CHARACTERIZATION OF WIND ENERGY POTENTIAL IN LADEBA, LAGOS STATE, NIGERIA

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ABSTRACT

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| Wind energy is a promising renewable resource for addressing power deficits and reducing greenhouse gas emissions. Wind resource assessment (WRA) is the first and most important step in the design and setting up of any wind power plant. It provides important input for sizing, siting and techno-economic feasibility of any wind power plant by accurately estimating its energy production. This study evaluates the wind energy potential of Ladeba, Ibeju Lekki, Lagos State, Nigeria, using wind speed data collected over 24 months (May 2021 to April 2023) from an observation mast at 81.5 m, 80 m, 61 m, and 41 m heights in line with the IEC 61400-12-1 standard. The Weibull and Rayleigh distribution models were employed in characterizing wind speed distribution using shape parameter (k), scale parameter (c), maximum wind speed (Vmax), Most probable wind speed (Vmp),wind power density (WPD), and wind energy density (WED). The results shows at the highest measurement height (81.5 m), the Weibull distribution estimated k, c, Vmax, Vmp, WPD and WED to be 10.89, 7.99 m/s, 7.32 m/s,7.25 m/s, 473.52 W/m², 410781.4 Wh/m2 respectively while the Rayleigh model estimated k, c, Vmax, Vmp, WPD and WED to be 2, 8.98 m/s, 10.40 m/s, 6.35 m/s, 8.86 W/m2 and 6547.50 Wh/m2 respectively. At the lowest height (41 m), the Weibull distribution estimated k, c, Vmax, Vmp, WPD and WED to be 6.25, 4.89 m/s, 4.22 m/s, 4.10 m/s, 132.90 W/m², 97265.94 Wh/m2 respectively while the Rayleigh model estimated k, c, Vmax, Vmp, WPD and WED to be 2, 5.45 m/s, 6.86 m/s, 3.85 m/s, 5.38 W/m² and 3928.95 Wh/m2 respectively with values dropping sharply due to reduced wind speeds at lower altitudes. At 81.5 meters, the Weibull distribution estimated a power density of 473.52 W/m², significantly higher than that of Rayleigh distribution’s 8.86 W/m². This trend persists even at lower heights, with the Weibull distribution always forecasting higher energy generation potential due to its flexibility in modeling more variable wind conditions. In contrast, the Rayleigh distribution tends to suggest lower power densities, as it is better suited for regions with more stable, unimodal wind profiles. The Weibull distribution consistently produces higher WPD & WED values compared to the Rayleigh distribution at all heights, reflecting its flexibility in capturing the variability of wind speeds. |

*Keywords:* *Wind Speed, Weilbull, Rayleigh, Wind Power Density, Wind Power Potential*

1. Introduction

Wind energy is one of the most promising renewable energy sources in the world, as it can provide clean, abundant, and affordable electricity for various applications. Recently, there has been an increased interest in wind energy technology (Shen *et al*., 2010; Ellabban *et al*., 2014; Ayodele *et al*., 2016; Mazzucato and Semieniuk, 2018). The availability and variability of wind resources are highly dependent on the local climate and terrain conditions, which affects the performance and reliability of wind power systems.

The global wind power business has developed at a rate of about 26% annually during the last 20 years (Twidell and Weir, 2015). The United States is reported to have a 20% share of the global wind market, with Europe and China steadily building reliable wind energy markets for a over decade (Aslani and Wong, 2014; Lin and Moubarak, 2014; Connolly *et al*., 2016). Brazil, South Africa, and India are projected to be among the next fast rising economies to profit from wind power in the next five years (Sasana and Ghozali, 2017). Wind energy is projected to provide 25–30% of the world's energy by 2030 (Moriarty and Honnery, 2012;Öztürk and Serkendiz, 2018). This is supported by the emergence of wind power as a cost-effective source in power grid applications across developed and developing markets. The growing interest in wind power investment by investors across Northern Europe and America is a testament to both the technical and financial viability of the technology (Ellabban *et al*., 2014; Sen and Ganguly, 2017).

Wind resource assessment (WRA) is the first and most important step in the design and setting up of any wind power plant. It provides important input for sizing, siting and techno-economic feasibility of any wind power plant by accurately estimating its energy production (Mortensen, 2012). WRA determines and/or verifies the sufficiency of wind resources in a selected site and also generates representative data to be used in estimating the performance and economic viability of wind turbines. In a nutshell, WRA is a comprehensive screening process for wind turbine installation sites (Lawan *et al*., 2013).

Nigeria is a country with a large population and a high demand for electricity, but also faces challenges such as power shortages, grid instability, and high costs of power generation. Wind energy could offer a viable solution to some of these challenges, as Nigeria has significant wind energy potential, especially in the northern and coastal regions of the country.Ladeba is a coastal community in Ibeju Lekki, Lagos, located on 6° 31' 0" North, 3° 43' 0" East. Measurements from preliminary feasibility study in Ladeba shows average three months (July to September 2015) wind speed of about 5.3 m/s, indicative of feasibility for wind power generation (Federal Ministry of Power, 2015). This study properly characterizes the wind energy potential of Ladeba in line with the globally accepted IEC 61400-12-1 standard.

**2.0 Wind Resource Assessment Studies in Nigeria**

Wind resource studies carried out in Nigeria are based on data from meteorological stations measured at 10 m height only (Ajayi *et al*., 2011a; Ajayi *et al*., 2011b; Fagbenle *et al*., 2011; Ohunakin and Akinnawonu, 2011; Ahmed *et al*., 2013; Ajayi *et al*., 2013; Ajayi *et al*., 2014). Results from just one data point (one measurement height) makes it difficult for estimation of wind gradient exponent/wind shear and site wind profile determination (Nelson, 2009; Sorensen, 2011; MEASNET,2016).

Researchers in Nigeria relied on extrapolated data to estimate energy potential at turbine hub heights (most hub heights of turbines are from 80 m and above) for study locations. Oyedepo *et al*. (2012) underscored the importance of the wind speed at hub height as the most important wind speed in wind power applications. Wind studies in Nigeria currently extrapolate (to hub height) data from wind speed measured at 10 m. Extrapolated data tinkers with the accuracy of prediction (Letcher, 2017).

The IEC 61400-12-1 wind assessment protocol stipulates that the topmost anemometer should positioned at a height of a least 2/3 of the height of the planned turbine (Letcher, 2009; MEASNET, 2016). Wind studies carried out in Nigeria lack this feature as measurements were all taken from weather stations at 10 m height. Data from meteorological stations used in wind speed assessment studies in Nigeria is mostly, gotten from measurement equipment mounted around airports or research/academic institution surrounded by wind breaks This could affect the Integrity of the data (Brower, 2012).

**2.1 Wind Energy Potential Characterization Parameters (Measured)**

**Wind Speed**Wind speed is the most important parameter for wind power potential, as it determines the amount of kinetic energy available in the wind. The power output of a wind turbine is proportional to the cube of the wind speed, which means that a small increase in wind speed can result in a large increase in power output. Wind speed varies with height, terrain, and time (Okeniyi *et al*., 2014). Therefore, it is important to measure and model the wind speed at different heights and locations, and to account for the temporal variations such as diurnal, seasonal, and interannual cycles. Different methods have been used to measure and model the wind speed, such as anemometers, Doppler radars, satellites, numerical weather prediction models, and statistical models. The accuracy and reliability of these methods depend on the quality and quantity of the data, the spatial and temporal resolution, and the validation procedures (Ajayi *et al*., 2011a; Ajayi *et al.* 2011b).

The wind speeds in Nigeria range from about 2 to 9.5 m/s (Ajayi *et al*., 2011a; Ahmed *et al*., 2013). Studies shows wind speeds are relatively low in the South and increases gradually upward toward the North (Idris, 2012; Agbetuyi *et al*., 2012). Ajayi *et al* (2011a) reported mean wind speeds of between 2.6 and 9.8 m/s in North-Western Nigerian. Ahmed *et al*., (2013) *and* Ajayi *et al*., (2011b)reported average wind speeds of 2.2 and 10.1 m/s respectively in stations across North Central Nigeria. Ajayi *et al*., (2014) from their 24-year data analysis in South Western Nigeria reported wind speeds of between 2.9 and 5.8 m/s.**Air Pressure**Air pressure is another parameter that affects the wind power potential of a site. Air pressure is the force exerted by the weight of air molecules on a unit area of surface. It can be measured by barometers or derived from temperature and altitude. Air pressure influences the density of air, which affects the power density of wind. The power density is the amount of power per unit area available in the wind. It depends on both the wind speed and the air density. The higher the air pressure (or density), the higher the power density.

Air pressure also influences the horizontal differences in pressure (or pressure gradient), which drive the wind flow (Letcher, 2009). The higher the pressure gradient, the higher the wind speed. Air pressure also varies with height, terrain, and time. Albani *et al*. (2014) measured the air pressure with a sensor built into the datalogger for 1(one) year recording daily readings. Baseer (2017) observed the air pressure using the ISO 2533 template. The pressure sensor was positioned at a point 10m higher than the data logger for a protective enclosure. He achieved the recommended accuracy numbers for the measurement.

**Temperature**Temperature is another parameter that affects the wind power potential of a site. Temperature is a measure of the average kinetic energy of air molecules. It can be measured by thermometers or derived from radiation measurements. Temperature influences the density of air, which affects the power density of wind. The higher the temperature, the lower the air density, and hence the lower the power density. Temperature also influences the horizontal differences in temperature (or temperature gradient), which drive the wind flow. The higher the temperature gradient, the higher the wind speed (Oyedepo *et al.*, 2012). Temperature also influences the capacity of air to hold water vapor, which affects the relative humidity, clouds, precipitation, and storms. Temperature also varies with height, terrain, and time.

