical maritime or equatorial air mass. Hence, wind energy generation in this region is optimal. A uniform average wind speed of 2.4 m/s spread across the major parts of the research location. The same trend was observed in the late dry season (JJA). It can be inferred that wind energy users would have almost the same experience during the wet seasons. Also, the same spread occurs in the early dry season (JJA) though wind speed is generally low across the research area. It was seen that the southwest coastal region has higher prospects than other directions. The wind rose for 1980 is presented in Figure 4.

Figure 3d presents the wind resources in DJF. It is further observed that the late and early dry season had almost same CDF and PDF patterns as presented above. It is therefore important to further analyze the wind pattern to see if it is consistent. Using the decal analysis (i.e., splitting the fortyyears into groups of ten years each, i.e., 1980-1989 (D1), 1990-1999 (D2), 2000-2009 (D3), and 2010-2020 (D4), it was observed that the D1 had four highest wind speed mean, D2 had seven highest wind speed mean, D3 had two highest wind speed mean, and D4 had one highest wind speed mean. The JJA season had the highest frequency, which depicts that the oceanic properties have a higher impact on the wind speed in Nigeria. Likewise, the highest magnitude of the maximum wind speed with its corresponding minimum value are reported in this research. The frequency of occurrence of maxima wind speed was displayed where D1 had five highest wind speed maxima, D2 had six highest wind speed maxima, D3 had five highest wind speed maxima, and D4 had six highest wind speed maxima. The DJF season had the highest frequency of maxima that depicts that the oceanic properties have a higher impact on the wind speed during this season in Nigeria. The range between the maximum and its corresponding minimum values matters as it shows the sustainability of the wind system for power generation purposes. For example, when the maximum and minimum wind speed in the dataset is close, i.e., the range (maximum-minimum wind speed), the sustainability of the wind generation is high. A large range shows that wind power generation may not be sustainable.

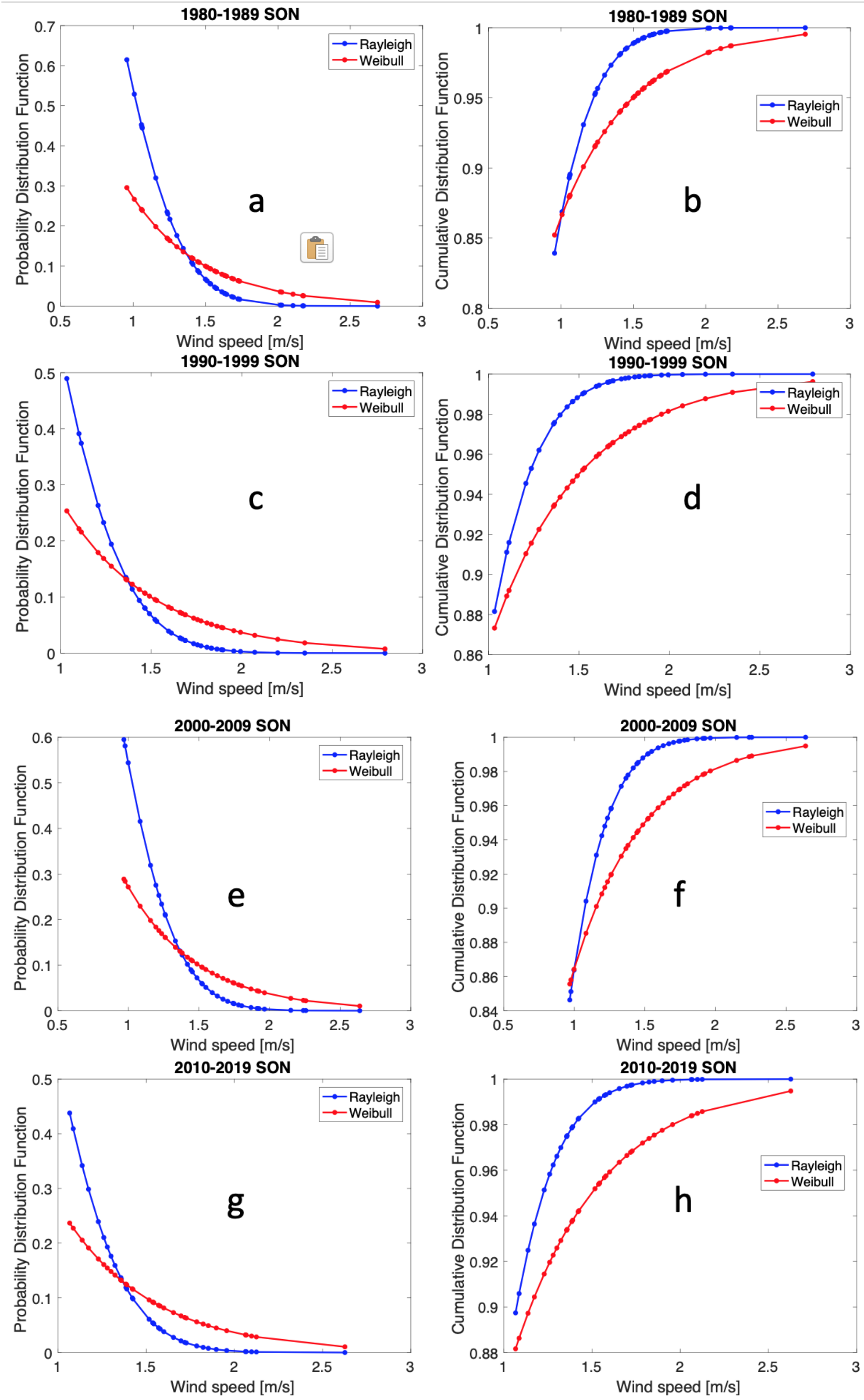

Fig 3a. Rayleigh and Weibull PDF and CDF for SON

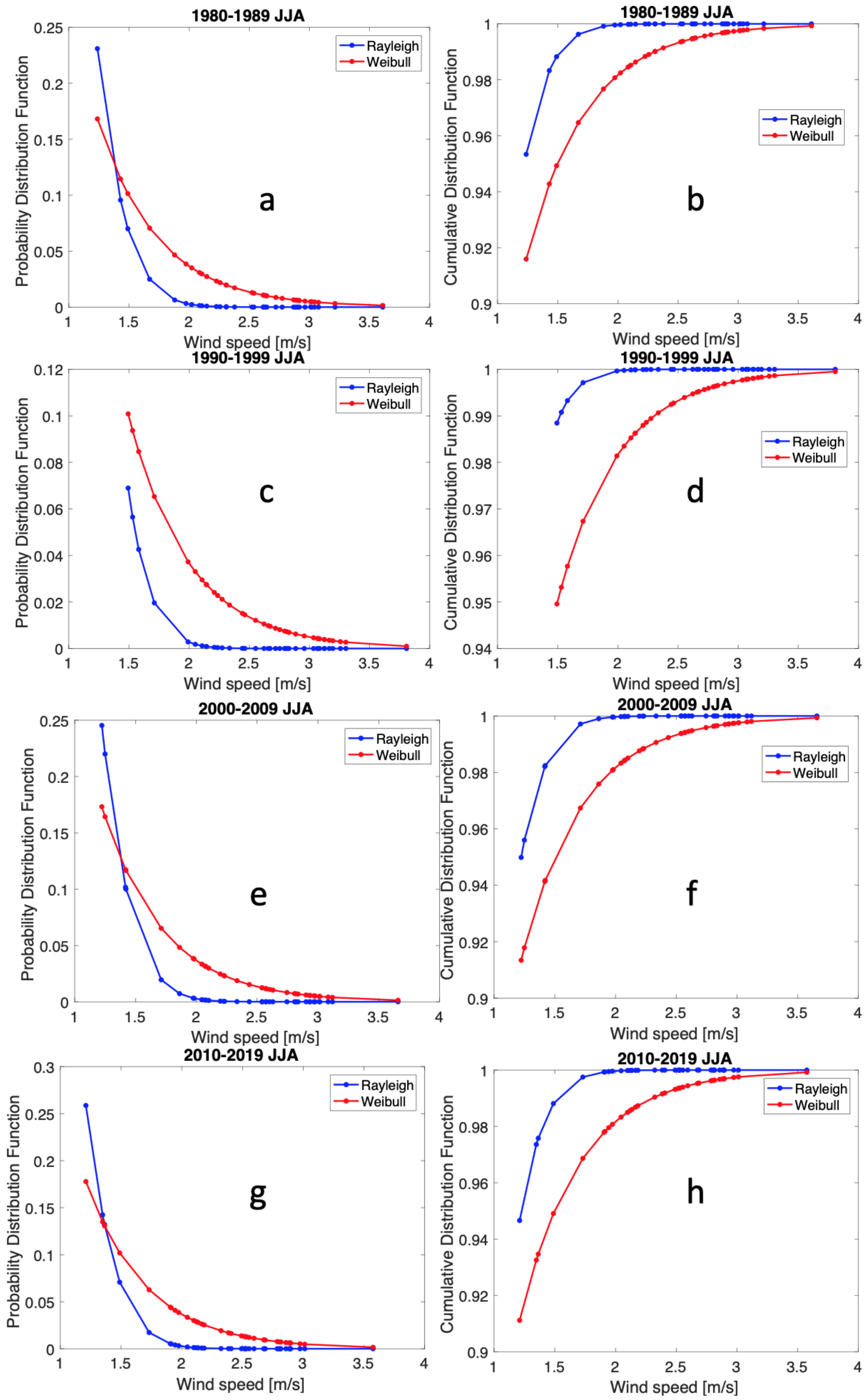

Fig 3b. Rayleigh and Weibull PDF and CDF for JJA

In 1980, the DJF season showed that the wind pattern corroborates with the research site's climatic pattern. The wind speed in the savannah and Sahel was the highest, while the rain forest climatic zone (RFCZ) had the lowest. This result is expected for the height considered in the research due to the interception of trees, hills, and mountains in RFC. With a wind speed of less than 2 m/s at 10 m, it is not easy to operate domestic wind turbines; however, in reality, different shows that the wind speed could be as high as 4.5 m/s (Dia-Diop et al., 2020). In the DJF, a wind speed> 4 m/s had the highest frequency (8%) in the northeast and northwest. More activity takes place in the northeast and northwest (Figure 4a-a). Hence, this direction is the best configuration of the domestic wind turbine during DJF.

