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**Original Research Article**

# Wind Speed Characterization and Energy Assessment of Abakaliki, Nigeria for Wind Turbines Installation

Okeoghene Eboibi[1]*, Emozino Donatus Edafeadhe[1], Enuabanosa Raymond[1], Diemone Tamaradi[1], Blessing Elo-Oghene Eboibi[2]

[1]Mechanical Engineering Department, Southern Delta University, Ozoro, Nigeria
[2]Chemical Engineering Department, Delta University, Abraka

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***Corresponding author:** Okeoghene Eboibi
Mechanical Engineering Department, Southern Delta University, Ozoro, Nigeria

## Abstract

The focus of this study is to provide an all-inclusive wind data characterization for Abakaliki in Ebonyi State of South-East region of Nigeria and to evaluate its potential wind energy generation to ascertain if wind energy could be a practical source of electricity in that region. A 10-years period (2012-2021) wind speed dataset obtained at 10 m anemometer height was collected from Nigerian Meteorological Agency. The Weibull distribution model was used to analyse the wind speed data. According to the findings, April had the most potential for wind energy capture, while November had the lowest. Important Weibull shape and scale values were found in the investigation, indicating a narrow range of constant wind speeds without the severe turbulence or erratic gusts that are frequently observed elsewhere. At 10 m, the maximum wind speed recorded was 2.56 m/s in 2015, while the minimum was 2.13 m/s in 2014, with an average over the decade being 2.25 m/s. The power density was notably responsive to changes in wind speed, varying from a low value of 5.92 W/m$^2$ in 2014 to a peak value of 10.28 W/m$^2$ in 2015, with an average decadal power density of 7.01 W/m$^2$ and the maximum energy output was 90.05 (K W/m$^2$).h in 2015. Average wind speeds, power densities, and energy outputs increased with increase in height (altitude). Thus, at 100 m, the average wind speed, average power density and energy output are 3.56 m/s, 27.63 W/m$^2$ and 242.04 (K W/m$^2$).h respectively. Conclusively, this study highlighted the potential of small-scale wind turbines for use in household electrification and agriculture.

**Keywords:** Wind Energy Potential, Wind Speed Characterization, Weibull Distribution, Wind Power Density, Renewable Energy, Small-Scale Wind Turbines, Wind Resource Assessment.

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## INTRODUCTION

A nation's advancement in social and economic sectors greatly depends on electricity, which may originate from renewable sources such as wind power [1]. There has been an increasing focus on energy technologies in recent years [2]. Countries facing energy deficits frequently report lower educational outcomes and higher poverty rates. Unresolved energy challenges can hinder advancements in fields like technology, communication, and education, particularly in developing nations. One potential, reliable, affordable and sustainable renewable energy source is wind power [2, 3]. Due to substantial advancements in understanding wind resources and their efficacy, wind power is becoming more popular worldwide due to its advantages, including established technology and environmental benefits [4,5,6]. Unlike solar energy, which often maintains a more steady presence in tropical areas, wind patterns can vary dramatically from one site to another, making accurate wind data for particular places crucial to the success of wind projects. According to forecasts, wind energy might account for 25–30% of the world's energy production by 2030 [7].

Despite Nigeria being the most populous country in Africa, having an abundance of renewable resources, such as solar, biomass, hydropower, and wind, is still facing energy challenges due to a weak electricity grid and inadequate power generation capacity [8]. The amount of electricity needed in Nigeria is far greater than what is now produced. Nigeria's main energy sources are

hydropower and fossil fuels, both of which contributes to climate change. Nigeria's energy portfolio might be expanded and electricity accessibility could be improved with the help of wind energy. A crucial component of using wind energy is the wind energy potential [3]. Wind energy is advantageous in areas where it is both technically and financially possible due to its versatility and capacity to serve as a decentralised energy source [9] [10] especially in Nigeria that there is need for renewable power [11]. There are many technical advantages to wind energy: it produces clean power because it doesn't require burning fuels, which means there are no greenhouse gas emissions or air pollution during operation [3]. Additionally, because it is renewable and sustainable, current turbines effectively convert energy. Grid stability can be supported by wind projects that are customised to fit the requirements of large electricity networks or small villages.