**1.4 Wind Energy Potential Characterization Parameters (Derived)**

**The Scale and Shape Parameters**

The scale parameter and the shape parameter are two parameters that describe the wind speed distribution at a site. The wind speed distribution is usually modeled by a probability density function (PDF), such as the Weibull PDF, which is widely used in wind energy assessment. The Weibull PDF has two parameters: the scale parameter (k) and the shape parameter (c). The scale parameter represents the average wind speed at a site, while the shape parameter reflects the variability of the wind speed. A higher shape parameter indicates a lower variability and a more peaked distribution. A lower shape parameter indicates a higher variability and a more spread distribution.

The scale and shape parameters can be estimated by different methods, such as graphical, method of moment, energy pattern factor, mean standard deviation, power density methods, and genetic algorithm. The accuracy of these methods depends on the quality and quantity of the wind speed data available. Different methods may result in different values of the parameters, which may affect the wind power potential estimation. Therefore, it is important to choose an appropriate method for estimating the Weibull parameters and to evaluate the goodness-of-fit of the estimated distribution.

Characterization (assessment of wind speed potential) of wind speed is done using the scale (c) and shape (k) parameters obtained from wind speed distribution (Weilbull, Rayleigh, Gumbel, Gaussian etc). These parameters are in turn used in the estimation of other useful site wind power indicators like the “wind speed that carries the maximum energy”, “most probable wind speed”, “the wind power density” and the “wind energy density".

Okeniyi *et al*. (2014) used the Gumbel and Weilbull probability functions in estimating the scale and shape parameters, the mean wind speed, and wind power density in Katsina, Katsina State, Warri, Delta State, Calabar, Cross River State in Nigeria. Their study however did not estimate the “most probable wind speed” and “wind speed that carries the maximum energy” and was limited to the aforementioned states. Their study also did not adhere to the standard measurement protocol as stipulated by IEC 61400-12-1. The climates of these states differ markedly with that of Lagos (the commercial nerve center of Nigeria).

Ajayi *et al*. (2011c) characterized the wind profile of Sokoto state using weather data from meteorological stations at 10 m height. The Weilbull function was used in the determination of the scale and shape parameters, “most probable wind”, “wind speed that carries the maximum energy” and “wind power density”. The IEC 61400-12-1 protocol for wind assessment wasn’t followed in this study. Oyedepo *et al*. (2012) assessed the wind energy potential of Enugu, Owerri and Onitsha in South-Eastern Nigeria using the two-parameter Weilbull function. Results were taken at a single point (10 m height) and characterized using the “most probable wind”, “wind speed that carries the maximum energy” and “wind power density” parameters. This study also did not adhere to the standard measurement protocol as stipulated by IEC 6140012-1.

**1.4.3 Most Probable and Maximum Energy Carrying Wind Speeds**

The most probable wind speed (Vmp) and the maximum energy carrying wind speed (VmE) are important parameters commonly used in assessing the wind energy potential of any given area. The most probable wind speed refers to the wind speed with the highest occurrence frequency in a given wind probability distribution. The maximum energy carrying wind speed denotes the wind speed that carries the highest amount of energy (Saeed *et al*., 2019). Equations 2 and 4 shows how the Vmp is estimated while equations 3 and 5 shows how VmE is computed from the average shape and scale parameters.

(Weibull Model) (1)

Or

(Raleigh Model) (2)

And

(Weibull Model) (3)

Or

(Raleigh Model) (4)

Where = Weilbull shape parameter, c = scale parameter.

VmE is a parameter normally considered before a wind turbine installation is done at any site. The wind speed that carries the maximum energy (VmE) is the wind speed that has the highest power density at a site. Turbine designers strongly recommend that, for optimal performance, the rated wind speed should be close to VmE (Saeed *et al*., 2019). The most probable wind speed is useful for determining the cut-in speed of a wind turbine, which is the minimum wind speed required for the turbine to start generating power. The cut-in speed should be close to or lower than the most probable wind speed to ensure that the turbine can operate frequently and efficiently.

Wind power potential in South-Western Nigeria (Lagos inclusive) was assessed by Ajayi *et al*. (2014). Wind speed from Meteorological station at 10 m height was used in the determination of Weilbull parameters, “most probable wind”, “wind speed that carries the maximum energy” and “wind power density”. This study even though carried out for some locations within Lagos did follow the standard measurement protocol (JEC 61400-12-1) for wind power assessment; with data obtained from just a single point (10 m height).

**Wind Power Density and Wind Energy Density**

The wind power density (WPD) and the wind energy density (WED) are two indicators of the wind power potential at a site. The WPD is defined as the average power per unit area available in the wind over a certain period of time, usually one year. The WED is defined as the average energy per unit area available in the wind over a certain period of time, usually one year.

Wind power density (WPD), sometimes called wind power potential or wind power per unit area, is defined as the ratio of the power in wind to the swept area of the wind turbine. It is a quantitative measure of the amount of power that can be generated from the wind regimes in a given area. WPD can be computed using the Weibull parameters in equation 5 (Pobocíkova *et al*., 2018) from

(5)

where

ρ is the density of air at the study site. At standard conditions (sea level, 15 0C) average air density, ρ0 is 1.225 kgm-3.

The WPD and WED are useful for comparing different sites in terms of their suitability for wind energy development. Different classifications have been proposed to categorize sites based on their WPD or WED values.Fagbenle *et al*. (2011) assessed the wind power potential of two (2) sites in North-Eastern Nigeria using all the characterization parameters except the “wind energy density”. Their study was however in the Sahelian part of the country; far off from Lagos State (a coastal location with high prospects for harnessing wind power). This study also did not adhere to the standard measurement protocol as stipulated by IEC 61400-12-1.

Ajayi *et al*. (2013) analyzed the wind profile characteristics of Kano using the Weilbull scale and shape parameter statistic as well as the “most probable wind speed” and “wind speed that carries the maximum energy”. Their study did not estimate the all-important “wind power density” required in the confirmation of the wind power potential of the location. This study also did not adhere to the standard measurement protocol as stipulated by IEC 61400-12-1. These studies (Ajayi *et al*., 2011a; Ajayi *et al*., 2011b; Ajayi *et al*., 2011c; Fagbenle *et al*., 2011; Ohunakin and Akinnawonu, 2011; Ahmed *et al*., 2013; Ajayi *et al*., 2013a; Ajayi *et al*., 2014) in Nigeria have mostly relied on the two parameter Weilbull distribution in the estimation of wind power density using long-term historical data from a single height of 10 m.

We can see that while there exists some wind assessments studies in Nigeria, none has actually assessed the wind speed potential according to the IEC 61400-12-1 standard. These studies take wind speed data from just a single measurement point (10 m height) contrary to standard requirements. According to Olsen and Robert (2015), the wind data should be measured at two or more different heights to make it possible to calculate the wind gradient exponent. The accuracy and reliability of from these studies pertaining techno-economic analysis for wind power applications are limited.