In the MAM, the southwest and southeast direction is the best configuration for the domestic wind turbine (Figure 4a-b). The northwest showed high frequency but was characterized by lower wind speed. Almost the same event occurred in JJA (Figure 4c) but with an almost constant wind speed of 2.5-3 m/s throughout the year. During SON, it was observed that higher wind speed magnitude had lower frequency throughout the year (Ojo et al., 2020; Dia-Diop et al., 2020). However, the northwest had a higher wind speed frequency though low. The wind rose results for 1980 proposed that when the domestic wind turbine (DWT) is placed at about 58o in the northwest direction, wind energy would be fairly stable to meet user's domestic demand.

After ten years, i.e., 1990, it is seen that not much has changed in the DJF, but there are significant changes in MAM, JJA, and SON. High variability, as seen in the year 1990, has a significant influence on wind energy production. It is shown that the peculiarity of the climatic zone driver in DJF extended into MAM. However, the changes did not change in some of the locations in JJA and SON. The coastal southwest region still maintained the same features as previously seen in 1980. The wind rose analysis clearly shows that the variability of the wind dynamics is significant. The northwest and southwest had the highest frequency for DJF, as presented in Figure 4b-a. The southwest and southeast had the highest frequency for MAM, as presented in Figure 4b-b. This result shows that the absence of northwest wind activities initiates the significant variance between both seasons. The wind rose analysis shows that varying wind energy generation is expected. Here, northeast wind dynamics are more pronounced in both JJA and SON (Shi *et al.,* 2022). Hence, through the vectorization of the wind dynamics in the research area, it is significant that there is significant wind variability over Nigeria.