Wind turbines provide a more reliable energy source because they can produce electricity at night and under rainy circumstances, unlike solar energy, which only works during the day. However, especially during the winter, taller turbines can drastically reduce carbon dioxide emissions [4]. Technological developments are improving the performance and dependability of turbines, and wind energy contributes to the creation of jobs in the technical and engineering fields Turbulence and appropriate parameters are important design consideration that can affect the energy yield capacity of wind turbines [12, 13].

Nigeria's coastal (south-south) and northern regions have strong wind potential, but the southeast region, particularly Abakaliki town in Ebonyi State, lacks adequate wind data. According to [14], wind speeds vary throughout Nigeria, with the interior and the northern areas frequently having higher potential. Wind speeds are lower in the south and progressively rise as one moves toward the north. According to [15], elevation, topography, and changes throughout time all affect wind speed. The general assessments of the wind energy potentials for the Southeast zone are available, however, there are lack of recent comprehensive wind data for Abakaliki town in Ebonyi State. This is because many of the recent studies use generalized wind data from nearby places or out-of-date information, ignoring the fact that the mountainous terrain of Abakiliki as well as its unique position between rainforest and savanna zones can produce distinct local weather or wind patterns. Furthermore, there aren't many studies that concentrate on contemporary low-wind speed turbines in this specific area. Therefore, to address this research gap, the major objective of this study is to provide a more accurate comprehensive Abakaliki's wind speed and energy potential as determined from the wind data obtained from Nigeria Meteorological (NiMet) Agency. Abakaliki is an important center for trade and industry, particularly for products like yams, cassava, rice, and palm oil. The residents of Abakaliki would profit immensely from the installation of wind energy solutions, which would be useful for both residential and commercial applications.

## 2.0 MATERIALS AND METHOD

### 2.1 Study area

Located in the southeast of Nigeria, between longitudes 7°0.50'E and 8°0.30'E and latitudes 5°0.50'N and 6°0.50'N, lies Ebonyi State, with Abakaliki Town as its capital. It shares borders with Benue State to the north, Enugu State to the west, Cross River State to the east, and Imo and Abia States to the south [16]. A map of the Abakaliki region is shown in Figure 1, which is based on the Environmental and Social Impact Assessment (ESIA) for the proposed Ebonyi State Special Agro-Industrial Processing Zone (SAPZ) hub that was finished in April 2024. The city of Abakaliki is located at latitude 6.33°N and longitude 8.12°E, with an elevation of 88.44 meters, according to [17].




**Figure 1: Ebonyi State map showing Abakiliki geographical location (ESIA report, 2024)**

### 2.2 Wind data collection

A ten-year wind speed dataset, which runs from 2012 to 2021 was collected from the Nigerian Meteorological (NiMet) Agency. The collected wind speed dataset is presented in Table 1.