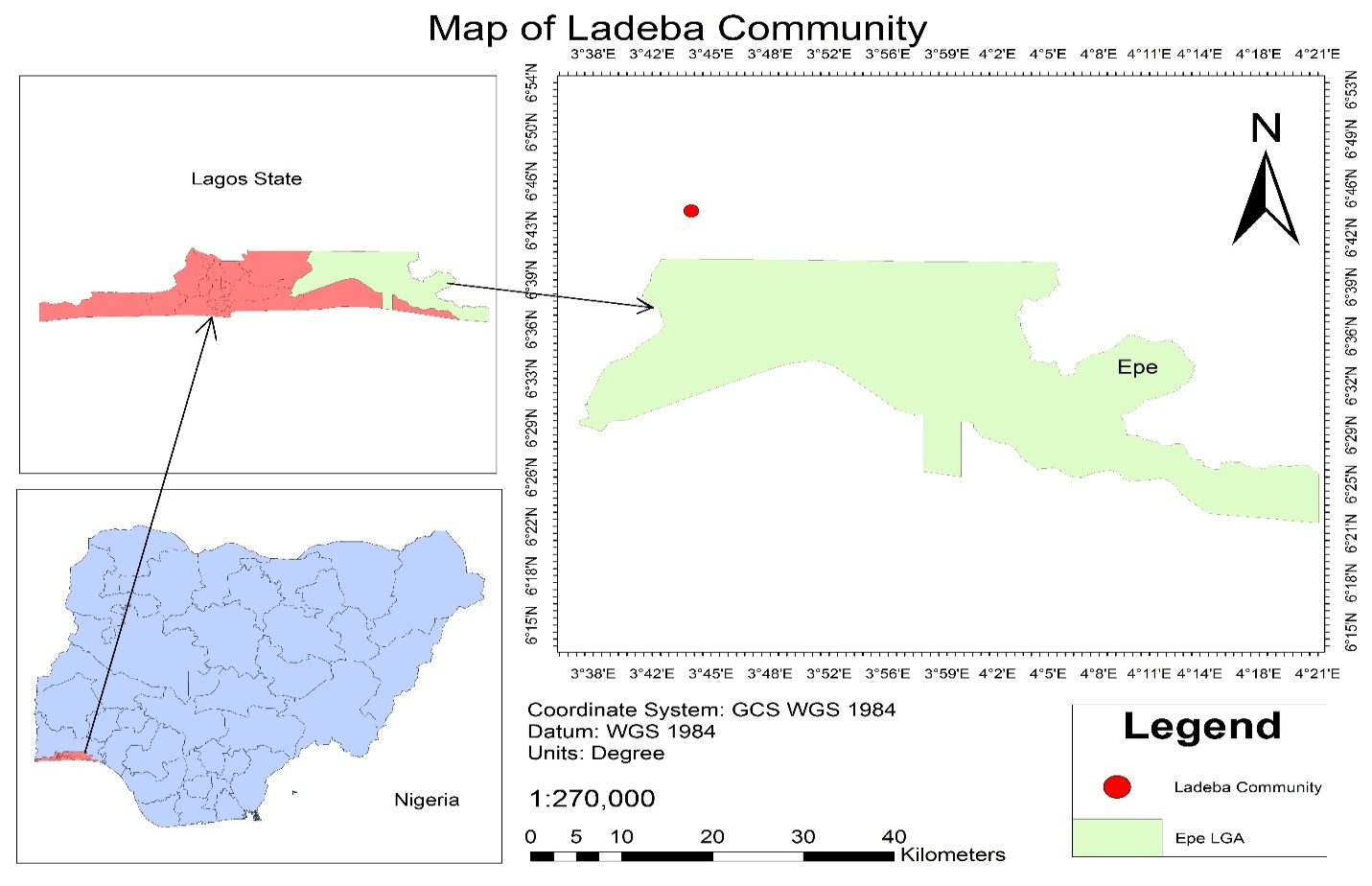
2.0 material and methods

2.1 Study aREA

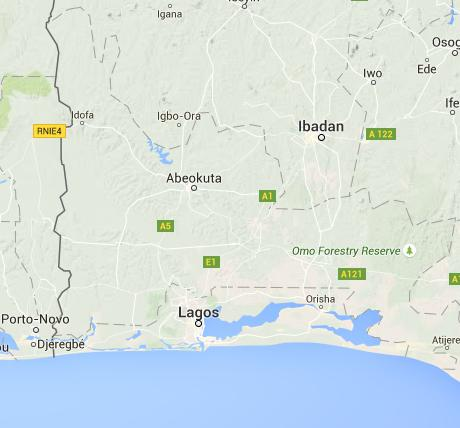
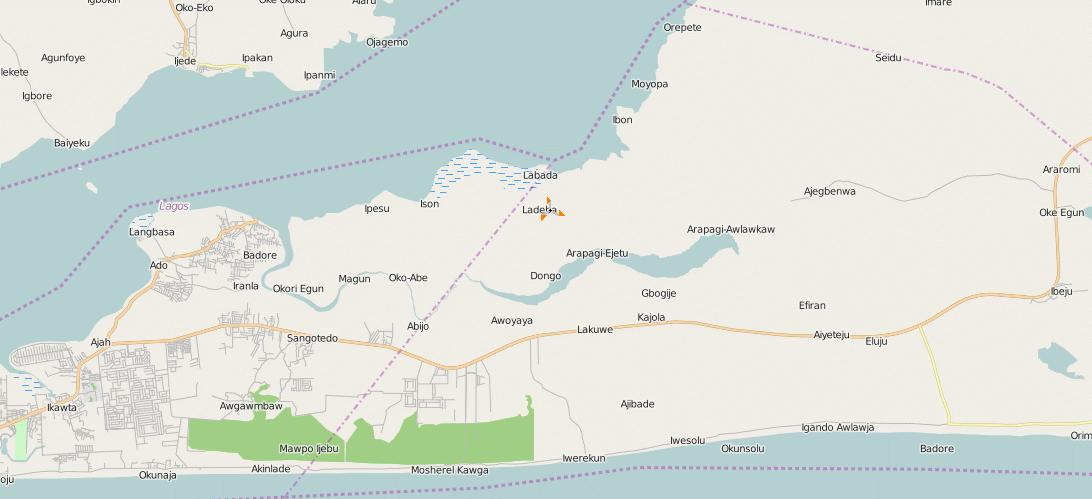
*Ladeba* community is located in Epe local government area of Lagos state. Its existence can be traced back to as early as 1940 and is under the leadership of the *Baale* and his council men. It is sparsely populated with about 600 persons, occupied by the Yoruba speaking tribe whom are predominantly Muslims.

There are practically little or no commercial activities happening within this community as the people mainly practice subsistence farming. Their major means of transportation is by water to the nearest town through another remote community called *Dongo*. *Dongo* is the closest community to Ladeba while *Awoyaya* is the closest town through the water way to it. The main motorable access road into *Ladeba* community is sandy, swampy, bushy and water logged, making it difficult for vehicles to access the community. The land formation is *Ladeba* varies from fairly level to relatively undulating terrain. The vegetation comprises of rough pasture with fine sand as the soil texture (Federal Ministry of Power, 2015).

The wind measurement mast for the study is located on latitude N6 ˚30’864’’ and longitude E3 ˚43’050’’ on leased farmland of 7000sqm, at an elevation of 1.2 m above sea level. The mast infrastructure is occupying a total of 4900sqm of the leased land in Ladeba community of Ibeju Lekki local government area of Lagos state (Federal Ministry of Power, 2015). Plate 1 shows Lagos State Map (with Ladeba/project site) with coordinates while Plate 2 shows project site (indicated) in Ladeba community. Data from meteorological sources clearly show a prevailing wind direction of SSW



**Plate 1: Geo-Map of Lagos State Showing Ladeba**



**Plate 2: Location of Lekki Mast/Project Site as Indicated by Red Circles**

**2.2 Experimental Design**

**2.2.1 Wind Data Measurement and Characterization**

Wind speed data was observed at four (4) heights (41 m, 61 m, 80 m, 81.5m) using a speed measurement system made up of three (3) thies first class advanced cup anemometers and three (3) back-up SWI C3 cup anemometers (Table 1).

The Weilbull and Raleigh functions were deployed in the characterization/assessment of wind power potential by way of scale parameter (c), shape parameter (k), “wind speed with maximum energy”, “most probable wind speed”, “wind power density” and “wind energy density” (Table 2).

**2.2.2 Data Collection, Storage and Retrieval**

Data was collected using a data logger (NOMAD 2) mounted at a 10 m height, on an 80m measurement mast in accordance with IEC 61400-2 (the standard measurement protocol) (IRENA, 2015). The NOMAD 2 (Figures 1) is an advanced data logger that serves as the central processing and storage system for data during the measurement campaign. Its major function is to receive electronic signals from the mounted instruments, process these signals, displays (on the monitor) and saves same in a compact flash (Plate 3). The NOMAD 2 achieves ±0.02% accuracy on counter inputs and ±0.2% accuracy on analog inputs. Besides the keypad and display, on the front panel are two 9V batteries, the Compact Flash card (Plate 4), and a communications port for direct connection to a laptop or desktop computer.

The NOMAD 2 stores your data on Windows-formatted Compact Flash cards that can be read by any PC. The large capacity of the Compact Flash cards(32MB) allows the NOMAD 2 to keep years of data on the card. Data was retrieved from the data logger manually by removing the compact flash, connecting it to a computer (via a RS-232 serial port) and taking readings using a preinstalled NOMAD 2 software. Figure 1 shows compact card slot. The Nomad Desktop advanced database software keeps all data organized, and provides powerful tools for analyzing and displaying wind data.



1

2

3

4

5

6

**Figure 1: Nomad 2 Front Panel: (1) Captive screw (2) Display (3) 9V Battery compartment (4) Keypad (5) Compact Flash in Card Slot (6) Serial Port**

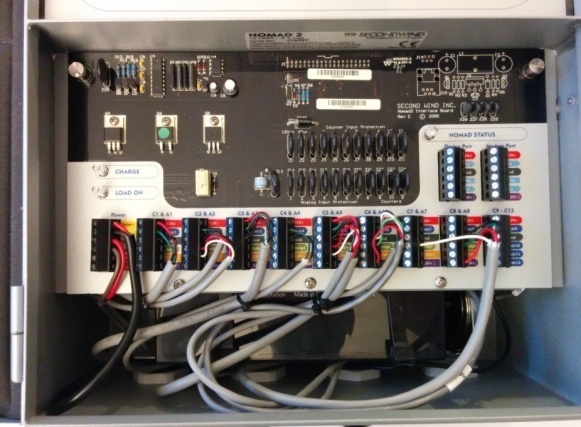
**Table 1: Measurements Instruments and their Position/Orientation on the Measurement Mast**

|  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- |
| **Instrument Type** | **Signal** | **Instrument Height(m)** | **Terminal channel** | **Angle (from N)** | **Distance to Mast(m)** | **Boom Length(m)** | **Stub-pole Length(m)** | **Stub-Pole Type** |
| A1 (Thies) | Speed | 81.5 | C1 | (top) | 3.75 | 4.5 | 0.9 | Hollow |
| A2 (SWI C3) | Speed | 80 | C2 | 135 | 3.75 | 4.5 | 0.9 | Solid |
| A3 (Thies) | Speed | 61 | C3 | 135 | 3.75 | 4.5 | 0.9 | Hollow |
| A4 (SWI C3) | Speed | 61 | C4 | 315 | 3.75 | 4.5 | 0.9 | Solid |
| A5 (Thies) | Speed | 41 | C5 | 135 | 3.75 | 4.5 | 0.9 | Hollow |
| A6 (SWI C3) | Speed | 41 | C6 | 315 | 3.75 | 4.5 | 0.9 | Solid |
| V1 (SWI C3) | Direction | 80 | A2 | 315 | 3.75 | 4.5 | 0.9 | Solid |
| V2 (SWI C3) | Direction | 51 | A5 | 315 | 3.75 | 4.5 | 0.9 | Solid |
| A6 Barometer | Pressure | 10 | A6 | On Mast | - | - | - | - |
| A7 Temp. Sensor | Temp | 80 | A7 | On Mast | - | - | - | - |
| A8 Rel. Hum. Sensor | Rel Hum | 80 | A8 | On Mast | - | - | - | - |

**Table 2:** **Formulae for Determination of Wind Characterization Parameters**

|  |  |  |
| --- | --- | --- |
| **Metric** | **Weilbull Model** | **Rayleigh Model** |
| Shape Parameter (k) |  |  |
| Scale Parameter (c) |  |  |
|  |
| Wind Speed with Maximum Energy |  |  |
| Most Probable Wind Speed |  |  |
| Wind Power Density |  |  |
| Wind Energy Density |  |  |

where; k = Weilbull shape parameter, c = scale parameter, = probability of observing wind speed (m/s), = gamma function, = air density (kg/



**Plate 3: Nomad 2 Datalogger (showing sensors connected to terminal board)**

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**Plate 4: 32MB Compact Flash for Data Storage**

**3.0 RESULTS AND DISCUSSION**

**3.1 Results**

**3.1.1 Wind speed data**

Table 3 displays monthly wind speed data (in m/s) measured at different heights (81.5m, 80m, 61m, and 41m) spanning from May 2021 to April 2023. The wind speeds varied seasonally, with higher speeds observed at greater altitudes. The mean wind speeds for each height over the 24-month period were 7.53 m/s at 81.5m, 6.98 m/s at 80m, 5.88 m/s at 61m, and 4.83 m/s at 41m.

