Wind Resource of Ilorin City for Vortex-Induced Wind Turbine Power Generation and Off-grid Electrification

Yahaya T.[1,1], Ajimotokan H. A.[1], Adebisi J. A.[2], Ahmed I. I.[2], Ajiboye T. K.[1], Abdulkareem S.[1], Ajao K. R.[1]

[1]Department of Materials and Metallurgical Engineering, University of Ilorin, Nigeria
[2]Department of Mechanical Engineering, University of Ilorin, Nigeria

ABSTRACT: This study examined the appraisal of wind resources of Ilorin, Nigeria for vortex-induced wind turbine power generation and off-grid electrification. The technical potential of Modern-Era Retrospective Analysis for Research and Application, version 2 (MERRA-2) was employed as a tool to generate an estimated wind resource of Ilorin city, using five different hub-heights (10, 30, 50, 70, and 90 m). A statistical analysis of wind characteristics for 21 years from 2001 to 2021 was carried out using Weibull distribution function. The daytime and night-time wind characteristics were studied to determine prospective and investment hub-height(s). It was observed that the study area is a low wind region with a minimum and maximum mean wind speed of 2.89 m/s at 10 m and 7.68 m/s at 90 m, respectively. Wind turbines with cut-in wind speed of 2, 2.5, and 3 m have operational chances of 98%, 95% and 88%, respectively. Wind power density at 10, 30, and 50 m elevations was classified as poor while at 70 and 90 m elevations, was regarded as marginal and fair, respectively.

KEYWORDS: MERRA-2 wind data, hub heights, Weibull distribution, low wind profile, wind power density, cut-in wind speed.

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I. INTRODUCTION

Vortex-Induced wind turbine is a device which syntheses vortices and thereby produce mechanical energy (Michaud, 2009). The device generates artificial vortices by harvesting free stream wind through a component which translates the wind flow into a curly pattern. The vortex is then heated up by solar thermal energy to create a buoyancy effect. Thus, accelerating the outflow of wind from the turbine chamber. This phenomenon in-turn increases the rotation of the rotor. The major components of the vortex-induced wind turbine include a heat source (solar energy), an inlet for ambient wind, turbine chamber and outlet source for warm air (Nizetic, 2011). The device can be used in regions with low wind profile and high solar intensity. It is useful in urban area since it is an enclosed turbine. It is suitable for power generation in the tropical regions of the world which include Nigeria (Mustafa *et al*., 2013).

Ilorin, the capital city of Kwara state in the North-Central, Nigeria with the global coordinates of latitude 8.54°N and longitude 4.54°E, experiences two climatic conditions, namely, harmattan and rain seasons. These seasons have significant impact on the wind condition of the environment (Olorunfemi & Raheem, 2013). Figure 1 shows the geographical location of Ilorin, Nigeria. The population of major cities in Nigeria, including Ilorin, is on the increase exponentially and consequently, the electricity consumption per capita has shown proportional increment. This has led to incessant demand for stable and sustainable electricity which cannot be over emphasized in the regional development of a nation. The strive to meet up with the energy demand has provoked investigation on the chances of local energy production from wind machine configuration suitable for urban settings (Emeis, 2018a).

Electrical energy plays vital role in the economic growth, progress, workforce development, poverty eradication and security of any region. Provision of uninterrupted power supply is a critical issue for all developing countries today. In fact, future economic growth depends on the long-term availability of energy from sources that are affordable, accessible, and environmentally friendly. Electricity as a foremost source of energy, its accessibility assists the ways of meeting both industrial and residential needs, it contributes to production factors (capital and labour) and improves export prowess of a nation (Hasanuzzaman *et al.*, 2016).

Globally, the generation of electric power still relies heavily on fossil fuels, which are fast depleting and non-recyclable. Fossil fuels are also environmentally hazardous since they emit greenhouse gases (GHGs) into the atmosphere. GHGs cause global warming and climate change which are closely associated with harmful weather patterns, environmental degradation, change in rainfall distribution, receding bodies of water and retreat of glaciers (Ramanathan & Feng, 2009).