**Table 1: The monthly wind speed (m/s) for each year from 2012 to 2021 for Abakaliki region**

| Year/Month | JAN | FEB | MAR | APR | MAY | JUNE | JULY | AUG | SEP | OCT | NOV | DEC |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **2012** | 2.27 | 2.73 | 2.33 | 3.06 | 2.35 | 2.04 | 2.22 | 2.85 | 1.77 | 1.69 | 1.94 | 1.66 |
| **2013** | 2..20 | 2.42 | 2.24 | 2.67 | 2.39 | 2.51 | 2.42 | 2.70 | 2.06 | 1.80 | 2.00 | 2.31 |
| **2014** | 1.73 | 1.71 | 2.65 | 2.67 | 2.32 | 2.08 | 2.70 | 2.68 | 1.89 | 1.60 | 1.77 | 1.69 |
| **2015** | 3.25 | 2.61 | 2.46 | 2.59 | 2.75 | 2.67 | 2.48 | 2.27 | 2.08 | 1.80 | 1.41 | 3.38 |
| **2016** | 2.78 | 1.95 | 2.86 | 2.72 | 2.39 | 2.16 | 2.07 | 2.54 | 1.67 | 1.99 | 1.82 | 1.77 |
| **2017** | 2.O2 | 1.55 | 2.76 | 2.63 | 2.37 | 2.06 | 2.52 | 2.58 | 2.26 | 1.92 | 1.79 | 1.74 |
| **2018** | 1.92 | 2.42 | 2.91 | 3.02 | 2.45 | 2.33 | 2.11 | 2.42 | 1.60 | 1.76 | 1.65 | 1.48 |
| **2019** | 2.07 | 2.06 | 2.88 | 2.92 | 2.32 | 2.43 | 2.09 | 2.20 | 2.11 | 1.45 | 1.77 | 1.43 |
| **2020** | 2.91 | 1.80 | 2.52 | 2.79 | 2.39 | 2.41 | 2.20 | 2.73 | 1.94 | 1.74 | 1.43 | 1.82 |
| **2021** | 1.51 | 1.69 | 2.31 | 2.92 | 2.60 | 2.61 | 2.37 | 1.92 | 2.11 | 2.01 | 2.13 | 2.02 |

### 2.3 Wind speed data processing and analysis

The collected wind speed dataset was processed by cleaning, filtering, organising, and transforming it into a format that can be used for analysis and decision-making. The cleaned and filtered wind dataset was then analyzed or evaluated using the Weibull distribution statistical model. Figure 2 depicts the flow or block diagram of the steps or methods used for the study.

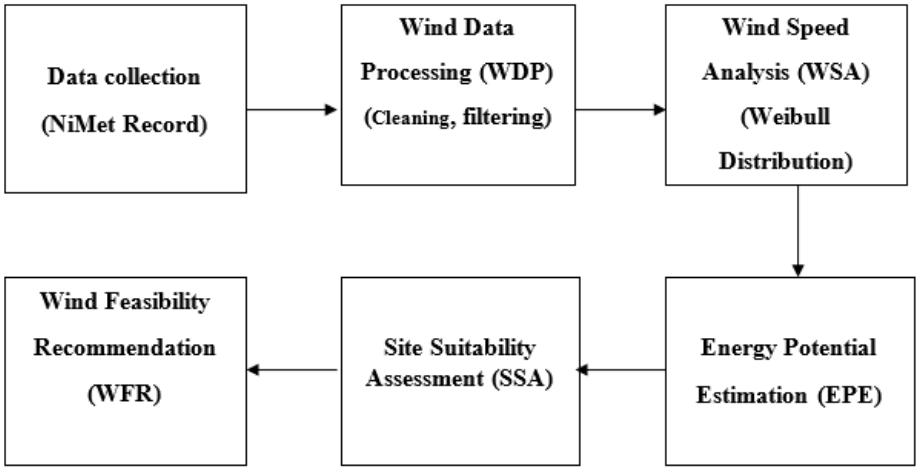



**Figure 2: Block diagram of the Wind Speed Characterization Stages (WSCS)**

The probability density function linked to the Weibull model known as Weibull probability density function was used to better understand wind speed fluctuations. This is expressed in Equation (1) [18]:

$$f(D_p) = \left(\frac{K}{C}\right)\left(\frac{V}{C}\right)^{K-1} \exp\left[-\left(\frac{V}{C}\right)^{K}\right] \quad \text{(k, c, and v > 0)} \qquad (1)$$

Where K= Shape parameter (dimensionless), C = Scale parameter (dimensionless), and $W_S$ =Wind speed (m/s)

The shape parameter (K) indicates the curvature of the distribution, which relates to the variability of wind speed, while the scale parameter (C) determines the location of the curve and relates to the average wind speed [19]. The cumulative distribution of the Weibull function is shown in Equation (2), as stated by [20] and the shape parameter was calculated using Equation (3), as provided by [21].

$$f(D_c) = 1 - \exp\left[-\left(\frac{W_S}{C}\right)^{K}\right] \qquad (2)$$

$$(K_{WEIBULL}) = K = \left(\frac{\delta}{W_{SA}}\right)^{-1.086} \qquad (3)$$

Where δ = Standard deviation and $W_{SA}$ = Average wind speed.