**3.1.2 Air density**

Calculated values of air density from the combination of ambient temperature and air pressure data shown in Table 4 and 5 respectively are represented in Table 6

**3.1.3 Wind data characterization (Weibull distribution)**

The wind speed data collected at four different heights (81.5m, 80m, 61m, and 41m) from May 2021 to April 2023 are characterized using the Weibull distribution. Tables 7, 8, 9, and 10, present the estimated Weibull parameters—the shape parameter (k), scale parameter, wind speed with maximum energy (Vmax), most probable wind speed (Vmp), wind power density (WPD), and wind energy density (WED) for each height.

**3.1.4 Wind data characterization (Rayleigh distribution)**

The Rayleigh distribution, a widely used model for wind speeds in regions where wind direction is assumed to be uniform, is applied to the wind speed data measured at four different heights (81.5m, 80m, 61m, and 41m) from May 2021 to April 2023. Tables 11, 12, 13, and 14, present the estimated Rayleigh distribution parameters such as shape parameter (k) (usually taken as 2), scale parameter, wind speed with maximum energy (Vmax), most probable wind speed (Vmp), wind power density (WPD), and wind energy density (WED).

A summary of the mean values of parameters at each height for the two distributions is depicted in Table 15.

|  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- |
| Table 3: Wind Speed (m/s) | | | | | |
| S/N | **Period** | **Height of Measurement (m)** | | | |
|  |  | **81.5** | **80** | **61** | **41** |
| 1 | May-21 | 7.59 | 7.04 | 5.94 | 4.89 |
| 2 | Jun-21 | 6.74 | 6.19 | 5.09 | 4.04 |
| 3 | Jul-21 | 8.84 | 8.29 | 7.19 | 6.14 |
| 4 | Aug-21 | 8.68 | 8.13 | 7.03 | 5.98 |
| 5 | Sep-21 | 7.16 | 6.61 | 5.51 | 4.46 |
| 6 | Oct-21 | 7.09 | 6.54 | 5.44 | 4.39 |
| 7 | Nov-21 | 6.34 | 5.79 | 4.69 | 3.64 |
| 8 | Dec-21 | 6.49 | 5.94 | 4.84 | 3.79 |
| 9 | Jan-22 | 6.40 | 5.85 | 4.75 | 3.7 |
| 10 | Feb-22 | 7.62 | 7.07 | 5.97 | 4.92 |
| 11 | Mar-22 | 8.46 | 7.91 | 6.81 | 5.76 |
| 12 | Apr-22 | 7.34 | 6.79 | 5.69 | 4.64 |
| 13 | May-22 | 6.94 | 6.39 | 5.29 | 4.24 |
| 14 | Jun-22 | 7.16 | 6.61 | 5.51 | 4.46 |
| 15 | Jul-22 | 9.08 | 8.53 | 7.43 | 6.38 |
| 16 | Aug-22 | 9.36 | 8.81 | 7.71 | 6.66 |
| 17 | Sep-22 | 8.36 | 7.81 | 6.71 | 5.66 |
| 18 | Oct-22 | 7.17 | 6.62 | 5.52 | 4.47 |
| 19 | Nov-22 | 6.44 | 5.89 | 4.79 | 3.74 |
| 20 | Dec-22 | 6.59 | 6.04 | 4.94 | 3.89 |
| 21 | Jan-23 | 7.20 | 6.65 | 5.55 | 4.50 |
| 22 | Feb-23 | 7.76 | 7.21 | 6.11 | 5.06 |
| 23 | Mar-23 | 8.11 | 7.56 | 6.46 | 5.41 |
| 24 | Apr-23 | 7.83 | 7.28 | 6.18 | 5.13 |
| Mean | | **7.53** | **6.98** | **5.88** | **4.83** |

**Table 4: Ambient Temperature (K)**

|  |  |  |
| --- | --- | --- |
| **S/N** | **Period** | **Measurement height (10 m)** |
| 1 | May-21 | 300.52 |
| 2 | Jun-21 | 301.63 |
| 3 | Jul-21 | 301.65 |
| 4 | Aug-21 | 301.12 |
| 5 | Sep-21 | 301.71 |
| 6 | Oct-21 | 300.99 |
| 7 | Nov-21 | 304.65 |
| 8 | Dec-21 | 301.15 |
| 9 | Jan-22 | 300.65 |
| 10 | Feb-22 | 301.90 |
| 11 | Mar-22 | 300.60 |
| 12 | Apr-22 | 299.73 |
| 13 | May-22 | 299.95 |
| 14 | Jun-22 | 301.05 |
| 15 | Jul-22 | 301.38 |
| 16 | Aug-22 | 300.65 |
| 17 | Sep-22 | 303.03 |
| 18 | Oct-22 | 301.65 |
| 19 | Nov-22 | 303.35 |
| 20 | Dec-22 | 301.60 |
| 21 | Jan-23 | 301.15 |
| 22 | Feb-23 | 301.15 |
| 23 | Mar-23 | 300.75 |
| 24 | Apr-23 | 301.35 |
| **Mean** | | **301.39** |

**Table 5: Wind Pressure (Pa)**

|  |  |  |
| --- | --- | --- |
| **S/N** | **Period** | **Measurement height (10 m)** |
| 1 | May-21 | 100900 |
| 2 | Jun-21 | 101100 |
| 3 | Jul-21 | 100500 |
| 4 | Aug-21 | 100700 |
| 5 | Sep-21 | 100800 |
| 6 | Oct-21 | 101000 |
| 7 | Nov-21 | 100700 |
| 8 | Dec-21 | 100800 |
| 9 | Jan-22 | 100800 |
| 10 | Feb-22 | 101200 |
| 11 | Mar-22 | 100900 |
| 12 | Apr-22 | 100700 |
| 13 | May-22 | 100800 |
| 14 | Jun-22 | 100900 |
| 15 | Jul-22 | 101000 |
| 16 | Aug-22 | 101100 |
| 17 | Sep-22 | 100900 |
| 18 | Oct-22 | 100600 |
| 19 | Nov-22 | 100800 |
| 20 | Dec-22 | 100800 |
| 21 | Jan-23 | 100900 |
| 22 | Feb-23 | 100900 |
| 23 | Mar-23 | 101000 |
| 24 | Apr-23 | 100900 |
| **Mean** | | **100863** |  |

**Table 6: Air Density (kg/m3)**

|  |  |  |
| --- | --- | --- |
| **S/N** | **Period** | **Obtainable values** |
| 1 | May-21 | 1.169702 |
| 2 | Jun-21 | 1.167708 |
| 3 | Jul-21 | 1.160701 |
| 4 | Aug-21 | 1.165058 |
| 5 | Sep-21 | 1.163934 |
| 6 | Oct-21 | 1.169033 |
| 7 | Nov-21 | 1.151558 |
| 8 | Dec-21 | 1.166099 |
| 9 | Jan-22 | 1.168038 |
| 10 | Feb-22 | 1.167817 |
| 11 | Mar-22 | 1.169391 |
| 12 | Apr-22 | 1.170461 |
| 13 | May-22 | 1.170764 |
| 14 | Jun-22 | 1.167643 |
| 15 | Jul-22 | 1.167521 |
| 16 | Aug-22 | 1.171514 |
| 17 | Sep-22 | 1.160014 |
| 18 | Oct-22 | 1.161856 |
| 19 | Nov-22 | 1.157642 |
| 20 | Dec-22 | 1.164359 |
| 21 | Jan-23 | 1.167255 |
| 22 | Feb-23 | 1.166481 |
| 23 | Mar-23 | 1.169966 |
| 24 | Apr-23 | 1.166481 |
| **Mean** | | **1.165875** |  |