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*Corresponding author: yahaya.t@unilorin.edu.ng

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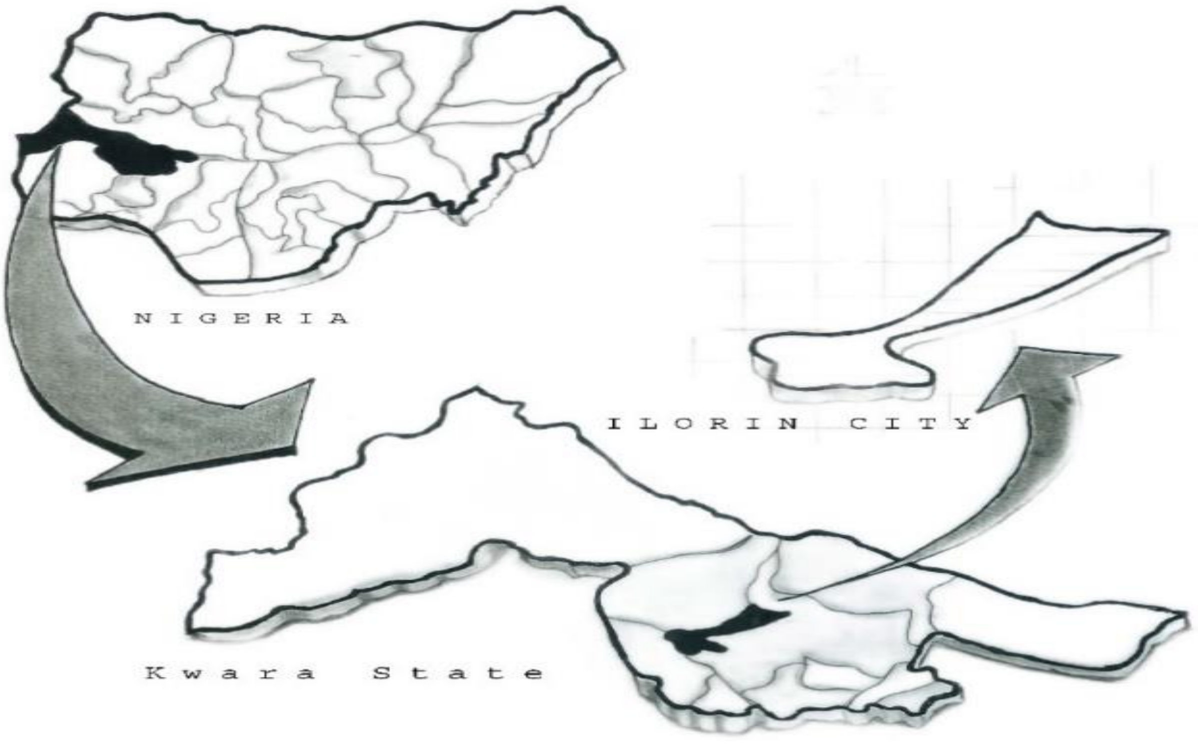


Figure 1: Nigeria map showing extruded view of Ilorin city.

The concept of power generation from wind is not new, the technology has existed for quite a while and has been used for grains grinding and water pumping for decades. Although, smartness in the design of the modern wind turbine has promoted the proliferation of the concept for the generation of electric power. The nascent surge witnessed in the application of wind turbines for the generation of electricity anchored on the pressing need to transit from non-renewable to renewable sources of power generation (Carlin *et al.*, 2003; Dang, 2009; Kaldellis & Zafirakis, 2011; Sorensen, 1995; Vestergaard *et al.*, 2004).

Globally, the application of wind turbine is not evenly spread over the continents. Europe and America are leading in the area of wind harvest for power generation while Asia come next in the trend. The adoption of wind energy is still at low in Africa. South Africa and some countries in the North of the continent have in recent time started embracing the technology which can still not be compared with what is obtainable in advanced nations due to little or no access to wind meteorological information for wind machine application. There is need for more expertise in this field in the region to quench major factor thwarting the readiness to embrace the system (Van der Linde, 1996; Wisse & Stigter, 2007).

Many studies have proposed decentralisation and adoption of power generation from solar and wind energy resources as means of attaining sustainable electricity provision in Nigeria. These recommendations have been proposed for major cities in Nigeria (Ajao *et al.*, 2009). The application of wind energy for generation of electricity is at conceptual stage in Nigeria due to lack of comprehensive information on wind resource assessment and poor power policy implementation (Onoruoiza *et al.*, 2021). However, the feasibility of wind power as a complementary energy source greatly counts on how consistent the resource is, in terms of its availability. In this credence, it is pertinent to evaluate the wind power density of Ilorin city. Thus, this study presents the appraisal of wind resource of Ilorin city for vortex-induced wind turbine power generation and off-grid electrification, employing empirical methods of Justus, power density method and empirical method of Lysen to determine Weibull distribution parameters, which are used to assess the wind power density.

II. METHODOLOGY

The assessment methodologies were conducted using Modern-Era Retrospective Analysis for Research and Application, version 2 (MERRA-2) – the current atmospheric reanalysis of the modern satellite era by NASA’s Global Modelling and Assimilation Office (GMAO). MERRA-2 has been upgraded to include evaluation beyond its antecedent – MERRA, and it also integrates observation types not available with the MERRA. The wind data for 21 years from 2001 to 2021 from MERRA-2 (Gelaro *et al.*, 2017) were obtained from ½° x ⅔° resolution dataset at 10 m and 50 m hub-height. Wind speed dataset at other hub-heights used for this analysis were extrapolated using power law formula.