The scale parameter ($C_{WEIBULL}$) of weibull distribution function was estimated using Equation (4) as given by [18].

$$C_{WEIBULL} = C = \frac{W_{SA}\,K^{2.6674}}{0.814+0.816K^{2.73855}} \qquad (4)$$

The most feasible wind speed $W(S)_F$ was calculated using Equation (5) [22]:

$$W(S)_F = 2C\,(0.5)\left(\frac{K-1}{K}\right)^{\frac{1}{K}} \qquad (5)$$

The wind speed carrying maximum energy $W(S)_{me}$was evaluated using the expression (Equation (6)) given by [22]:

$$W(S)_{ME} = 2C\,(0.5)\left(\frac{K+2}{K}\right)^{\frac{1}{K}} \qquad (6)$$

The average wind speed was estimated using Equation (7) as given by [23] Suthyajith (2006).

$$W_{SA} = \left(\frac{1}{n}\sum_{i=1}^{n}(V_W)^3\right)^{\frac{1}{3}} \quad (7)$$

Where n = Number of wind data, $V_W$ = Wind velocity (m/s), and $W_{SA}$ = Average wind speed (m/s).

The standard deviation (S.D) is given in Equation (8):

$$S.D = \sqrt{\frac{1}{n}\sum_{i=1}^{n}(V_W - W_{SA})^2} \quad (8)$$

Power law is important in wind resource because it gives the expression of wind speed at various hub heights (h) and this is expressed as Equation (9).

$$V_{wsc} = V_{wsr}\left(\frac{h_c}{h_r}\right)^{\alpha} \quad (9)$$

Where $V_{wsc}$ = Wind speed at $h_c$; $V_{wsr}$ = Wind speed at reference height $h_r$; $h_c$ = Height at which the wind speed is to be calculated; $h_r$ = Reference height; and $\alpha$ = Wind shear exponent, which is usually 0.143 for terrain roughness coefficient of the turbine as stated by [27].

The power in the wind is given in Equation (10):

$$P_w = F \times V \quad (10)$$

Where, $P_w$ = Wind power, F = Force and V = the velocity of the rotating wind turbine

The average power that can be extracted from the wind turbine is expressed in Equation (11) as stated by [20] Oluseyi et al. (2012).

$$P_A = 0.5(P_C)(D_{air}h)A(W_S)^3 \quad (11)$$

Where, $P_A$ = Average power (watt); $W_S$ = wind speed (m/s); $D_{airh}$ = Air density at height (h) (Given as 1.225kg/m$^3$); $P_C$ = Coefficient of power, which implies the part of wind energy captured by wind turbine [24]; and A = Area in square meter (m$^2$).

Wind power density is a key measurement for evaluating wind resources at a location, measured as the wind power available passing through a vertical area over a set time period [25] In a research area, wind speed distribution and turbine power curves were combined to turn wind speed into power density [4]. This transformation allowed for the estimation of yearly energy output, providing a thorough evaluation of the wind energy potential in the area [26]. This study looks at wind power density at a standard measurement height of 10 m, using Equation (12) for calculation, as reported by [4].

$$W_{PDh} = 0.5(D_{air}h)(W_{SA})^3 \quad (12)$$

Where, $W_{PDh}$= Average Wind power density at height (h); $W_{SA}$ = Average wind speed at height (h); and $D_{airh}$ = Air density at height (h) (Given as 1.225kg/m$^3$).

The available energy output per unit area over a given period of time is given by the kinetic energy flux as stated in Equation (13) [27]:

$$E_{WA} = 0.5(D_{air}h)A(W_{SA})^3 = W_{PD} \times t \quad (13)$$

Where t = Time in hours and $E_{WA}$ = Average wind energy ((W/m$^2$.h)

## 3.0 RESULTS AND DISCUSSION

**3.1 Wind Characterization:** Average wind speed, power density and energy output

The monthly wind speed for each year starting from 2012 to 2021 (Table 1) is presented graphically in Figure 3. As seen in Figure 1, the month of April had the highest average wind speed followed by the month of March and the lowest was in the month of November, while the maximum average wind speed occurred in the year 2015.