**Table 7: Wind Data Characterization (Weibull distribution)**

|  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
| Period   |  | | --- | | May-21 | | Jun-21 | | Jul-21 | | Aug-21 | | Sep-21 | | Oct-21 | | Nov-21 | | Dec-21 | | Jan-22 | | Feb-22 | | Mar-22 | | Apr-22 | | May-2 | | Jun-22 | | Jul-22 | | Aug-22 | | Sep-22 | | Oct-22 | | Nov-22 | | Dec-22 | | Jan-23 | | Feb-23 | | Mar-23 | | Apr-23 |   Mean | Weibull Parameters at 81.5 m | | | | | |
| c | k |  |  |  |  |
| |  | | --- | | 7.60 | | 6.78 | | 8.87 | | 8.71 | | 7.20 | | 7.13 | | 6.38 | | 6.53 | | 6.44 | | 7.65 | | 8.49 | | 7.38 | | 6.98 | | 7.20 | | 9.11 | | 9.39 | | 8.39 | | 7.21 | | 6.48 | | 6.63 | | 7.24 | | 7.79 | | 8.14 | | 7.86 | | **7.99** | | |  | | --- | | 10.20 | | 8.97 | | 12.32 | | 12.07 | | 9.78 | | 9.67 | | 8.56 | | 8.78 | | 8.64 | | 10.45 | | 11.74 | | 10.05 | | 9.45 | | 9.78 | | 12.68 | | 13.11 | | 11.59 | | 9.79 | | 8.70 | | 8.93 | | 9.84 | | 10.68 | | 11.21 | | 10.78 | | **10.89** | | |  | | --- | | 6.92 | | 6.10 | | 8.20 | | 8.04 | | 6.53 | | 6.46 | | 5.71 | | 5.86 | | 5.77 | | 6.99 | | 7.82 | | 6.71 | | 6.31 | | 6.53 | | 8.44 | | 8.72 | | 7.72 | | 6.54 | | 5.81 | | 5.96 | | 6.57 | | 7.13 | | 7.48 | | 7.20 | | **7.32** | | |  | | --- | | 6.85 | | 6.02 | | 8.15 | | 7.99 | | 6.46 | | 6.39 | | 5.64 | | 5.79 | | 5.70 | | 6.92 | | 7.77 | | 6.64 | | 6.24 | | 6.46 | | 8.39 | | 8.67 | | 7.67 | | 6.47 | | 5.74 | | 5.89 | | 6.50 | | 7.06 | | 7.42 | | 7.13 | | **7.25** | | 460.55   |  | | --- | | 325.10 | | 735.23 | | 698.14 | | 389.00 | | 379.30 | | 266.76 | | 289.79 | | 278.36 | | 471.46 | | 648.16 | | 421.71 | | 356.11 | | 389.44 | | 802.42 | | 883.11 | | 620.13 | | 389.96 | | 281.09 | | 303.01 | | 396.74 | | 497.40 | | 570.35 | | 511.14 | | **473.52** | | |  | | --- | | 342647 | | 234069 | | 547015 | | 519419 | | 280080 | | 282199 | | 192070 | | 215607 | | 207103 | | 316824 | | 482233 | | 303629 | | 264949 | | 280399 | | 597000 | | 657034 | | 446492 | | 290127 | | 202382 | | 225440 | | 295176 | | 334253 | | 424343 | | 368021 | | **410787** | |

**Table 8: Wind Data Characterization (Weibull distribution)**

|  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- |
| **Period** | **Weibull Parameters at 80 m** | | | | | |
|  | c | k | Vmax | Vmp | WPD | WED |
| **21-May** | 7.08 | 9.40 | 6.4 | 6.33 | 385.40 | 286734 |
| **21-Jun** | 6.23 | 8.17 | 5.56 | 5.48 | 266.80 | 192095 |
| **21-Jul** | 8.32 | 11.23 | 7.64 | 7.58 | 639.73 | 475960 |
| **21-Aug** | 8.16 | 10.99 | 7.48 | 7.42 | 605.45 | 450457 |
| **21-Sep** | 6.65 | 8.78 | 5.97 | 5.89 | 324.07 | 233327 |
| **21-Oct** | 6.58 | 8.68 | 5.90 | 5.82 | 315.21 | 234519 |
| **21-Nov** | 5.84 | 7.60 | 5.16 | 5.07 | 215.22 | 154959 |
| **21-Dec** | 5.99 | 7.82 | 5.31 | 5.22 | 235.36 | 175108 |
| **22-Jan** | 5.90 | 7.69 | 5.22 | 5.13 | 225.17 | 167526 |
| **22-Feb** | 7.11 | 9.44 | 6.43 | 6.36 | 398.22 | 267603 |
| **22-Mar** | 7.95 | 10.67 | 7.26 | 7.20 | 559.44 | 416226 |
| **22-Apr** | 6.83 | 9.04 | 6.15 | 6.08 | 353.37 | 254425 |
| **22-May** | 6.43 | 8.46 | 5.75 | 5.67 | 294.38 | 219018 |
| **22-Jun** | 6.65 | 8.78 | 5.97 | 5.89 | 325.10 | 234071 |
| **22-Jul** | 8.56 | 11.58 | 7.88 | 7.82 | 701.41 | 521846 |
| **22-Aug** | 8.84 | 11.99 | 8.16 | 8.10 | 775.82 | 577207 |
| **22-Sep** | 7.85 | 10.52 | 7.16 | 7.10 | 534.07 | 384532 |
| **22-Oct** | 6.66 | 8.79 | 5.98 | 5.90 | 324.97 | 241778 |
| **22-Nov** | 5.94 | 7.75 | 5.26 | 5.17 | 227.79 | 164011 |
| **22-Dec** | 6.09 | 7.96 | 5.41 | 5.32 | 247.11 | 183848 |
| **23-Jan** | 6.69 | 8.84 | 6.01 | 5.93 | 330.95 | 246229 |
| **23-Feb** | 7.25 | 9.65 | 6.57 | 6.50 | 421.99 | 283578 |
| **23-Mar** | 7.60 | 10.16 | 6.92 | 6.85 | 488.30 | 363294 |
| **23-Apr** | 7.32 | 9.75 | 6.64 | 6.57 | 434.46 | 312808 |
| **Mean** | **7.02** | **9.32** | **6.34** | **6.27** | **401.24** | **293382** |

**Table 9: Wind Data Characterization (Weibull distribution)**

|  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- |
| **Period** | **Weibull Parameters at 61 m** | | | | | |
|  | c | k | Vmax | Vmp | WPD | WED |
| **21-May** | 5.99 | 7.82 | 5.31 | 5.22 | 222.94 | 165866 |
| **21-Jun** | 5.14 | 6.61 | 4.47 | 4.37 | 140.76 | 101347 |
| **21-Jul** | 7.23 | 9.62 | 6.55 | 6.48 | 392.69 | 292159 |
| **21-Aug** | 7.07 | 9.39 | 6.39 | 6.32 | 368.29 | 274006 |
| **21-Sep** | 5.56 | 7.20 | 4.88 | 4.79 | 177.37 | 127703 |
| **21-Oct** | 5.49 | 7.10 | 4.81 | 4.72 | 171.52 | 127611 |
| **21-Nov** | 4.75 | 6.05 | 4.07 | 3.96 | 109.24 | 78649 |
| **21-Dec** | 4.90 | 6.26 | 4.22 | 4.11 | 121.25 | 90212 |
| **22-Jan** | 4.81 | 6.13 | 4.13 | 4.02 | 114.98 | 85544 |
| **22-Feb** | 6.02 | 7.86 | 5.34 | 5.25 | 225.95 | 151836 |
| **22-Mar** | 6.85 | 9.07 | 6.17 | 6.10 | 335.88 | 249891 |
| **22-Apr** | 5.74 | 7.46 | 5.06 | 4.97 | 196.25 | 141297 |
| **22-May** | 5.34 | 6.89 | 4.67 | 4.57 | 158.12 | 117641 |
| **22-Jun** | 5.56 | 7.20 | 4.88 | 4.79 | 177.93 | 128110 |
| **22-Jul** | 7.47 | 9.97 | 6.79 | 6.72 | 436.22 | 324550 |
| **22-Aug** | 7.75 | 10.38 | 7.07 | 7.00 | 489.6 | 364260 |
| **22-Sep** | 6.75 | 8.92 | 6.07 | 5.99 | 318.64 | 229421 |
| **22-Oct** | 5.57 | 7.22 | 4.89 | 4.80 | 178.00 | 132430 |
| **22-Nov** | 4.85 | 6.19 | 4.17 | 4.06 | 116.78 | 84079 |
| **22-Dec** | 5.00 | 6.40 | 4.32 | 4.21 | 128.55 | 95639 |
| **23-Jan** | 5.60 | 7.26 | 4.92 | 4.83 | 181.72 | 135202 |
| **23-Feb** | 6.16 | 8.06 | 5.48 | 5.39 | 241.88 | 162541 |
| **23-Mar** | 6.5 | 8.56 | 5.82 | 5.74 | 286.71 | 213310 |
| **23-Apr** | 6.22 | 8.16 | 5.55 | 5.46 | 250.27 | 180195 |
| **Mean** | **5.93** | **7.74** | **5.25** | **5.16** | **230.9** | **168896** |