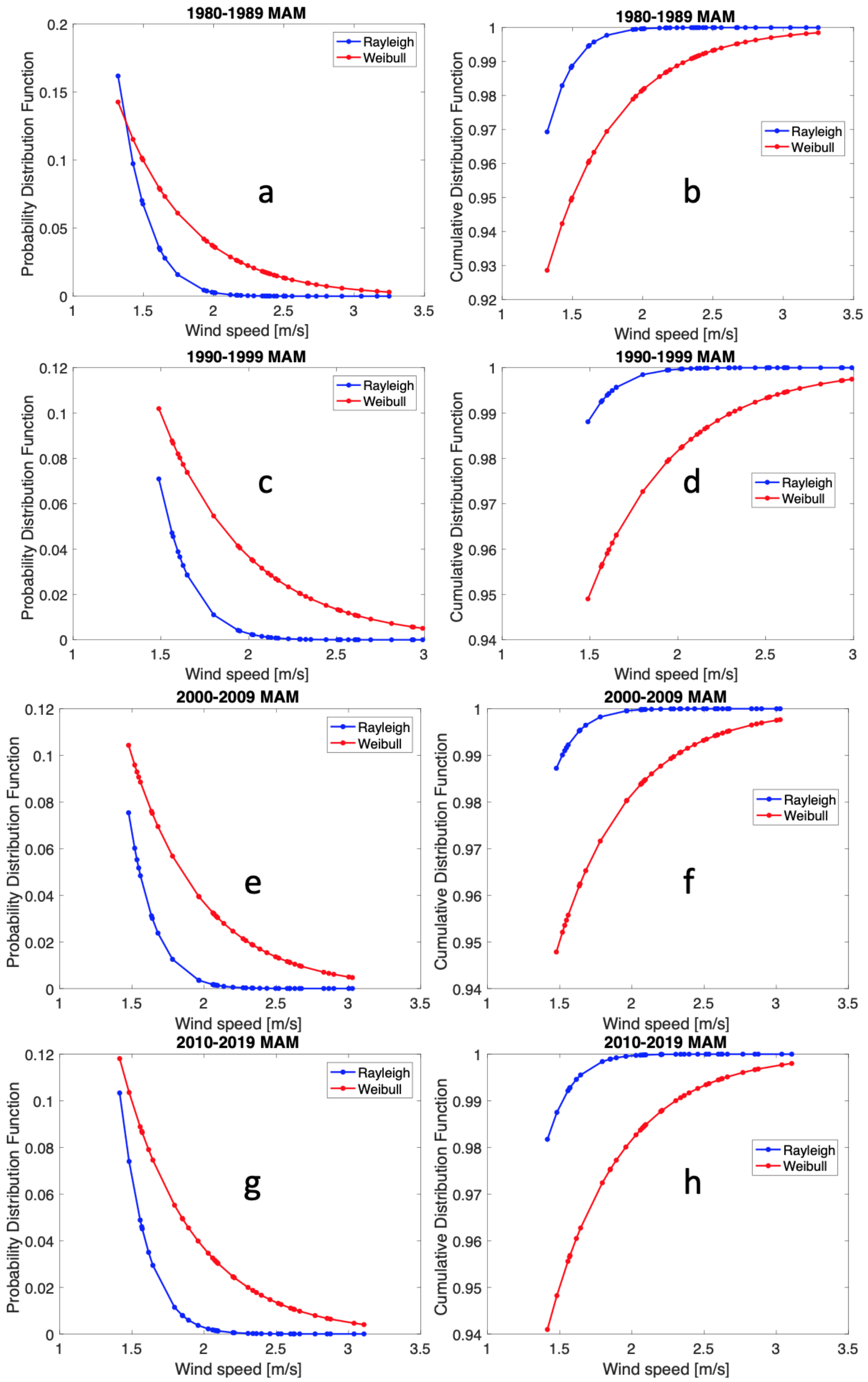

Fig 3c. Rayleigh and Weibull PDF and CDF for MAM

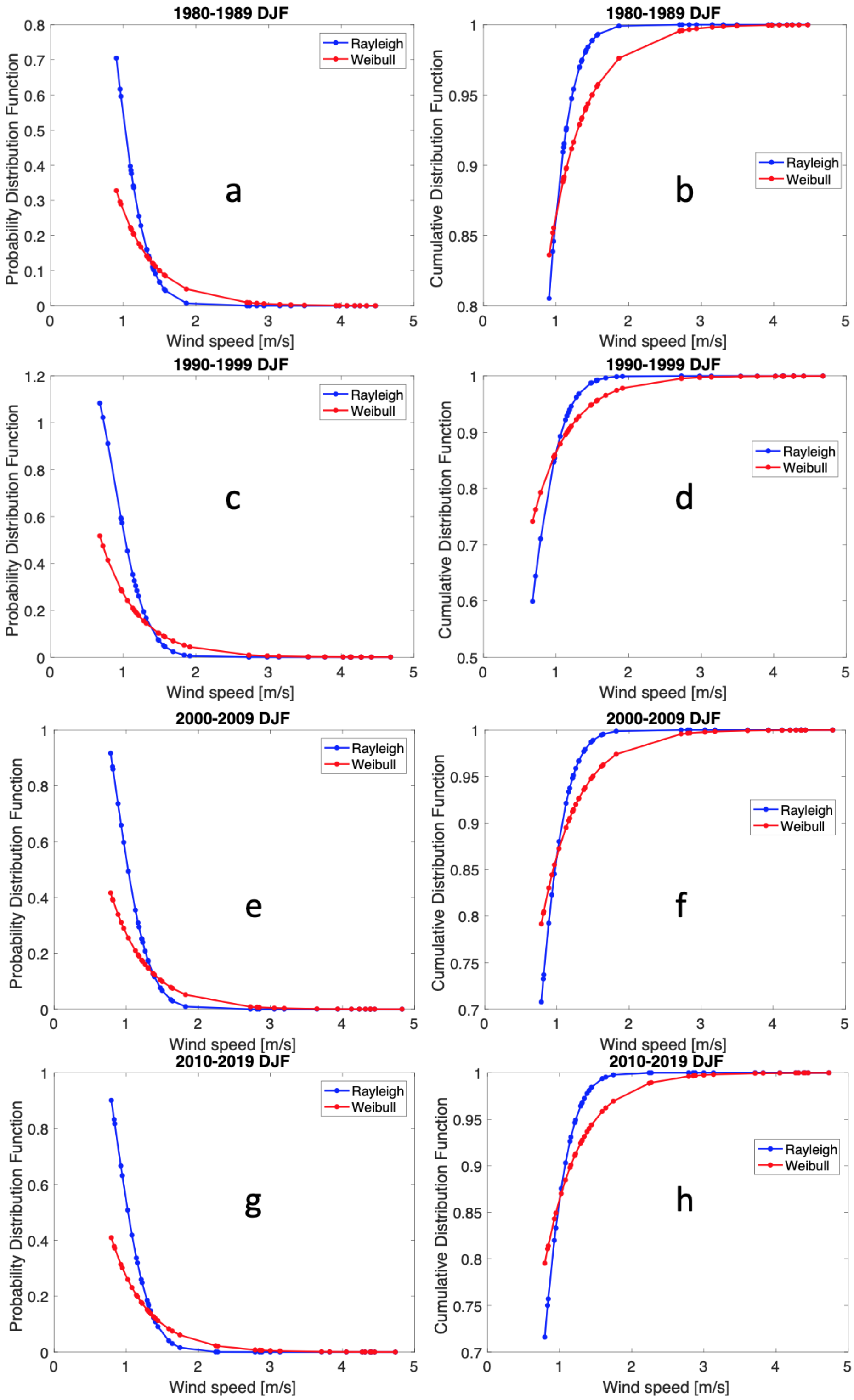

Fig 3d. Rayleigh and Weibull PDF and CDF for DJF

In the year 2000, the DJF seasons, like the previous decade, are driven by climatic systems. However, MAM shows that there is a significant variance in the wind dynamics across the research location (Figure 3a-d). There seems to be a slight difference between JJA and SON; however, the wind rose analysis reveals that the variance is somewhat significant. The wind activities had shifted to northeast and southwest for DJF in the year 2000. The resemblance in MAM 1990 and MAM is the continuance of the western wind dynamics.

The southwest winds are dominant in JJA, showing that the wind dynamics in this direction built over the ten years. An alternative trend was seen in the northwest is seen in the SON, i.e., the activities for SON 1980 and 2000 are almost the same, while 1990 is significantly different. The wind rose analysis that DJF had an almost uniform multi-directional wind dynamic (Figure 4c-a). It is particularly unique across the fortyyears considered. The MAM had more activities in the northwest and southwest. However, the duration of the wind dynamics is lower than 11%, which shows that there was a lot of atmospheric disturbance in MAM for 2000. The wind vectors are mainly in the southwest and southeast of the JJA. This result corroborates the spatial map where the south had higher wind speed. In the SON, the wind vectors are more prominent in the northwest direction; however, unlike the JJA, it does not directly influence the spatial distribution of the wind speed, as seen in Figure 4c-(a-d).

Recall that Figure 3d showed that DJF had almost the same trend within ten years as seen in the forty years data. This stability is advantageous to wind energy generation in the research site as users are expected to optimize usage via an innovative small-scale wind turbine. The MAM has high variability as unique spatial maps are seen every ten years. This result means that the influence of oceanic properties on MAM is enormous. The users' experience in this scenario is not specific, as both high and low power generation is accruable. JJA, like DJF is slightly stable. Hence the wind energy user experience can be further optimized via technology. Also, it is seen that the wind vectorization in SON is fairly stable all through thirty years (Figure 4d).

The wind rose analysis reveals that the JJA also had alternating trends as described above (Figure 4d-b). This result means that there may be an alternating pattern that occurs due to reduced north-east winds. The early wet (MAM) season had a higher frequency in the southwest and southeast directions. This result is almost similar to the event in 1990 and further confirms the alternative trend at intervals of ten years. However, only the SON did not follow the alternating trend as shown in other seasons. JJA and SON are seen to have a multi-dimensional wind dynamic. Hence, wind energy enthusiasts could only have full experience if the wind turbine rotates horizontally during energy generation.

Recall earlier that DJF, MAM, JJA, and SON had the same observation as regards to the patterns of CDF and PDF (Figure 3a-d). Hence, the following conclusion can be made in this regard, i.e., Wind speed distribution is fairly stable in DJF, JJA, and SON. At the same time, the variability of the wind dynamics is driven within the MAM only. The MAM drives the magnitude of the wind speed in other seasons. Hence, users' experience is sustainable and reliable.

The wind rose shows that the wind vectorization in DJF, MAM, JJA, and SON is multi-directional (Figure 4d-d). Hence, as suggested above, a small-scale wind turbine with horizontal rotation is advised to avoid re-configuring the wind turbine within different seasons. The sudden multi-directionality of the wind vectorization after forty years may be evidence of the climate change to wind energy generation (Figure 4e).

3.2 Decal Analysis of Seasonal Wind Energy Potentials

The statistical analysis for ten years seasonal dataset was reported for DJF (Tables 1), MAM (Tables 2), JJA (Tables 3), and SON (Tables 4). Table 1a shows the descriptive decal analysis of DJF that shows that wind speed increased from 2000-2020. This result means that the wind energy resources are on the increase within a specific time. The mean result shows that group 1990-1999 had the lowest value. Also, it showed that the mean wind speed is on the increase between 2000-2020. The year 2000-2009 had the highest and lowest value for maximum and minimum wind speed, respectively. The ANOVA is presented in Table 1b. The significant difference is given as 0.988, which is greater than the standard, i.e., 0.05. Hence, the null hypothesis is rejected and concludes a significant difference in the DJF values for the fortyyears. The sum of the square within groups further corroborates the spatial and wind rose analysis that wind energy generation is sustainable and reliable in the DJF. Based on the statistically significant difference, the posthoc of Least Significant Difference (LSD), Dunnett-C, and Games-Howell test was done as presented in Table 1c. Using the LSD test, it is reported that there is a significant difference in the values of DJF within the group.

Furthermore, the mean difference shows that group 1980-1989 had a significant positive difference to group 1990-1999. Group 2010-2020 also had a significant positive difference to all the groups. This result is in tandem with the outcome presented using the Dunnett-C and Games-Howell test.

Table 1a shows the descriptive decal analysis of MAM that shows that wind speed was the highest in the group 1980-1989. The mean distribution among the group corroborated an alternating pattern that was discussed in the spatial maps. The highest value of maximum and minimum group mean was in the group 1980-1989.

The spatial distribution of the energy (kWh) within a month (Figure 5a). For accruable energy during DJA season, it is observed that energy between 539-1700 kWh is visible where more locations in the southwest and southeast geopolitical regions likely to have the maximum wind energy. It is observed the maximal energy reduced over years i.e. considering the decline from 1980-1989 and 2010-2019.

The descriptive statistics for forty years of the MAM is presented in Table 2a. The pattern of the maximum values follows a positive parabola when the minimum values describe a negative parabola. This event describes the variability of the wind speed in MAM over the forty years. The group range, i.e., the difference between the maximum and minimum values were seen to be alternating as the mean. The ANOVA is presented in Table 2b. The significant difference is given as 0.962, which is greater than the standard, i.e., 0.05. Hence, the null hypothesis is rejected and concludes that there is a significant difference in the MAM values for the forty years. The sum of squares with the group showed that it is much lower than the DJF. It is expected that wind energy users will have varying experiences during the MAM. Hence, wind generation in this season is sustainable and fairly reliable. Based on the statistically significant difference, the posthoc of Least Significant Difference (LSD), Dunnett-C, and Games-Howell test was done as presented in Table 2c. Using the LSD test, it is reported that there is a significant difference in the values of MAM within the group. This assertion is corroborated by Akinsanola *et al*. (2021).

Furthermore, the mean difference shows that group 1980-1989 positively impacted all other groups, while group 1990-1999 also had a positive mean difference with group 2010-2020. The significant difference for each group interaction exceeded the standard, i.e., 0.05. Hence, there is a clear significant difference for all years. This result is in tandem with the outcome presented using the Dunnett-C and Games-Howell test.