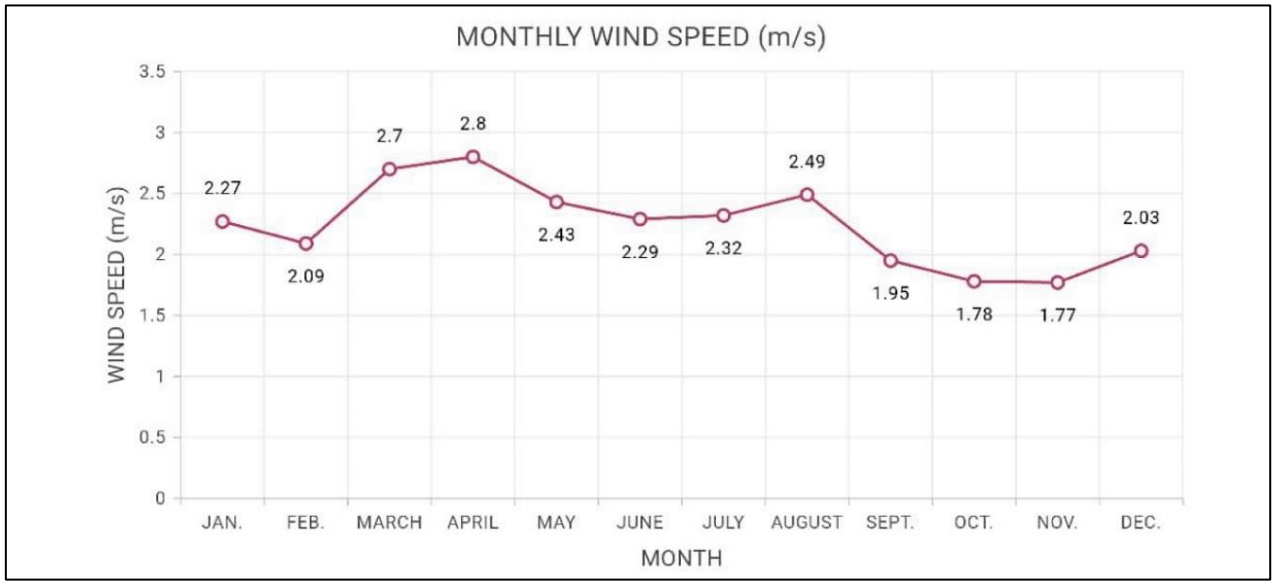



**Figure 3: The average monthly wind speed for the period of ten years (2012 - 2021).**

The average monthly wind speed for the 10-year period is depicted in Figure 3. From Figure 3, it can be seen that April had the strongest wind with an average wind speed of 2.80 m/s, closely followed by the month

of March with an average wind speed of 2.70 m/s. The month of November recorded the weakest wind with an average wind speed of 1.77 m/s.

Table 2 shows the annual wind speed, standard deviation, and calculated values of the Weibull distribution functions at 10 m height. Table 2 revealed that there were variations in the annual wind speed recorded at 10 m height for the 10-years period. The results in Table 2 indicates that wind speed with its corresponding power density and energy output changed annually from 2012 to 2021. As seen in Table 2, the strongest or highest annual wind speed at 10 m anemometer height was documented in 2015 as 2.56 m/s, approximately 3.0 m/s, with the highest Weibull shape (K), scale parameters (C), wind power density ($W_{PDh}$) and energy output (**E**$_{WA}$) of 3.54, 2.85 m/s, 10.28 W/m² and 90.05 (KW/m$^2$).h, respectively. This was followed by the year 2013 with an annual wind speed of 2.39 m/s having a Weibull shape (K), scale parameters (C), wind power density ($W_{PDh}$) and energy output (**E**$_{WA}$) of 3.33, 2.67 m/s, 8.36 W/m² and 73.23 (KW/m$^2$).h, respectively. While year 2014 had the lowest annual wind speed with a Weibull shape, scale parameters, power density and energy output of 2.13 m/s, 3.30, 2.38 m/s, 5.92 W/m², and 51.86 KW/m$^2$).h, respectively.