**Table 10: Wind Data Characterization (Weibull distribution)**

|  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- |
| **Period** | **Weibull Parameters at 41 m** | | | | | |
| c | k | Vmax | Vmp | WPD | WED |
| **21-May** | 4.95 | 6.33 | 4.27 | 4.16 | 125.35 | 93264 |
| **21-Jun** | 4.11 | 5.14 | 3.44 | 3.31 | 72.09 | 51908 |
| **21-Jul** | 6.19 | 8.10 | 5.51 | 5.42 | 244.25 | 181720 |
| **21-Aug** | 6.03 | 7.87 | 5.35 | 5.26 | 225.66 | 167892 |
| **21-Sep** | 4.52 | 5.73 | 3.85 | 3.73 | 95.40 | 68688 |
| **21-Oct** | 4.45 | 5.63 | 3.78 | 3.66 | 91.56 | 68117 |
| **21-Nov** | 3.71 | 4.59 | 3.05 | 2.90 | 53.06 | 38202 |
| **21-Dec** | 3.86 | 4.80 | 3.19 | 3.06 | 60.13 | 44735 |
| **22-Jan** | 3.77 | 4.67 | 3.11 | 2.96 | 56.32 | 41901 |
| **22-Feb** | 4.98 | 6.37 | 4.30 | 4.19 | 127.40 | 85614 |
| **22-Mar** | 5.81 | 7.56 | 5.13 | 5.04 | 203.32 | 151269 |
| **22-Apr** | 4.70 | 5.98 | 4.03 | 3.91 | 107.62 | 77487 |
| **22-May** | 4.30 | 5.42 | 3.63 | 3.51 | 82.97 | 61732 |
| **22-Jun** | 4.52 | 5.73 | 3.85 | 3.73 | 95.72 | 68918 |
| **22-Jul** | 6.42 | 8.45 | 5.74 | 5.66 | 275.59 | 205040 |
| **22-Aug** | 6.70 | 8.85 | 6.02 | 5.94 | 314.65 | 234096 |
| **22-Sep** | 5.71 | 7.42 | 5.03 | 4.94 | 191.44 | 137840 |
| **22-Oct** | 4.53 | 5.74 | 3.86 | 3.74 | 95.87 | 71329 |
| **22-Nov** | 3.81 | 4.73 | 3.15 | 3.01 | 57.51 | 41411 |
| **22-Dec** | 3.96 | 4.94 | 3.29 | 3.16 | 64.59 | 48058 |
| **23-Jan** | 4.56 | 5.78 | 3.89 | 3.77 | 98.20 | 73059 |
| **23-Feb** | 5.11 | 6.57 | 4.44 | 4.34 | 138.19 | 92863 |
| **23-Mar** | 5.46 | 7.06 | 4.78 | 4.69 | 168.86 | 125630 |
| **23-Apr** | 5.18 | 6.67 | 4.51 | 4.41 | 143.90 | 103610 |
| **Mean** | **4.89** | **6.25** | **4.22** | **4.10** | **132.90** | **97266** |

**Table 11:** **Wind Data Characterization (Rayleigh distribution)**

|  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- |
| **Period** | **Rayleigh Parameters at 81.5 m** | | | | | |
| k | c | Vmax | Vmp | WPD | WED |
| **21-May** | 2 | 8.56 | 9.98 | 6.05 | 8.48 | 6307 |
| **21-Jun** | 2 | 7.60 | 9.02 | 5.38 | 7.51 | 5411 |
| **21-Jul** | 2 | 9.97 | 11.39 | 7.05 | 9.80 | 7289 |
| **21-Aug** | 2 | 9.79 | 11.21 | 6.92 | 9.66 | 7184 |
| **21-Sep** | 2 | 8.08 | 9.49 | 5.71 | 7.96 | 5729 |
| **21-Oct** | 2 | 8.00 | 9.41 | 5.66 | 7.91 | 5888 |
| **21-Nov** | 2 | 7.15 | 8.57 | 5.06 | 6.97 | 5019 |
| **21-Dec** | 2 | 7.32 | 8.74 | 5.18 | 7.23 | 5376 |
| **22-Jan** | 2 | 7.22 | 8.63 | 5.11 | 7.14 | 5310 |
| **22-Feb** | 2 | 8.60 | 10.01 | 6.08 | 8.50 | 5710 |
| **22-Mar** | 2 | 9.54 | 10.96 | 6.75 | 9.45 | 7028 |
| **22-Apr** | 2 | 8.28 | 9.69 | 5.86 | 8.20 | 5906 |
| **22-May** | 2 | 7.83 | 9.24 | 5.54 | 7.76 | 5772 |
| **22-Jun** | 2 | 8.08 | 9.49 | 5.71 | 7.98 | 5747 |
| **22-Jul** | 2 | 10.24 | 11.66 | 7.24 | 10.12 | 7531 |
| **22-Aug** | 2 | 10.56 | 11.97 | 7.47 | 10.47 | 7790 |
| **22-Sep** | 2 | 9.43 | 10.85 | 6.67 | 9.26 | 6667 |
| **22-Oct** | 2 | 8.09 | 9.50 | 5.72 | 7.95 | 5918 |
| **22-Nov** | 2 | 7.27 | 8.68 | 5.14 | 7.12 | 5125 |
| **22-Dec** | 2 | 7.43 | 8.85 | 5.26 | 7.33 | 5451 |
| **23-Jan** | 2 | 8.12 | 9.54 | 5.74 | 8.02 | 5970 |
| **23-Feb** | 2 | 8.75 | 10.17 | 6.19 | 8.64 | 5808 |
| **23-Mar** | 2 | 9.15 | 10.56 | 6.47 | 9.06 | 6740 |
| **23-Apr** | 2 | 8.83 | 10.25 | 6.25 | 8.72 | 6279 |
| **Mean** | **2** | **8.98** | **10.40** | **6.35** | **8.86** | **6547** |

**Table 12: Wind Data Characterization (Rayleigh distribution)**

|  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- |
| **Period** | **Rayleigh Parameters at 80 m** | | | | | |
| k | c | Vmax | Vmp | WPD | WED |
| **21-May** | 2 | 7.94 | 9.36 | 5.62 | 7.86 | 5850 |
| **21-Jun** | 2 | 6.98 | 8.40 | 4.94 | 6.90 | 4969 |
| **21-Jul** | 2 | 9.35 | 10.77 | 6.61 | 9.19 | 6835 |
| **21-Aug** | 2 | 9.17 | 10.59 | 6.49 | 9.04 | 6729 |
| **21-Sep** | 2 | 7.46 | 8.87 | 5.27 | 7.35 | 5289 |
| **21-Oct** | 2 | 7.38 | 8.79 | 5.22 | 7.30 | 5431 |
| **21-Nov** | 2 | 6.53 | 7.95 | 4.62 | 6.37 | 4584 |
| **21-Dec** | 2 | 6.70 | 8.12 | 4.74 | 6.61 | 4921 |
| **22-Jan** | 2 | 6.60 | 8.01 | 4.67 | 6.52 | 4854 |
| **22-Feb** | 2 | 7.98 | 9.39 | 5.64 | 7.88 | 5298 |
| **22-Mar** | 2 | 8.92 | 10.34 | 6.31 | 8.83 | 6571 |
| **22-Apr** | 2 | 7.66 | 9.07 | 5.42 | 7.59 | 5464 |
| **22-May** | 2 | 7.21 | 8.62 | 5.10 | 7.14 | 5314 |
| **22-Jun** | 2 | 7.46 | 8.87 | 5.27 | 7.37 | 5306 |
| **22-Jul** | 2 | 9.62 | 11.04 | 6.80 | 9.51 | 7075 |
| **22-Aug** | 2 | 9.94 | 11.35 | 7.03 | 9.85 | 7332 |
| **22-Sep** | 2 | 8.81 | 10.23 | 6.23 | 8.65 | 6228 |
| **22-Oct** | 2 | 7.47 | 8.88 | 5.28 | 7.34 | 5464 |
| **22-Nov** | 2 | 6.64 | 8.06 | 4.70 | 6.51 | 4687 |
| **22-Dec** | 2 | 6.81 | 8.23 | 4.82 | 6.71 | 4996 |
| **23-Jan** | 2 | 7.50 | 8.92 | 5.30 | 7.41 | 5514 |
| **23-Feb** | 2 | 8.13 | 9.55 | 5.75 | 8.03 | 5396 |
| **23-Mar** | 2 | 8.53 | 9.94 | 6.03 | 8.45 | 6283 |
| **23-Apr** | 2 | 8.21 | 9.63 | 5.81 | 8.11 | 5838 |
| **Mean** | **2** | **7.88** | **9.29** | **5.57** | **7.77** | **5676** |

**Table 13: Wind Data Characterization (Rayleigh distribution)**

|  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- |
| **Period** | **Rayleigh Parameters at 61 m** | | | | | |
| k | c | Vmax | Vmp | WPD | WED |
| **21-May** | 2 | 6.70 | 8.12 | 4.74 | 6.63 | 4936 |
| **21-Jun** | 2 | 5.74 | 7.16 | 4.06 | 5.68 | 4086 |
| **21-Jul** | 2 | 8.11 | 9.53 | 5.74 | 7.97 | 5928 |
| **21-Aug** | 2 | 7.93 | 9.35 | 5.61 | 7.82 | 5818 |
| **21-Sep** | 2 | 6.22 | 7.63 | 4.40 | 6.12 | 4409 |
| **21-Oct** | 2 | 6.14 | 7.55 | 4.34 | 6.07 | 4518 |
| **21-Nov** | 2 | 5.29 | 6.71 | 3.74 | 5.16 | 3713 |
| **21-Dec** | 2 | 5.46 | 6.87 | 3.86 | 5.39 | 4009 |
| **22-Jan** | 2 | 5.36 | 6.77 | 3.79 | 5.30 | 3941 |
| **22-Feb** | 2 | 6.74 | 8.15 | 4.76 | 6.66 | 4473 |
| **22-Mar** | 2 | 7.68 | 9.10 | 5.43 | 7.60 | 5657 |
| **22-Apr** | 2 | 6.42 | 7.83 | 4.54 | 6.36 | 4578 |
| **22-May** | 2 | 5.97 | 7.38 | 4.22 | 5.91 | 4400 |
| **22-Jun** | 2 | 6.22 | 7.63 | 4.40 | 6.14 | 4423 |
| **22-Jul** | 2 | 8.38 | 9.80 | 5.93 | 8.28 | 6162 |
| **22-Aug** | 2 | 8.70 | 10.11 | 6.15 | 8.62 | 6416 |
| **22-Sep** | 2 | 7.57 | 8.98 | 5.35 | 7.43 | 5351 |
| **22-Oct** | 2 | 6.23 | 7.64 | 4.40 | 6.12 | 4556 |
| **22-Nov** | 2 | 5.40 | 6.82 | 3.82 | 5.29 | 3812 |
| **22-Dec** | 2 | 5.57 | 6.99 | 3.94 | 5.49 | 4086 |
| **23-Jan** | 2 | 6.26 | 7.68 | 4.43 | 6.19 | 4602 |
| **23-Feb** | 2 | 6.89 | 8.31 | 4.87 | 6.81 | 4573 |
| **23-Mar** | 2 | 7.29 | 8.70 | 5.15 | 7.22 | 5369 |
| **23-Apr** | 2 | 6.97 | 8.39 | 4.93 | 6.88 | 4956 |
| **Mean** | **2** | **6.63** | **8.05** | **4.69** | **6.55** | **4782** |