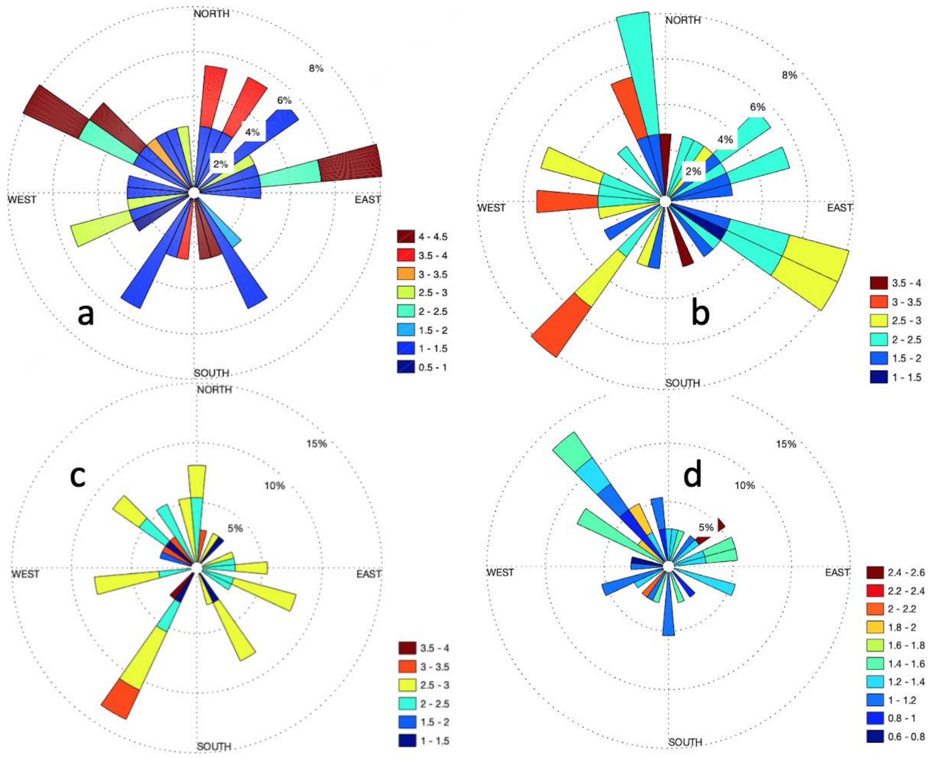

Fig 4a. Spatial analysis of wind speed (1980)

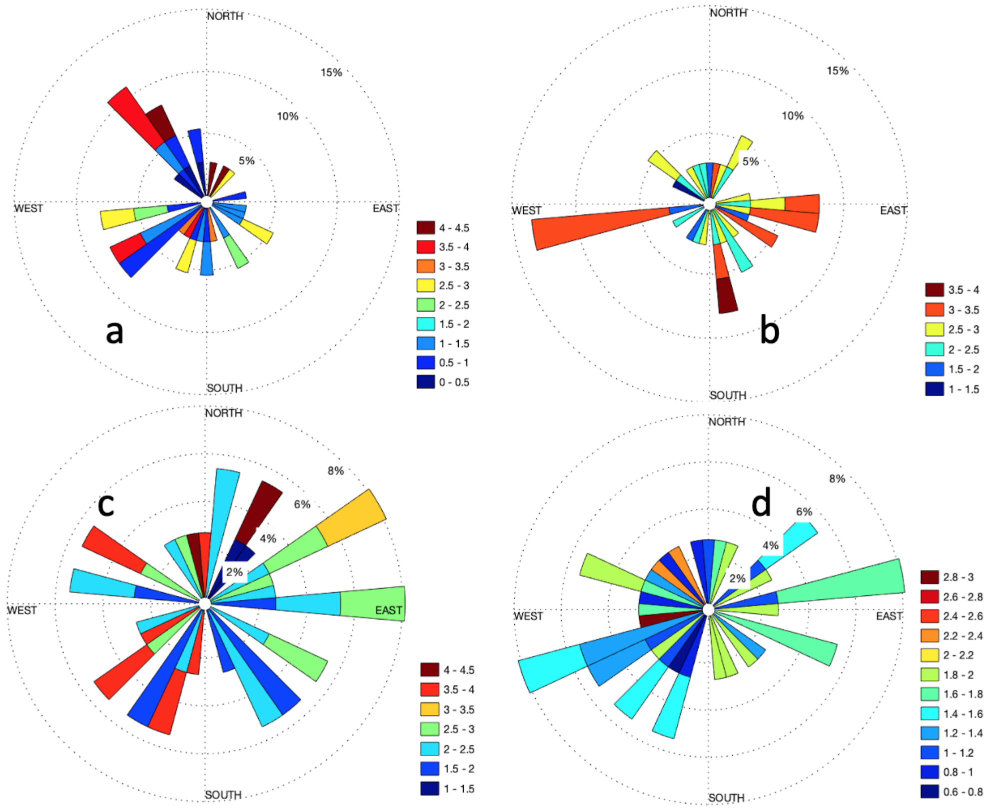

Fig 4b. Spatial analysis of wind speed (1990)

Table 1a
Statistical descriptive for DJF for forty years

	N	Mean	Std. Deviation	Std. Error	95% Confidence Interval		Min	Max
					Lower Bound	Upper Bound		
1980-1989	37	2.1699	1.20880	.19873	1.7669	2.5729	.90	4.47
1990-1999	37	2.1507	1.26925	.20866	1.7276	2.5739	.68	4.61
2000-2009	37	2.2338	1.39282	.22898	1.7694	2.6982	.77	4.92
2010-2020	37	2.2387	1.32566	.21794	1.7968	2.6807	.79	4.73
Total	148	2.1983	1.28816	.10589	1.9891	2.4076	.68	4.92

Table 1b
ANOVA for DJF for forty years

	Sum of Squares	df	Mean Square	F	Sig.
Between Groups	.221	3	.074	.043	.988
Within Groups	243.703	144	1.692		
Total	243.924	147			

Table 1c
Multiple Comparisons of Test for DJF for forty years

	(I) Factor	(J) Factor	Mean Difference (I-J)	Std. Error	Sig.	95% Confidence Interval	
						Lower Bound	Upper Bound
LSD	1980-1989	1990-1999	.01915	.30246	.950	-.5787	.6170
		2000-2009	-.06394	.30246	.833	-.6618	.5339
		2010-2020	-.06885	.30246	.820	-.6667	.5290
	1990-1999	1980-1989	-.01915	.30246	.950	-.6170	.5787
		2000-2009	-.08309	.30246	.784	-.6809	.5147
		2010-2020	-.08800	.30246	.772	-.6858	.5098
	2000-2009	1980-1989	.06394	.30246	.833	-.5339	.6618
		1990-1999	.08309	.30246	.784	-.5147	.6809
		2010-2020	-.00491	.30246	.987	-.6027	.5929
	2010-2020	1980-1989	.06885	.30246	.820	-.5290	.6667
		1990-1999	.08800	.30246	.772	-.5098	.6858
		2000-2009	.00491	.30246	.987	-.5929	.6027
Games-Howell	1980-1989	1990-1999	.01915	.28815	1.000	-.7388	.7771
		2000-2009	-.06394	.30319	.997	-.8617	.7338
		2010-2020	-.06885	.29494	.995	-.8447	.7070
	1990-1999	1980-1989	-.01915	.28815	1.000	-.7771	.7388
		2000-2009	-.08309	.30979	.993	-.8980	.7318
		2010-2020	-.08800	.30172	.991	-.8816	.7056
	2000-2009	1980-1989	.06394	.30319	.997	-.7338	.8617
		1990-1999	.08309	.30979	.993	-.7318	.8980
		2010-2020	-.00491	.31611	1.000	-.8364	.8265
	2010-2020	1980-1989	.06885	.29494	.995	-.7070	.8447
		1990-1999	.08800	.30172	.991	-.7056	.8816
		2000-2009	.00491	.31611	1.000	-.8265	.8364
Dunnett C	1980-1989	1990-1999	.01915	.28815		-.7569	.7952
		2000-2009	-.06394	.30319		-.8805	.7526
		2010-2020	-.06885	.29494		-.8632	.7255
	1990-1999	1980-1989	-.01915	.28815		-.7952	.7569
		2000-2009	-.08309	.30979		-.9174	.7513
		2010-2020	-.08800	.30172		-.9006	.7246
	2000-2009	1980-1989	.06394	.30319		-.7526	.8805
		1990-1999	.08309	.30979		-.7513	.9174
		2010-2020	-.00491	.31611		-.8563	.8465
	2010-2020	1980-1989	.06885	.29494		-.7255	.8632
		1990-1999	.08800	.30172		-.7246	.9006
		2000-2009	.00491	.31611		-.8465	.8563

Table 2a
Statistical descriptive for MAM for forty years

	N	Mean	Std. Deviation	Std. Error	95% Confidence Interval		Minimum	Maximum
					Lower Bound	Upper Bound		
1980-1989	37	2.2431	.49144	.08079	2.0793	2.4070	1.32	3.25
1990-1999	37	2.2037	.44234	.07272	2.0563	2.3512	1.47	3.00
2000-2009	37	2.2365	.44376	.07295	2.0885	2.3844	1.54	3.01
2010-2020	37	2.1959	.45640	.07503	2.0437	2.3481	1.45	3.09
Total	148	2.2198	.45466	.03737	2.1459	2.2937	1.32	3.25

Table 2b
ANOVA for MAM for forty years

	Sum of Squares	df	Mean Square	F	Sig.
Between Groups	.061	3	.020	.097	.962
Within Groups	30.326	144	.211		
Total	30.387	147			