The required wind speed, U_z for wind over Ilorin city was computed using Eqn. 1 (Emeis, 2018b):

$$U_z = U_r\left(\frac{z}{z_r}\right)^{\alpha} \tag{1}$$

where U_r is the wind speed at the reference height, Z is the hub-height, Z_r is reference height and α is the Hellmann exponent, which is 0.4 for this study. The maximum and minimum points of the variation of the mean annual wind speed at hub-heights: 10, 30, 50, 70 and 90 m were used for the evaluation. The probable prevailing wind speeds for the 21 years at these elevations were also calculated.

A. *Diurnal wind variation*

Hourly wind speed data were analysed to determine the month with minimum and maximum mean wind speed. The diurnal wind variations and speeds for these months were studied at different hub-heights.

B. *Wind direction*

The use of wind rose in this study is used majorly on its application for wind direction estimation. The study considered the reference height of 10 m and 50 m hub-height for the evaluation. Since the study area is not susceptible to gusts, it is assumed that the other hub-heights have the same phenomenon regarding wind direction. The wind direction data from 2001 to 2021 obtained from NASA site, in degrees, were then converted to cardinal directions in Microsoft Excel using the following code:

$$Cardinal = choose\,(1 + abs\big(rnd(Deg./45)\big),\text{"N","NE","E","SE","S","SW","W","NW","N"}) \quad (2)$$

C. *Available power estimation from wind stream*

The stochastic nature of wind has called for comprehensive meteorological analysis of the resource to ascertain the period for optimum energy. The theoretical energy, P obtained from wind can be expressed as follows:

$$P = \frac{1}{2}\rho A_s v^3 \qquad (3)$$

Where ρ is the air density in kg/m^3 and A_s is the rotor swept area in m^2 and v is the wind speed in m/s. The air density, ρ at sea level is taken to be 1.225 kg/m^3 and this was adopted in this study.

Eqn. 3 is usually multiplied by Betz limit to estimate the plausible energy that can be obtained from wind in a particular location. Although there are other necessary factors to be considered when installing wind turbine such as: turbine efficiency, capacity factor, and other governmental policies. However, Betz limit is prominent when assessing wind power of a wind turbine (Jangamshetti & Ran, 2001; Joselin Herbert *et al.*, 2007).

Average wind speed and wind speed frequency distribution were parameters mostly considered when evaluating wind power density of a location. The reliability from frequency distribution for wind characteristic assessment is better compared with average wind speed (Ben *et al.*, 2021). Studies have verified and validated the application of frequency distribution as a trustworthy model tool for wind resource assessment, especially Weibull distribution model (Garcia *et al.*, 1998; Hennessey Jr, 1977). Of all statistical frequency distribution tool, two-parameter Weibull distribution has proved reliable and mostly used for wind energy appraisal. This is because its takes into cognisance the skewness associated with wind speed distribution. Moreover, the utilization of the two-parameter Weibull distribution effectively characterizes the frequency of low wind speeds in Nigeria, facilitating precise estimation of the likelihood of encountering low wind speeds. This is a crucial aspect in evaluating the viability of harnessing wind energy in particular geographical areas (Chang, 2011; Oral *et al.*, 2015). The Weibull distribution function, $f(v)$ can be expressed as follows: Average wind speed and wind speed frequency distribution were parameters mostly considered when evaluating wind power density of a location. The reliability from frequency distribution for wind characteristic assessment is better compared with average wind speed (Ben *et al.*, 2021). Studies have verified and validated the application of frequency distribution as a trustworthy model tool for wind resource assessment, especially Weibull distribution model (Garcia *et al.*, 1998; Hennessey Jr, 1977). Of all statistical frequency distribution tool, two-parameter Weibull distribution has been proved reliable and most used for wind energy appraisal. This is because its take into cognisance the skewness associated with wind speed distribution (Chang, 2011; Oral *et al.*, 2015). The Weibull distribution function, *f(v)* can be expressed as follows:

$$f(v) = \left(\frac{k}{c}\right)\left(\frac{v}{c}\right)^{k-1} exp\left[-\left(\frac{v}{c}\right)^{k}\right] \;(v > 0; k, c > 0) \quad (4)$$

Where k is the shape factor and c is the scale factor.