**Table 14: Wind Data Characterization (Rayleigh distribution)**

|  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- |
| **Period** | **Rayleigh Parameters at 41 m** | | | | | |
| k | c | Vmax | Vmp | WPD | WED |
| **21-May** | 2 | 5.52 | 6.93 | 3.90 | 5.46 | 4063 |
| **21-Jun** | 2 | 4.56 | 5.97 | 3.22 | 4.50 | 3243 |
| **21-Jul** | 2 | 6.93 | 8.34 | 4.90 | 6.80 | 5063 |
| **21-Aug** | 2 | 6.75 | 8.16 | 4.77 | 6.65 | 4949 |
| **21-Sep** | 2 | 5.03 | 6.45 | 3.56 | 4.96 | 3569 |
| **21-Oct** | 2 | 4.95 | 6.37 | 3.50 | 4.90 | 3646 |
| **21-Nov** | 2 | 4.11 | 5.52 | 2.90 | 4.00 | 2882 |
| **21-Dec** | 2 | 4.28 | 5.69 | 3.02 | 4.22 | 3140 |
| **22-Jan** | 2 | 4.17 | 5.59 | 2.95 | 4.13 | 3070 |
| **22-Feb** | 2 | 5.55 | 6.96 | 3.92 | 5.49 | 3687 |
| **22-Mar** | 2 | 6.50 | 7.91 | 4.59 | 6.43 | 4785 |
| **22-Apr** | 2 | 5.23 | 6.65 | 3.70 | 5.19 | 3734 |
| **22-May** | 2 | 4.78 | 6.20 | 3.38 | 4.74 | 3526 |
| **22-Jun** | 2 | 5.03 | 6.45 | 3.56 | 4.97 | 3580 |
| **22-Jul** | 2 | 7.20 | 8.61 | 5.09 | 7.11 | 5291 |
| **22-Aug** | 2 | 7.51 | 8.93 | 5.31 | 7.45 | 5543 |
| **22-Sep** | 2 | 6.39 | 7.80 | 4.52 | 6.27 | 4514 |
| **22-Oct** | 2 | 5.04 | 6.46 | 3.57 | 4.96 | 3689 |
| **22-Nov** | 2 | 4.22 | 5.63 | 2.98 | 4.13 | 2976 |
| **22-Dec** | 2 | 4.39 | 5.80 | 3.10 | 4.32 | 3218 |
| **23-Jan** | 2 | 5.08 | 6.49 | 3.59 | 5.02 | 3731 |
| **23-Feb** | 2 | 5.71 | 7.12 | 4.04 | 5.64 | 3787 |
| **23-Mar** | 2 | 6.10 | 7.52 | 4.32 | 6.04 | 4496 |
| **23-Apr** | 2 | 5.79 | 7.20 | 4.09 | 5.71 | 4114 |
| **Mean** | **2** | **5.45** | **6.86** | **3.85** | **5.38** | **3929** |

**Table 15:** **Mean Result Across Heights for Both Models**

|  |  |  |  |  |  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
| **Height** | **Weilbull** | | | | | |  | **Rayleigh** | | | | | |
| (m) | c | k |  |  |  |  | c | k |  |  |  |  |
| 81.5 | 7.99 | 10.89 | 7.32 | 7.25 | 473.52 | 410781.4 |  | 8.98 | 2 | 10.40 | 6.35 | 8.86 | 6547.50 |
| 80 | 7.02 | 9.32 | 6.34 | 6.27 | 401.24 | 293381.7 |  | 7.88 | 2 | 9.29 | 5.57 | 7.77 | 5676.12 |
| 61 | 5.93 | 7.74 | 5.25 | 5.16 | 230.90 | 168895.8 |  | 6.63 | 2 | 8.05 | 4.67 | 6.55 | 4782.22 |
| 41 | 4.89 | 6.25 | 4.22 | 4.10 | 132.90 | 97265.94 |  | 5.45 | 2 | 6.86 | 3.85 | 5.38 | 3928.95 |

**3.2 Discussion**

**3.2.1 Wind speed data**

The monthly wind speed data analyzed for the period from May 2021 to April 2023 reveal distinct seasonal trends in wind speeds, with variations observed across different months and heights of measurement. The wind speeds exhibit a clear seasonal pattern, with higher wind speeds generally occurring in the summer months (June to August) and lower wind speeds observed in the winter months (November to January). These trends are consistent with wind regimes typically found in coastal regions, where seasonal changes in atmospheric pressure systems significantly influence wind patterns.

1. **Seasonal Trends**

**Summer (June – August):** The highest wind speeds were recorded in the summer months, particularly in July and August, with values reaching up to 9.36 m/s at 81.5 meters. This peak in wind speed is characteristic of many regions that experience stronger winds during summer due to monsoon systems, tropical storm activity, or storm-induced winds. The seasonal increase in wind speeds during the summer months is often linked to higher temperature gradients between land and sea, leading to more active wind systems. This finding aligns with other studies (Ajayi *et al*., 2014; Hulio *et al*., 2015) that have reported higher wind speeds in summer, especially in coastal and lowland areas, where wind patterns are influenced by local climatic conditions.

Maximum wind speeds during the rainy season have been reported to reach up to 8.5 m/s in Lagos (Okogbue *et al*., 2013). These higher wind speeds are typically associated with the intertropical convergence zone (ITCZ), which brings increased storm activity and stronger winds. The wind speed data from this study corroborate this trend, with July and August exhibiting wind speeds up to 9.36 m/s at 81.5 meters.

This aligns with findings from Ayanshola *et al*. (2017), who also observed higher wind speeds at Ibeju Lekki during the rainy season in Lagos, driven by enhanced storm systems and the ITCZ. For example, in July, the wind speed averaged 8.84 m/s, and in August, it reached the highest value of 9.36 m/s. These results are consistent with coastal wind regimes, where winds strengthen during the wet season due to the convergence of moist winds from the ocean and the equator, enhancing overall wind energy potential during this period. This reinforces the importance of the rainy season for wind energy harvesting in coastal areas like Lagos, which experiences these seasonal wind boosts.

**Winter (November – February):** In contrast, the winter months (November, December, and January) show the lowest recorded wind speeds, particularly in November (average of 6.44 m/s at 81.5 meters) and December (average of 6.59 m/s at 81.5 meters). These lower wind speeds are typical of regions where stable high-pressure systems dominate in winter, leading to calmer weather conditions with less frequent storm activity. The reduced wind speeds suggests the dominance of more stable, calmer atmospheric conditions.

During the dry season (November to February), Lagos experiences the harmattan, a period characterized by weaker wind speeds. This trend is consistent with findings by Ojo (2009) who also observed lower wind speeds in Lagos during the harmattan season, with wind speed dropping to about 5.5 - 6.0 m/s in December and January respectively due to the stable air and high-pressure systems over the Sahara.

Okogbue *et al.* (2013) reported average wind speeds of 5.5 m/s during this period, with even lower values during the peak of harmattan. This observation is consistent with the findings in this study, where November recorded an average wind speed of 6.34 m/s at 81.5 meters, and December averaged 6.49 m/s. The reduction in wind speeds during the harmattan is linked to the dominance of high-pressure systems over the Sahara Desert, which suppresses the intensity of wind activity along the coast of West Africa. During this period, the winds are dry, stable, and less intense, with reduced atmospheric disturbances. As Saharan air masses move toward the equator, they result in lower moisture content and reduced turbulence, leading to weaker winds in Lagos.

**Spring and Fall (March – May, September – October):** The spring (March, April, May) and fall (September, October) months exhibit moderate wind speeds, with fluctuations depending on specific atmospheric conditions. During March, for example, the wind speed averaged 8.11 m/s at 81.5 meters, showing a return to more active wind conditions following the calmer harmattan period. Similarly, in October, wind speeds showed a slight decrease, averaging 7.17 m/s at 81.5 meters, which is still moderate compared to the lower values observed in winter but lower than the peak summer months.This decline is typical of the shift from active summer winds to the calmer conditions of fall, where high-pressure systems often dominate, particularly in the northern hemisphere.

These results are consistent with findings from Ayanshola *et al*. (2017), who observed moderate wind speeds ranging from 6 m/s to 8 m/s in the transitional months of Lagos. Such values reflect the transition from the harmattan period to the more active rainy season winds, with a gradual buildup of tropical systems during the spring and a decline toward the dry season during the fall.

The observed wind speeds in March and September reflect these seasonal transitions and indicate a stable, moderate wind environment for much of the spring and fall, which is common in coastal climates where trade winds and oceanic influences fluctuate seasonally.

1. **Height-dependent wind speeds**

The data also reveal a typical height-dependent trend in wind speeds, where wind speeds consistently decrease as the measurement height decreases. For instance, at the highest measurement height of 81.5 meters, wind speeds are generally higher compared to those measured at 80 meters, 61 meters, and 41 meters (Table 3). This trend is consistent with the logarithmic increase in wind speed with height typically observed in the atmosphere due to reduced surface friction at higher altitudes. This height-dependent variation in wind speeds is a well-documented phenomenon in wind resource assessments and is often used in wind energy studies to estimate the potential for energy generation at different hub heights.