**Table 2: The annual wind speed, standard deviation, and calculated values of the Weibull distribution functions at 10 m height**

| YEAR | $(W_{SA})$(m/s) | S.D | K | C(m/s) | $W(S)_{ME}$ (m/s) | $W(S)_F$ (m/s) | $W_{PDh}$ (W/m$^2$) | EWA (KW/m$^2$)h |
|---|---|---|---|---|---|---|---|---|
| **2012** | 2.24 | 0.76 | 3.23 | 2.50 | 2.90 | 2.23 | 6.88 | 60.43 |
| **2013** | 2.39 | 0.79 | 3.33 | 2.67 | 3.08 | 2.40 | 8.36 | 73.23 |
| **2014** | 2.13 | 0.71 | 3.30 | 2.38 | 2.75 | 2.13 | 5.92 | 51.86 |
| **2015** | 2.56 | 0.80 | 3.54 | 2.85 | 3.23 | 2.59 | 10.28 | 90.05 |
| **2016** | 2.23 | 0.84 | 2.89 | 2.50 | 3.00 | 2.16 | 6.79 | 59.64 |
| **2017** | 2.19 | 0.79 | 3.03 | 2.45 | 2.90 | 2.15 | 6.43 | 56.32 |
| **2018** | 2.17 | 0.70 | 3.42 | 2.42 | 2.77 | 2.19 | 6.26 | 54.84 |
| **2019** | 2.14 | 0.69 | 3.42 | 2.38 | 2.72 | 2.15 | 6.00 | 52.56 |
| **2020** | 2.26 | 0.90 | 2.72 | 2.54 | 3.11 | 2.15 | 7.07 | 62.10 |
| **2021** | 2.15 | 0.85 | 2.74 | 2.42 | 2.96 | 2.05 | 6.09 | 53.49 |
| **Decadal average** | 2.25 | 0.97 | 3.16 | 2.51 | 2.94 | 2.22 | 7.01 | 61.45 |

The strong winds with the highest energy output experienced in year 2015 were probably due to more powerful pressure differences and regional weather factors, which helped produce more wind energy (i.e. boosted energy production) while the low winds observed in year 2014 could be due to the fact that the air circulation was not strong (i.e. weaker wind flow), which had a decreased impact on energy output. Over the 10-years period, the wind speed, Weibull shape, scale parameters, power density and energy output are 2.25 m/s, 3.16, 2.51 m/s, 7.01 W/m², and 61.45 K W/m$^2$).h, respectively.

The computation of the average wind speed ($W_{SA}$) power density( $W_{PDh}$ ) and energy output($E_{WA}$) at 10 m to 100 m anemometer heights from year 2012 to 2021 are graphically represented in Figure 4 (a) – (c), respectively.

Figure 4(a) show that over the 10-years period (2012-2021), the average wind speed increased as the anemometer heights increased from 10 m to 100 m indicating that stronger winds occur at higher elevations. In addition, from year 2012 to 2021 at all heights the year 2015 recorded the highest average wind speeds (2.56 – 3.56 m/s) while year 2014 had the lowest (2.13 – 2.96 m/s). This suggests that there are annual changes in wind patterns.