Table 2c
Multiple Comparisons of Test for MAM for forty years

	(I) Factor	(J) Factor	Mean Difference (I-J)	Std. Error	Sig.	95% Confidence Interval	
						Lower Bound	Upper Bound
LSD	1980-1989	1990-1999	.03936	.10669	.713	-.1715	.2503
		2000-2009	.00663	.10669	.951	-.2043	.2175
		2010-2020	.04722	.10669	.659	-.1637	.2581
	1990-1999	1980-1989	-.03936	.10669	.713	-.2503	.1715
		2000-2009	-.03273	.10669	.759	-.2436	.1782
		2010-2020	.00786	.10669	.941	-.2030	.2188
	2000-2009	1980-1989	-.00663	.10669	.951	-.2175	.2043
		1990-1999	.03273	.10669	.759	-.1782	.2436
		2010-2020	.04059	.10669	.704	-.1703	.2515
	2010-2020	1980-1989	-.04722	.10669	.659	-.2581	.1637
		1990-1999	-.00786	.10669	.941	-.2188	.2030
		2000-2009	-.04059	.10669	.704	-.2515	.1703
Games-Howell	1980-1989	1990-1999	.03936	.10870	.984	-.2466	.3253
		2000-2009	.00663	.10886	1.000	-.2797	.2930
		2010-2020	.04722	.11026	.973	-.2428	.3372
	1990-1999	1980-1989	-.03936	.10870	.984	-.3253	.2466
		2000-2009	-.03273	.10301	.989	-.3036	.2382
		2010-2020	.00786	.10449	1.000	-.2670	.2827
	2000-2009	1980-1989	-.00663	.10886	1.000	-.2930	.2797
		1990-1999	.03273	.10301	.989	-.2382	.3036
		2010-2020	.04059	.10465	.980	-.2347	.3158
	2010-2020	1980-1989	-.04722	.11026	.973	-.3372	.2428
		1990-1999	-.00786	.10449	1.000	-.2827	.2670
		2000-2009	-.04059	.10465	.980	-.3158	.2347
Dunnett C	1980-1989	1990-1999	.03936	.10870		-.2534	.3321
		2000-2009	.00663	.10886		-.2865	.2998
		2010-2020	.04722	.11026		-.2497	.3442
	1990-1999	1980-1989	-.03936	.10870		-.3321	.2534
		2000-2009	-.03273	.10301		-.3102	.2447
		2010-2020	.00786	.10449		-.2736	.2893
	2000-2009	1980-1989	-.00663	.10886		-.2998	.2865
		1990-1999	.03273	.10301		-.2447	.3102
		2010-2020	.04059	.10465		-.2413	.3224
	2010-2020	1980-1989	-.04722	.11026		-.3442	.2497
		1990-1999	-.00786	.10449		-.2893	.2736
		2000-2009	-.04059	.10465		-.3224	.2413

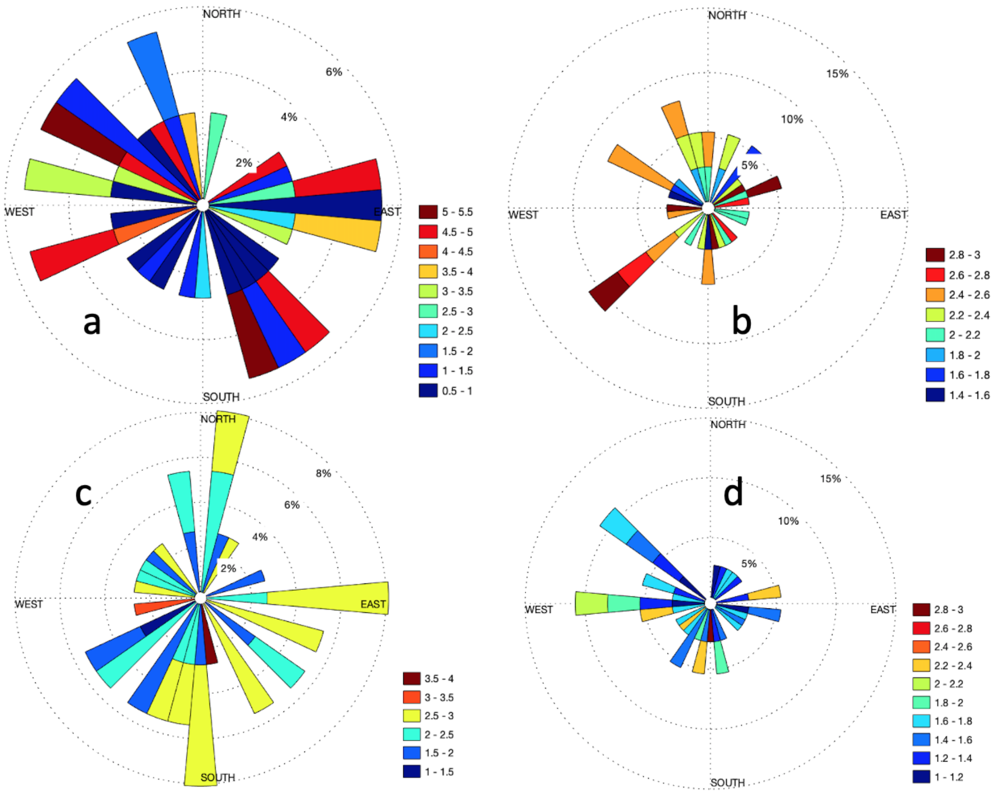

Fig 4c. Spatial analysis of wind speed (2000)

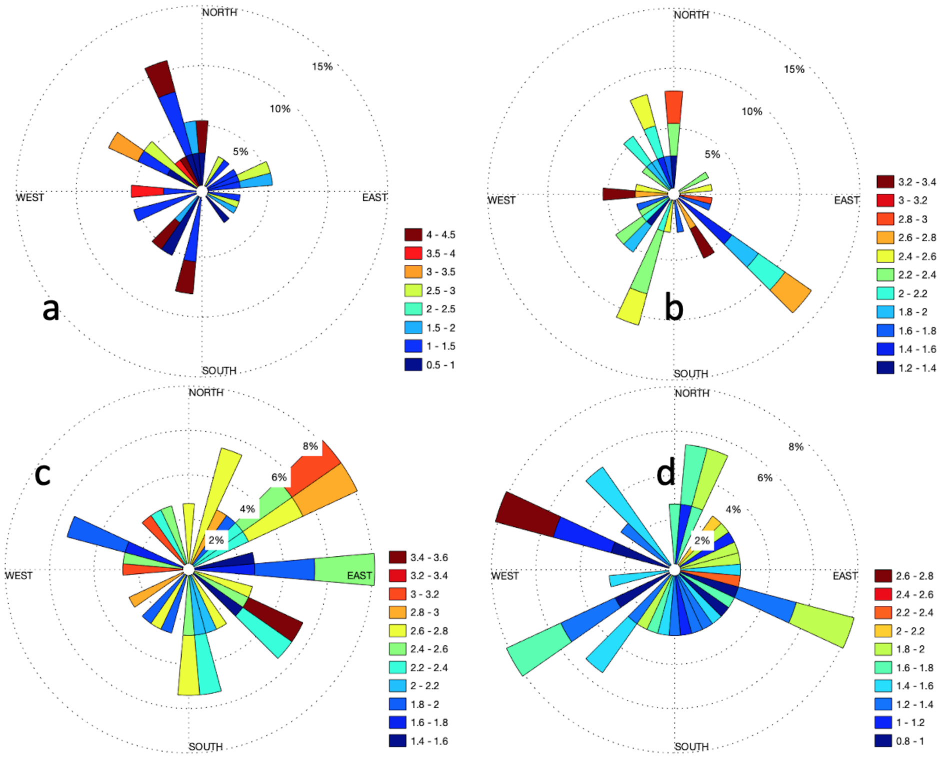

Fig 4d. Spatial analysis of wind speed (2010)

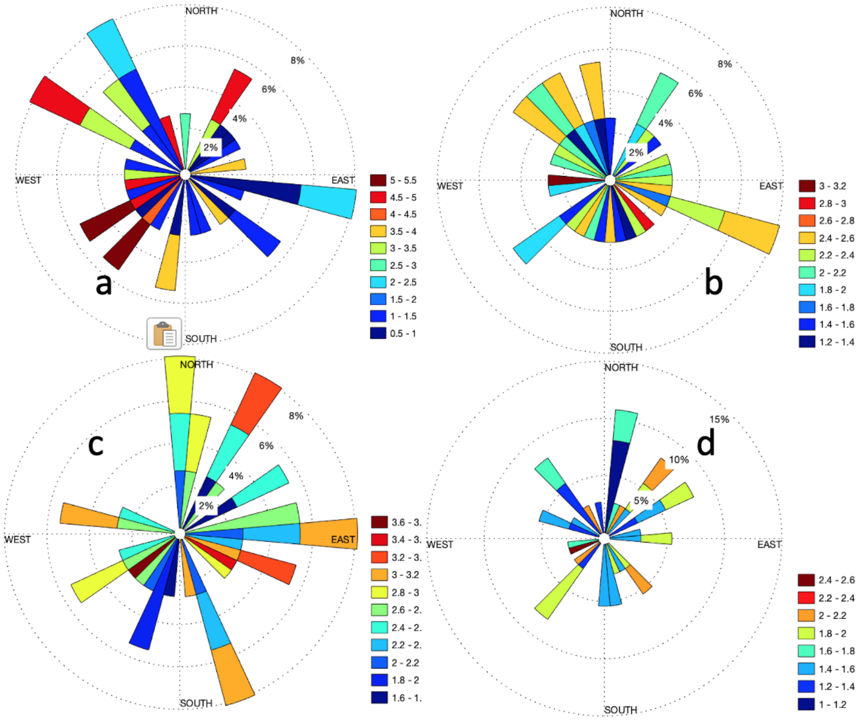

Fig 4e. Spatial analysis of wind speed (2020)

Figure 5b shows the spatial distribution of wind energy (kWh) within the MAM. It is observed that wind energy distribution was between 161-650 kWh. More than half of the country would have low wind energy supply; however, the energy needs in the rural settlement would naturally not exceed this minimum energy of 161 kWh. In the urban settlements, there is an improve power supply from the grid system due to full functioning of the hydroelectric station.