**3.2.2 Shape parameter (k)**

The K parameter in the Weibull and Rayleigh distributions at various heights reveals important insights into the wind speed characteristics in the study area. The higher K values for the Weibull distribution at greater heights suggest that wind speeds are more variable and concentrated around specific values, while the constant K = 2 for the Rayleigh distribution indicates stable, unimodal wind conditions with low variability. These findings are consistent with studies from other regions (Husain *et al.,* 2012; Kumar, *et al.,* 2015) affirming that the Weibull distribution is more appropriate for capturing variability at higher altitudes, while the Rayleigh distribution is best suited for modeling consistent wind conditions at lower altitudes.

**3.2.3 Scale parameter (c)**

The c parameter values from both the Weibull and Rayleigh distributions show a general trend of decreasing values with height, suggesting that as you move closer to the ground, wind speed variability tends to decrease. This is consistent with the fact that near-surface wind speeds are typically more influenced by friction and turbulence, resulting in lower variability compared to higher altitudes where the wind is less affected by surface roughness and more by atmospheric dynamics. At 81.5 meters, the c parameter for the Rayleigh distribution (8.98) is slightly higher than for the Weibull distribution (7.99), indicating that the wind speed data follows a more consistent, unimodal pattern with less variability in the Rayleigh model. The Weibull distribution, with its lower c value, captures a broader spread of wind speeds, suggesting more variability.

At 80 meters, the difference between the c parameters of the Weibull (7.02) and Rayleigh (7.88) distributions narrows, but the Rayleigh distribution still reflects a more stable, less variable wind speed profile, consistent with its characteristic of modeling more unimodal distributions.

At 61 meters, the c values for both distributions decrease, indicating a reduction in wind speed variability with height. The Rayleigh distribution's c value (6.63) remains higher than the Weibull's (5.93), suggesting it better fits the more stable wind conditions at this altitude, as the influence of surface roughness diminishes.

At 41 meters, the c values are at their lowest, with the Rayleigh distribution (5.45) still showing higher variability compared to the Weibull (4.89). This trend emphasizes that at lower altitudes, wind speed variability decreases, and the wind follows a more consistent, unimodal pattern

Ayanshola *et al.* (2017) study of wind speeds in Lagos, Nigeria, reported a mean “c” value of approximately 8.2 for the Rayleigh distribution in coastal conditions, which is close to the value we observed at 81.5 meters. This indicates that the Rayleigh distribution is indeed a suitable model for coastal regions with less variability in wind speeds at this height.Ojo (2009) found a mean C value of 7.0 for the Weibull distribution in Lagos during the harmattan season, which aligns closely with the observed Weibull value of 7.02. This supports the idea that at this height (80 m), the wind speed variability is still moderate, particularly in the dry season**.**

**3.2.4 Maximum wind speed (Vmax)**

The Rayleigh distribution consistently estimated higher optimal wind speeds for energy production, indicating a better fit for stable, unimodal wind conditions, with values ranging from 10.40 m/s at 81.5 meters to 6.86 m/s at 41 meters. In contrast, the Weibull distribution shows lower wind speeds for maximum energy (e.g., 7.32 m/s at 81.5 meters and 4.22 m/s at 41 meters), reflecting greater variability in wind conditions. Both distributions show a general decrease in optimal wind speeds with height, typical of surface-based turbulence and atmospheric stability. These findings agree with existing literature ( Tadesse *et al*., 2017;Hussain *et al.,* 2012) corroborating that the Rayleigh distribution is better suited for modeling stable wind conditions, while the Weibull distribution is more flexible in capturing a wider range of wind speeds, making it ideal for more variable conditions.

**3.2.5 Most probable wind speed (Vmp)**

The comparison of most probable wind speeds between the Weibull and Rayleigh distributions across various heights demonstrated that the Weibull distribution consistently predicted higher wind speeds than the Rayleigh distribution. For instance, at 81.5 meters, the Weibull model estimates a most probable wind speed of 7.25 m/s, while the Rayleigh distribution predicts 6.35 m/s. This pattern persists across all heights, with the Weibull distribution capturing greater wind variability, indicative of a more dynamic wind environment. The Weibull distribution with its shape parameter k (not fixed at 2) is more flexible, which allows it to predict a higher most probable wind speed at each level compared to the Rayleigh distribution (which is a special case of the Weibull with k = 2). Ololade and Akinmoladun (2015) reported a high level of consistency in wind patterns at certain heights (e.g., 80–100 meters), with the Rayleigh distribution often fitting best in areas with less wind variability. Both distributions exhibit a general decline in the most probable wind speed with decreasing altitude, reflecting the increased atmospheric stability and surface-induced turbulence at lower heights. Overall, the Weibull distribution proves more adept at modeling regions with variable, fluctuating wind profiles, whereas the Rayleigh distribution is better suited for environments with consistent, predictable wind behavior.

**3.2.6 Wind power density (WPD)**

Wind power density estimated by the Weibull and Rayleigh distributions at different heights reveals that the Weibull distribution consistently estimates much higher power densities across all altitudes, reflecting its ability to capture a broader range of wind speeds and greater variability in wind conditions. At 81.5 meters, the Weibull distribution estimated a power density of 473.52 W/m², significantly higher than that of Rayleigh distribution’s 8.86 W/m². This trend persists even at lower heights, with the Weibull distribution always forecasting higher energy generation potential due to its flexibility in modeling more variable wind conditions. In contrast, the Rayleigh distribution tends to suggest lower power densities, as it is better suited for regions with more stable, unimodal wind profiles. These results align with existing studies, such as those by Ayanshola *et al*. (2017) and Husain *et al*. (2012), which found that the Weibull distribution is more appropriate for modeling wind energy potential in areas with fluctuating and turbulent winds.

**3.2.7 Wind energy density (WED)**

Considering the magnitude difference, the Weibull distribution generally results in much higher values of wind energy density compared to the Rayleigh distribution, which is consistent with the typical characteristics of the two models. The Weibull distribution is more flexible, with two shape parameters (scale and shape), allowing it to model a wider variety of wind regimes more accurately, leading to higher energy densities. The Rayleigh distribution, on the other hand, is a special case of the Weibull distribution where the shape parameter is fixed at 2, which constrains its ability to capture wind variations accurately in more complex wind regimes. In terms of behavior with height, both distributions show a general decrease in energy density as the height decreases. This aligns with the expectation that wind speed typically decreases with height due to factors like surface roughness and turbulence near the ground.

Weibull-derived energy density values are often found to be higher compared to Rayleigh, due to the increased flexibility in modeling wind speed distribution. Wind energy densities of 400,000 W/m² or more are observed at higher altitudes, such as 80 - 100 meters, in areas with robust wind regimes(Mahrt, 2014).

The Rayleigh distribution is typically used as a simplification when only a single parameter (the scale) is known or assumed to follow a simple Gaussian-like distribution. The Rayleigh model often underestimates the energy potential in regions with highly variable wind speeds, as it is limited by the fixed shape parameter of 2. While it can still provide useful approximations, its application is generally limited to situations where wind speed distributions are roughly symmetric around the mean (Liu *et al.,* 2015; Rajapaks*e et al*., 2016*)*.

4. Conclusion

The Weibull distribution consistently produces higher WED values compared to the Rayleigh distribution at all heights, reflecting its flexibility in capturing the variability of wind speeds. For instance, at 81.5 meters, the Weibull-derived WED is significantly higher (410,781.4 W/m²) than the Rayleigh-based WED (6,547.5 W/m²). This difference highlights the Weibull distribution’s ability to more accurately model the energy potential in regions with varying wind regimes. As height decreases, both models show a decrease in wind energy density, which is expected due to the natural decline in wind speed closer to the ground. However, the rate of decline in WED is much more pronounced in the Weibull results, which suggests that the higher variability in wind speeds at lower altitudes is better captured by the Weibull distribution’s shape parameter.

Conversely, the Rayleigh distribution, with its fixed shape parameter of 2, provides lower WED estimates and fails to account for the greater wind speed variation at lower heights. This highlights the Rayleigh model’s limitation in accurately representing wind energy potential in regions with significant wind variability. Overall, the findings confirm that the Weibull distribution offers a more accurate and flexible approach for estimating wind energy potential, particularly in areas with highly variable wind speeds, whereas the Rayleigh distribution can provide a more conservative estimate in less dynamic wind environments. The observed trends in WED also emphasize the importance of height in wind energy estimation, as wind speeds and energy densities tend to decrease closer to the surface due to surface roughness and turbulence.

**4.1 RECOMMENDATIONS**

Based on the findings of this study, the following are recommendations for future research, and practical applications in wind energy assessments:

* The Weibull distribution’s ability to adjust to different wind patterns (through its shape parameter) makes it highly suitable for regions with complex or fluctuating wind behavior. It provides more accurate estimates of wind energy density, especially at higher altitudes where wind energy potential is typically higher.
* Weibull and Rayleigh model deployment in wind potential estimation should prioritize the use of wind speed data from higher altitudes (80 meters or more) to more accurately estimate wind energy potential, especially in areas where wind speed increases with height. At lower altitudes, the effects of surface roughness, turbulence, and local topography can significantly impact wind speed and, in turn, wind energy density.
* Weibull and Rayleigh distributions should be locally calibrated based on real, site-specific wind data. This will ensure that the shape and scale parameters are adjusted according to local wind conditions. Regular wind speed measurements over extended periods are crucial for accurately estimating energy potential and optimizing turbine placement.
* While both the Weibull and Rayleigh distributions are commonly used, it is advisable to consider integrating additional statistical models (e.g., log-normal or Pearson Type III distributions) to enhance the accuracy of wind energy estimates in locations with unique or extreme wind conditions. The use of multiple models can provide a more robust understanding of local wind dynamics and offer a broader perspective on potential energy yield.

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