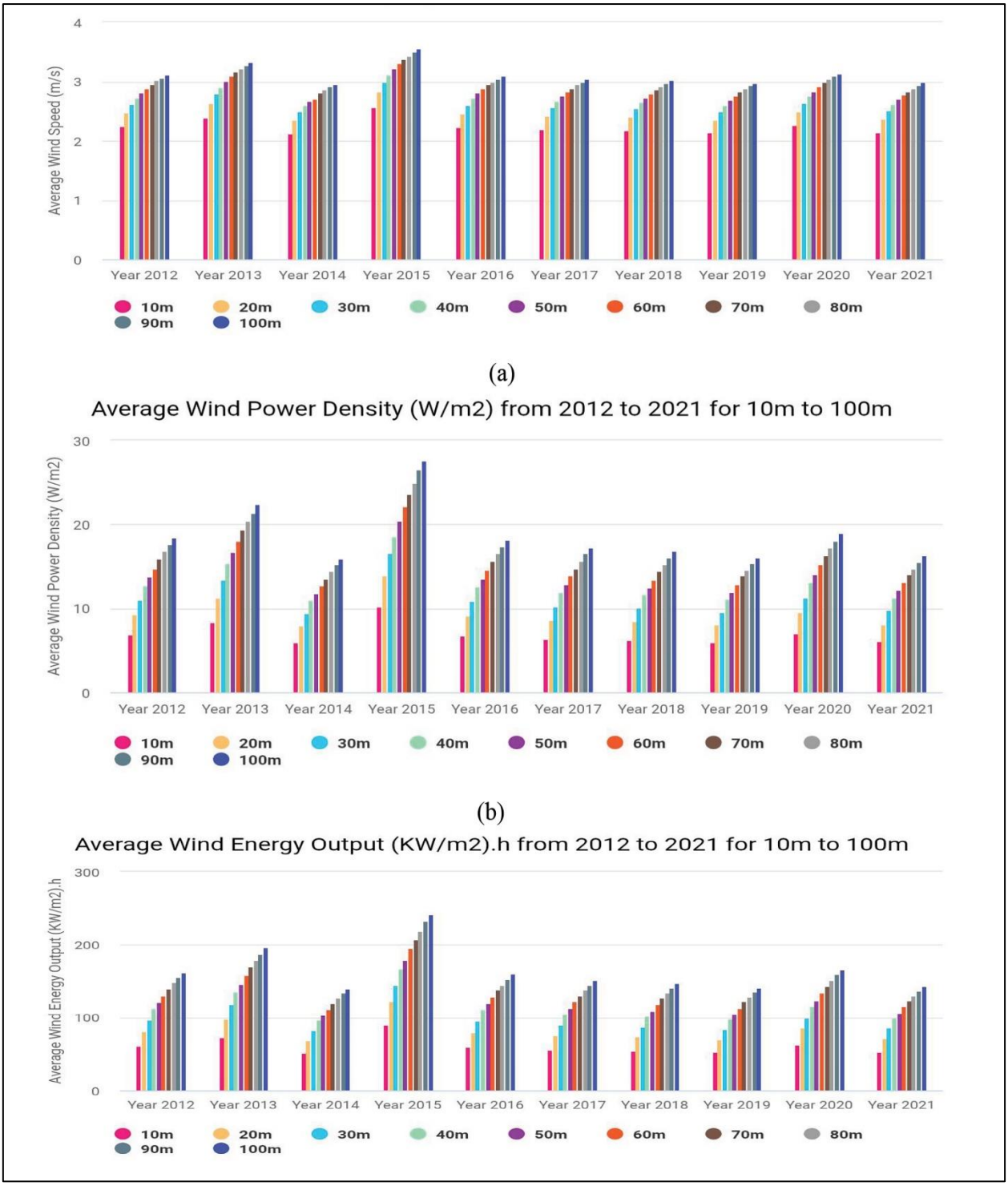



**Figure 4: (a) Average wind speed (m/s) from 2012 to 2021 for different heights from 10m to 100m (b) Average wind power density (W/m$^2$) from 2012 to 2021 for different heights from 10m to 100m. (c) Average wind energy output ((KW/m$^2$).h) from 2012 to 2021 for different heights from 10m to 100m.**