Table 3a shows the descriptive decal analysis of JJA that shows that wind speed was the highest in the group 1990-1999. The mean distribution among the group that group mean is in a downward trend till 2020. The maximum and minimum group mean value was in the group 1990-1999 and group 2000-2009, respectively. The ANOVA analysis presented in Table 3b shows that there is a significant difference in the JJA dataset. The sum of the square shows that it is slightly higher than MAM. The group range was fairly stable. This result means that the wind energy prospect within the JJA is sustainable and reliable. As reported in the ANOVA, the significant difference is a favorable condition to probe to the posthoc, which examines the significance between each group (Table 3c).

Furthermore, the mean difference shows that group 1990-1999 had a positive mean difference with all other groups, while group 2010-2020 had a negative mean difference with all groups. The significant difference for each group interaction exceeded the standard, i.e., 0.05. Hence, there is a clear significant difference for all years. This result is in tandem with the outcome presented using the Dunnett-C and Games-Howell test. Hence, wind energy users would have varying experiences over the years and within each season.

Figure 5c shows the spatial distribution of wind energy (kWh) within the JJA. It is observed that wind energy distribution was between 761-3650 kWh. This is the season with the highest expected wind energy generation. More than half of the country are expected to be at the minimum wind energy generation which is adequate (761 kWh) for both rural and urban domestic users. Extreme locations in both the northeast and northwest are expected to have abundant energy that small and medium enterprise could leverage on for wealth creation.

Like the JJA, the decal descriptive analysis of SON that shows that wind speed was the highest in the group 1990-1999 (Table 4a). The mean distribution among the group that group mean is in a downward trend till 2020. This trend was observed to be the same as JJA though the mean was lower compared to JJA. The highest value of the maximum and minimum group mean was in the group 1990-1999 and group 2000-2009, respectively. The ANOVA analysis presented in Table 4b shows that there is a significant difference in the SON dataset. The sum of the square is the lowest compared to other seasons. The group range significantly varies. This result means that the wind energy prospect within the JJA is sustainable but fairly reliable. The ANOVA shows a significant difference in the SON dataset, which gives further probe to the posthoc, including LSD, Dunnett-C, and Games-Howell test (Table 4c).

Furthermore, the mean difference shows that group 1990-1999 had a positive mean difference with all other groups, while group 1980-1989 had a negative mean difference with all groups. The significant difference for each group interaction exceeded the standard, i.e., 0.05. Hence, there is a clear significant difference for all years. This result is in tandem with the outcome presented using the Dunnett-C and Games-Howell test. The implication of this results shows that the wind erosion in parts of Nigeria is not significant when comparing years or seasons for large years but occurs at specific times (Pierre *et al.,* 2022).

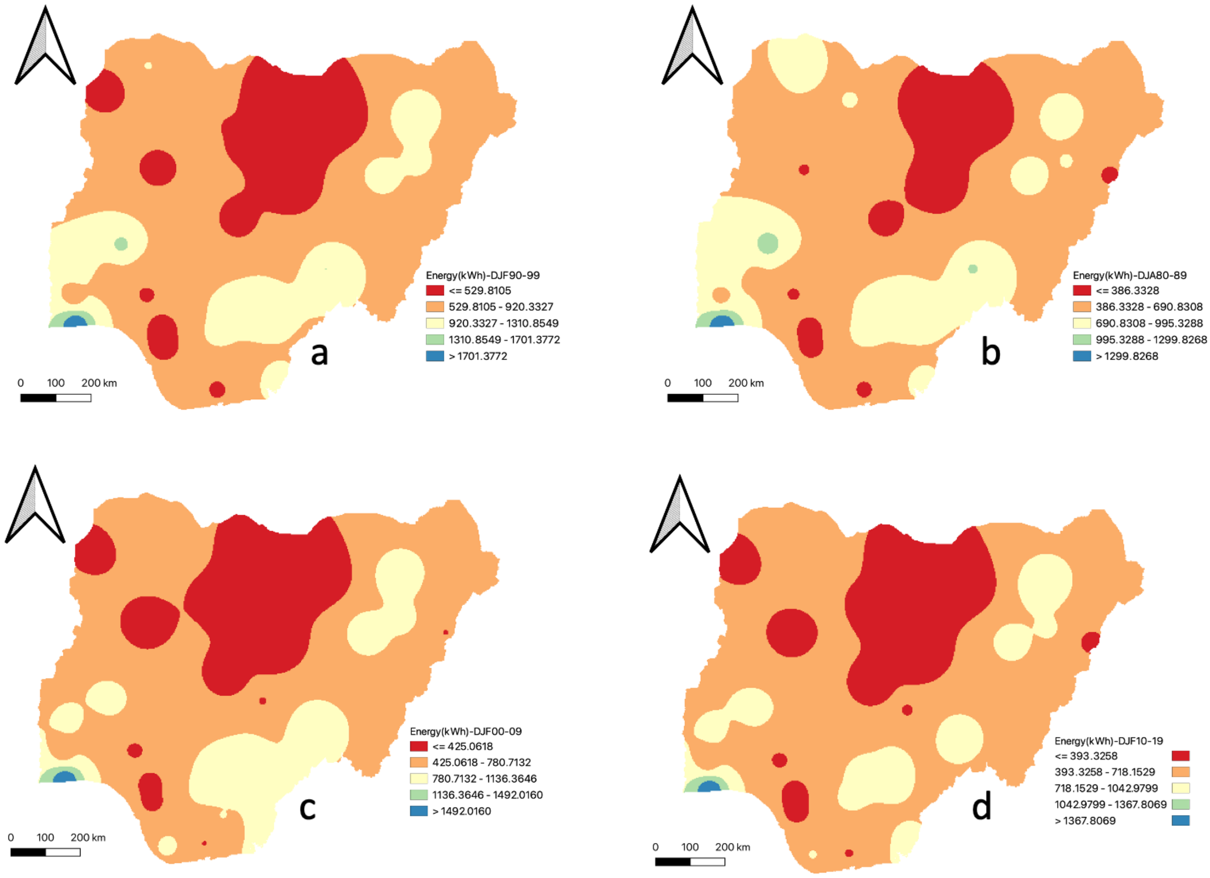

Fig 5a. Accruable energy within DJF months system due to full functioning of the hydroelectric station.