The strong winds in 2015 came from intense air movement while the weak or lowest wind in year 2014 at all altitudes may likely be as a result of stagnant air or unexpected weather. As seen in Figure 4(b), the average wind power density increased with incremental rise in heights (10 m to 100 m altitude) over the 10-years period, which implies that higher wind power densities are obtained at higher elevations or altitudes. Nevertheless, year 2015 had the highest average wind power density at all heights (10.28 – 27.63 W/m$^2$) while year 2014 had the lowest average wind power density (5.92 – 15.98 W/m$^2$). This shows significant yearly variations, and that strong wind pressure and better air circulation were most likely be the cause of the high wind power densities observed in 2015 at the different heights. In contrast, the lower wind power densities at all heights in year 2014 indicated

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weak air movement, which could have been brought on by stable weather or climate abnormalities. Reduced wind power density and energy efficiency could result from this unaltered atmosphere.

Figure 4(c) revealed that the average wind energy output rises with increase in the anemometer heights (10 – 100 m) for the 10-years period (2012-2021), implying that higher energy output is obtained at higher altitude or elevation. Also, as seen in Figure 4(c), at the different heights of 10 to 100 m, the highest average wind energy output (90.05 – 242.04 KW/m$^2$)h) was obtained in year 2015 while lowest average wind energy output (51.86 - 139.11 KW/m$^2$)h) was achieved in year 2014. The increased wind energy output in 2015 was related to enhanced air movement. Conversely, the decline in wind energy output across all heights in 2014 resulted from inadequate air flow.

### 3.2 Comparison of wind speed and power density with other literature values

The annual wind speed and power density values obtained in this study are compared with the values obtained at 10 m and 50 m heights by other researchers for other locations as reported in the literature. The comparisons are presented in Table 4.

**Table 3: Comparison of annual wind speed and power density values for Abakaliki with values obtained for other locations in Nigeria**

| Height (m) | Location | Annual Peak Wind Speed (m/s) | Annual Peak Power Density (W/m$^2$) | Reference |
|---|---|---|---|---|
| 10 | Enugu | 5.42 | 96.98 | [30] |
| | Onitsha | 3.59 | 28.34 | |
| | Owerri | 3.30 | 23.23 | |
| | Benin | 1.496 | 2.692 | [28] |
| | Lafia (Nasarawa State) | 3.12 | 27.11 | [29] |
| | Abakaliki | 2.56 | 10.28 | This study |
| 50 | Lafia (Nasarawa State) | 4.71 | 92.89 | [29] |
| | Abakaliki | 3.22 | 20.45 | This study |

From Table 4, it can be seen that average wind speed obtained in this study for Abakaliki is relatively lower than the values reported Enugu and Onitsha but higher than the values that was obtained for Benin and comparatively similar to the reported values for Owerri and Lafia at 10 m height. Furthermore, the average power density achieved in this study for Abakaliki is lower than the reported values for Enugu, Onitsha, Owerri and Lafia, respectively. The values obtained for Abakaliki in this study highlights the potential for small-scale wind turbines, for home electrification and agriculture. As the height increases from 10m to 50m, the wind speed and power density also rises, leading to higher wind energy production at 50 m.

## CONCLUSION

The analysis of wind speed data for Abakaliki found an annual peak wind speed of 2.56 m/s at a height of 10 m in April 2015, which is below the minimum threshold for effective wind energy use. The Weibull shape parameter indicated consistent but low wind speeds, with a decadal average of 2.25 m/s, average power density of 10.28 W/m² and average energy output of 90.05 (K W/m$^2$).h in 2015, categorizing Abakaliki as wind energy class one. Although projects of this magnitude are not practical, the study highlighted the potential of small-scale wind turbines, such as Vertical Axis Wind Turbines, for uses including household electrification and agriculture. In 2015, the average wind speed, power density, and energy output at 100 meters were 3.56 m/s, 27.63 W/m$^2$, and 242.04 (K W/m$^2$).h, respectively. The value of taller turbine installations is highlighted, and the significance of height in wind energy production is reinforced, as increasing height from 10 to 100 meters dramatically increases wind speed, power density, and energy output. The study comes to the conclusion that, although large-scale projects are not practical, there are chances for small-scale renewable energy solutions designed for low-wind conditions.

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