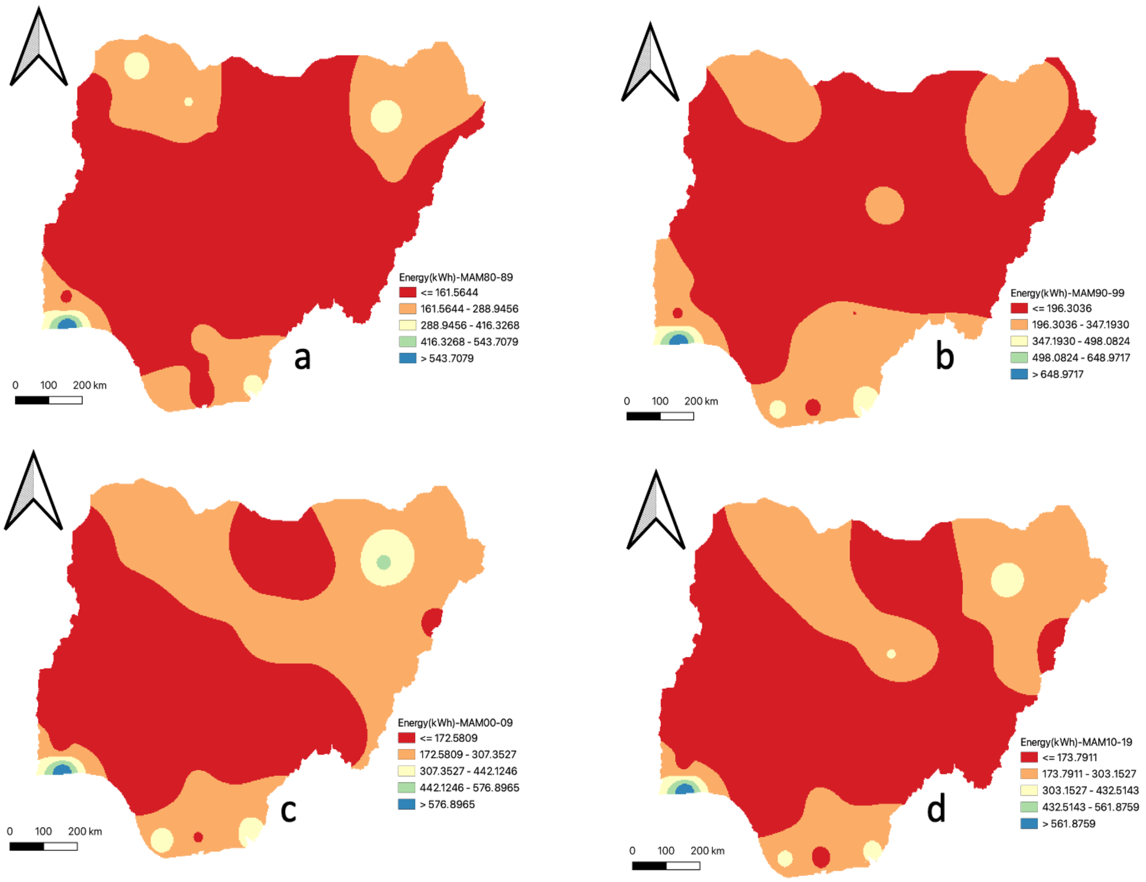

Fig 5b. Accruable energy within DJF months

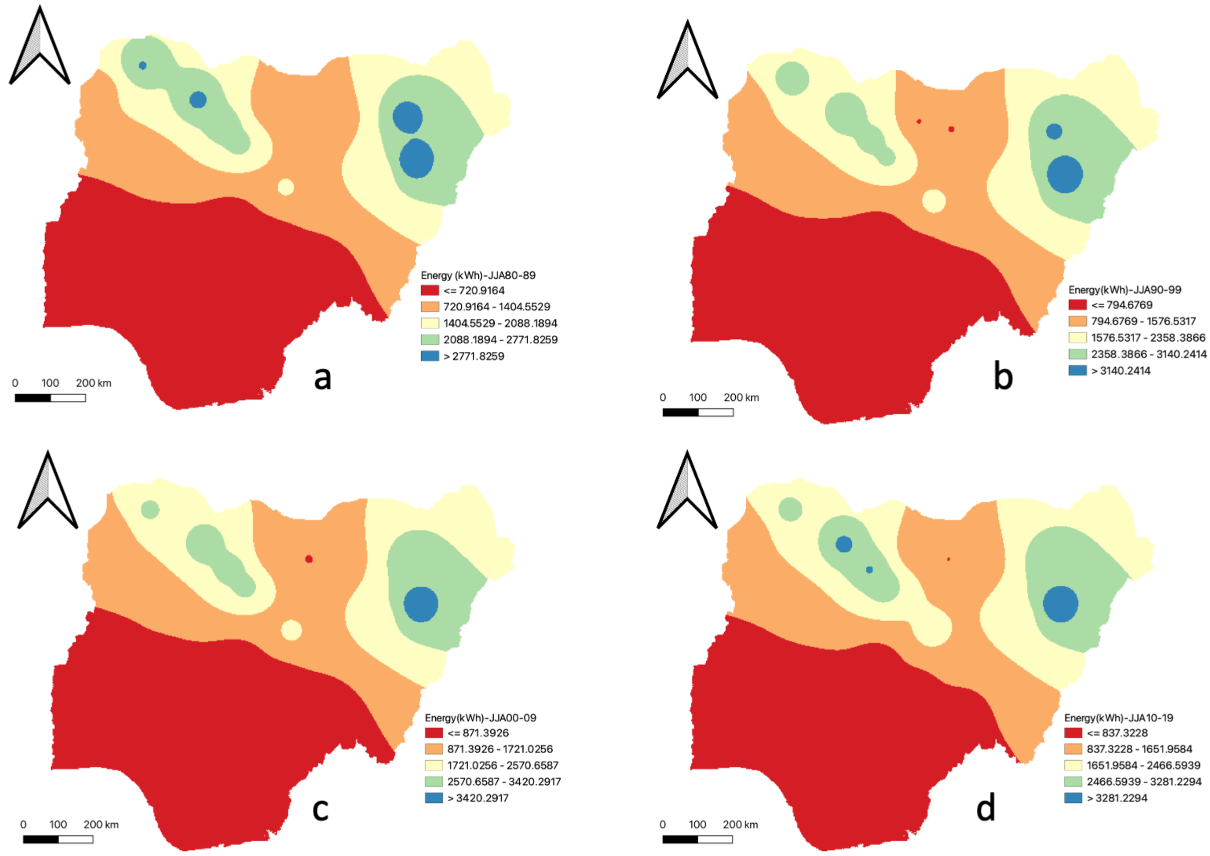

Fig 5c. Accruable energy within JJA months

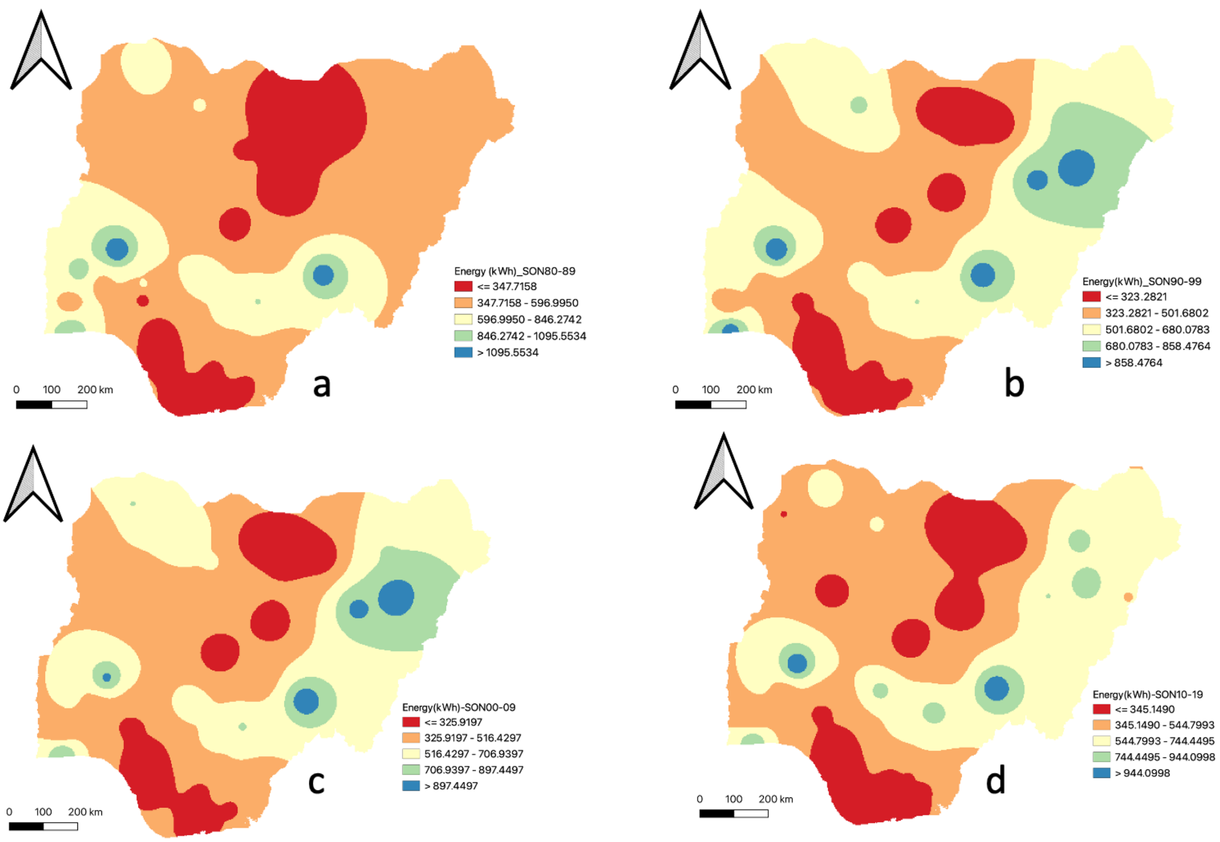

Fig 5d. Accruable energy within SON months

Table 3a
Statistical descriptive for JJA for forty years

	N	Mean	Std. Deviation	Std. Error	95% Confidence Interval for Mean		Minimum	Maximum
					Lower Bound	Upper Bound		
1980-1989	37	2.4867	.52981	.08710	2.3100	2.6633	1.24	3.61
1990-1999	37	2.6226	.55400	.09108	2.4379	2.8073	1.53	3.84
2000-2009	37	2.4230	.58093	.09550	2.2293	2.6167	1.19	3.66
2010-2020	37	2.3733	.52364	.08609	2.1987	2.5479	1.24	3.56
Total	148	2.4764	.55000	.04521	2.3871	2.5657	1.19	3.84

Table 3b
ANOVA for JJA for forty years

	Sum of Squares	df	Mean Square	F	Sig.
Between Groups	1.294	3	.431	1.438	.234
Within Groups	43.175	144	.300		
Total	44.468	147			

Table 3c
Multiple Comparisons of Test for JJA for forty years

	(I) Factor	(J) Factor	Mean Difference (I-J)	Std. Error	Sig.	95% Confidence Interval	
						Lower Bound	Upper Bound
LSD	1980-1989	1990-1999	-.13593	.12731	.287	-.3876	.1157
		2000-2009	.06364	.12731	.618	-.1880	.3153
		2010-2020	.11340	.12731	.375	-.1382	.3650
	1990-1999	1980-1989	.13593	.12731	.287	-.1157	.3876
		2000-2009	.19957	.12731	.119	-.0521	.4512
		2010-2020	.24933	.12731	.052	-.0023	.5010
	2000-2009	1980-1989	-.06364	.12731	.618	-.3153	.1880
		1990-1999	-.19957	.12731	.119	-.4512	.0521
		2010-2020	.04976	.12731	.696	-.2019	.3014
	2010-2020	1980-1989	-.11340	.12731	.375	-.3650	.1382
		1990-1999	-.24933	.12731	.052	-.5010	.0023
		2000-2009	-.04976	.12731	.696	-.3014	.2019
Games-Howell	1980-1989	1990-1999	-.13593	.12602	.704	-.4674	.1955
		2000-2009	.06364	.12926	.961	-.2764	.4037
		2010-2020	.11340	.12246	.791	-.2087	.4355
	1990-1999	1980-1989	.13593	.12602	.704	-.1955	.4674
		2000-2009	.19957	.13197	.436	-.1475	.5467
		2010-2020	.24933	.12532	.202	-.0803	.5790
	2000-2009	1980-1989	-.06364	.12926	.961	-.4037	.2764
		1990-1999	-.19957	.13197	.436	-.5467	.1475
		2010-2020	.04976	.12858	.980	-.2885	.3880
	2010-2020	1980-1989	-.11340	.12246	.791	-.4355	.2087
		1990-1999	-.24933	.12532	.202	-.5790	.0803
		2000-2009	-.04976	.12858	.980	-.3880	.2885
Dunnett C	1980-1989	1990-1999	-.13593	.12602		-.4753	.2035
		2000-2009	.06364	.12926		-.2845	.4118
		2010-2020	.11340	.12246		-.2164	.4432
	1990-1999	1980-1989	.13593	.12602		-.2035	.4753
		2000-2009	.19957	.13197		-.1559	.5550
		2010-2020	.24933	.12532		-.0882	.5868
	2000-2009	1980-1989	-.06364	.12926		-.4118	.2845
		1990-1999	-.19957	.13197		-.5550	.1559
		2010-2020	.04976	.12858		-.2965	.3960
	2010-2020	1980-1989	-.11340	.12246		-.4432	.2164
		1990-1999	-.24933	.12532		-.5868	.0882
		2000-2009	-.04976	.12858		-.3960	.2965

Table 4a
Statistical descriptive for SON for forty years

	N	Mean	Std. Deviation	Std. Error	95% Confidence Interval		Minimum	Maximum
					Lower Bound	Upper Bound		
1980-1989	37	1.5525	.37129	.06104	1.4288	1.6763	.96	2.69
1990-1999	37	1.6589	.36000	.05918	1.5388	1.7789	1.02	2.78
2000-2009	37	1.5836	.38828	.06383	1.4542	1.7131	.98	2.66
2010-2020	37	1.5757	.33905	.05574	1.4627	1.6888	1.07	2.63
Total	148	1.5927	.36356	.02988	1.5336	1.6518	.96	2.78

Table 4b
ANOVA for SON for forty years

	Sum of Squares	df	Mean Square	F	Sig.
Between Groups	.235	3	.078	.589	.623
Within Groups	19.194	144	.133		
Total	19.429	147			

Table 4c
Multiple Comparisons of Test for SON for forty years

	(I) Factor	(J) Factor	Mean Difference (I-J)	Std. Error	Sig.	95% Confidence Interval	
						Lower Bound	Upper Bound
LSD	1980-1989	1990-1999	-.10633	.08488	.212	-.2741	.0614
		2000-2009	-.03110	.08488	.715	-.1989	.1367
		2010-2020	-.02317	.08488	.785	-.1909	.1446
	1990-1999	1980-1989	.10633	.08488	.212	-.0614	.2741
		2000-2009	.07523	.08488	.377	-.0925	.2430
		2010-2020	.08316	.08488	.329	-.0846	.2509
	2000-2009	1980-1989	.03110	.08488	.715	-.1367	.1989
		1990-1999	-.07523	.08488	.377	-.2430	.0925
		2010-2020	.00793	.08488	.926	-.1598	.1757
	2010-2020	1980-1989	.02317	.08488	.785	-.1446	.1909
		1990-1999	-.08316	.08488	.329	-.2509	.0846
		2000-2009	-.00793	.08488	.926	-.1757	.1598
Games-Howell	1980-1989	1990-1999	-.10633	.08502	.597	-.3299	.1173
		2000-2009	-.03110	.08832	.985	-.2634	.2012
		2010-2020	-.02317	.08266	.992	-.2406	.1943
	1990-1999	1980-1989	.10633	.08502	.597	-.1173	.3299
		2000-2009	.07523	.08705	.823	-.1537	.3042
		2010-2020	.08316	.08130	.737	-.1307	.2970
	2000-2009	1980-1989	.03110	.08832	.985	-.2012	.2634
		1990-1999	-.07523	.08705	.823	-.3042	.1537
		2010-2020	.00793	.08474	1.000	-.2151	.2309
	2010-2020	1980-1989	.02317	.08266	.992	-.1943	.2406
		1990-1999	-.08316	.08130	.737	-.2970	.1307
		2000-2009	-.00793	.08474	1.000	-.2309	.2151
Dunnett C	1980-1989	1990-1999	-.10633	.08502		-.3353	.1227
		2000-2009	-.03110	.08832		-.2690	.2068
		2010-2020	-.02317	.08266		-.2458	.1995
	1990-1999	1980-1989	.10633	.08502		-.1227	.3353
		2000-2009	.07523	.08705		-.1592	.3097
		2010-2020	.08316	.08130		-.1358	.3021
	2000-2009	1980-1989	.03110	.08832		-.2068	.2690
		1990-1999	-.07523	.08705		-.3097	.1592
		2010-2020	.00793	.08474		-.2203	.2362
	2010-2020	1980-1989	.02317	.08266		-.1995	.2458
		1990-1999	-.08316	.08130		-.3021	.1358
		2000-2009	-.00793	.08474		-.2362	.2203

Figure 5D shows the spatial distribution of wind energy (kWh) within the SON. It is observed that wind energy distribution was between 325-950 kWh. Less than 10% of the locations within the country would experience minimum wind energy generation which is adequate (325 kWh) for rural domestic users. Despite the variation of energy generation over the years within all seasons over Nigeria, it was found that it is predictable and can be optimized using various technological solutions.

4. Conclusion

A wholistic investigation on the potentials of wind energy generation for domestic users in Nigeria. The forty years dataset revealed that the magnitude of the wind speed in SON is < 2 m/s (at 10 m above the ground) due to the low influence of oceanic properties. Also, the maximum wind speed in SON was observed to be generally low compared to other seasons. The range between the maximum and minimum value for SON was fairly stable as a large range shows that wind power generation may not be sustainable. The range shows the sustainability of the wind system for power generation purposes. The wind vectorization and distribution supported this assertion, i.e., using wind rose and spatial analysis, respectively. The descriptive decal analysis of SON was highest in the group 1990-1999. The mean distribution among the group clearly showed that the group mean in a downward trend till 2020.

DJF is driven by the peculiarity of the climatic zones across the research site. This stability is advantageous to wind energy generation in the research site as users are expected to optimize usage via innovative small-scale wind turbines. The MAM has high variability due to the influence of oceanic properties on wind dynamics. The descriptive decal analysis of MAM shows that wind speed was the highest in 1980-1989. The mean distribution among the group corroborated an alternating pattern that was discussed in the spatial maps. The users' experience in this scenario is not specific, as both high and low power generation is expected. It was reported that JJA was slightly stable as DJF. The wind rose analysis reveals that the JJA is also had an alternating trend due to reduced north-east winds.

Wind speed distribution is fairly stable in DJF, JJA, and SON. At the same time, the variability of the wind dynamics is driven within the MAM only. The wind rose shows that the wind vectorization in DJF, MAM, JJA, and SON is multi-directional in some years. It was suggested that small-scale wind turbines with horizontal rotation be used to avoid re-configuring the wind turbine within different seasons. The sudden multi-directionality of the wind vectorization after forty years may be evidence of the climate change to wind energy generation.

The ANOVA analysis shows that there is a significant difference in all the seasons. Hence, the post-hoc (LSD, Dunnett-C, and Games-Howell test) was further used to affirm that there was a significant difference within each year. Within the SON, wind energy distribution is expected to between 325-950 kWh. MAM, DJF and JJA are to have energy distribution of 539-1700 kWh, 161-650 kWh and 761-3650 kWh respectively. Despite the variation of energy generation over the years within all seasons over Nigeria, it was found that it is predictable and can be optimized using various technological solutions.

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