The distribution entails two parameters: the scale factor, c (in m/s) and the shape factor, k, which is dimensionless. The shape factor has great influence on the distribution. It also reflects the reliability and maintainability of wind characteristic of a region. A stable wind has a scale factor between 1.51 and 1.99 while gust wind is estimated to have a factor less than or equal to 1.50. A shape factor of 2 indicates a moderately stable wind phenomenon and when it is greater than or equal to 3 the wind trend is characterised as very stable (Bhattacharya & Bhattacharjee, 2010; Jiang & Murthy, 2011; Shaban *et al.*, 2020; Wais, 2017).

Wind characteristics differ from region to region in spatial and temporal, so also the shape factor. For instance, the shape factor for UK has been estimated to vary between 1.43 to 2.23 (Earl *et al.*, 2013; Watson, 2019) while the shape parameter in Braunschweig, North Germany plain ranges from 1.92 to 2.42. The research in Braunschweig was carried out for 40 to 500 m altitude above ground level at interval of 20 m (Lampert *et al.*, 2016). Mohammed *et al.* (2019) analysed wind speed data in Zagora, Morocco, and asserted that the shape factor at 10 m elevation varies between 1.53 and 1.75 in a year cycle. In the work of Ben *et al.* (2021), the author claimed, the average shape factor at 50 m elevation for Ilorin, Nigeria is 3.68. Fortified with the aforementioned information, this study has calculated the shape and scale factors of the Weibull distribution at 5 altitudes: 10, 30, 50, 70, and 90 m. Three Weibull parameters estimators were used for the evaluation namely: empirical method of Justus (EMJ) (Justus *et al.*, 1978), the empirical method of Lysen (EML) (Lysen, 1982), and the power density method (PDM) (Akdağ & Dinler, 2009). The formulas for the estimators are as given in Eqns. 5 to 12.

The empirical method of Justus can be expressed as follows:

$$k = \left(\frac{\sigma_v}{\bar{v}}\right)^{-1.086} (1 \leq k \leq 10) \quad (5)$$

$$c = \frac{\bar{v}}{\Gamma(1 + 1/k)}, \quad (6)$$

Where σ_v and $\bar{v}$ are the standard deviation and average of the wind speed, respectively, Γ is gamma function, and $\bar{v}$, is the average wind speed.

The standard deviation of the wind speed, σ_v, and gamma function, Γ can be estimated as follows:

$$\bar{v} = \frac{1}{n}\sum_{i=1}^{n} v_i \quad (7)$$

$$\sigma_v = \left[\frac{1}{n-1}\sum_{i=1}^{n}(v_i - \bar{v})^2\right]^{1/2} \quad (8)$$

$$\Gamma(\gamma) = \int_0^{\infty} x^{\gamma-1} e^{-x} dx \quad (9)$$

The empirical method of Lysen can be expressed as follows:

$$\mathrm{c} = \bar{v}\left(0.568 + \frac{0.433}{k}\right) \quad (10)$$

The calculation of the shape factor, k is done using Eqn. 5.

Akdağ and Dinler (2009), formulated a correlation for appraising Weibull parameters and established that the estimator is adequate for evaluating the parameters. This is given as power density method (E_{pf}) which is as follows.

$$E_{pf} = \frac{\overline{v^3}}{\bar{v}^3} \quad (11)$$

$$\mathrm{k} = 1 + \frac{3.69}{(E_{pf})^2} \quad (12)$$

Where $\overline{v^3}$ is the average of the cubed wind speed. The scale factor, c, is calculated with Eqn. 6.

D. *Most probable wind speed and Maximum energy wind speed*

The Weibull probability distribution also characterised two important wind speeds that are used in the assessment of technical potential of wind energy in a particular location of interest. These wind speeds are called most probable wind speed, v_{mp} and maximum energy wind speed, $v_{Max.E}$. The formula for estimating these parameters is expressed in Eqns. 13 and 14, respectively:

$$v_{mp} = \mathrm{c}\left(1 - \frac{1}{k}\right)^{1/k} \quad (13)$$

$$v_{Max.E} = c\left(1 + \frac{2}{k}\right)^{1/k} \quad (14)$$

E. *Wind turbines operational probability*

Wind turbines operate based on three wind speed thresholds: cut-in, cut-out and rated speed. The cut-in speed, v_a, is the wind speed that is enough for the wind turbine to trickle electricity. This is mostly taken as 3 to 5 m/s for majority of wind turbines. The cut-out speed, v_b, can be referred to as turbine safety wind speed. It is wind speed at which wind turbine is shutdown from electricity generation, either manually or automatically to prevent any damage. The cut-out wind speed is at most 25 m/s. Rated speed, v_r, is the wind speed at which wind turbine is at maximum rated power generation. It ranges from 11 to 12 m/s. Once the scale and shape factor is known, the prospective possibility of wind turbine productivity can be calculated by cumulative Weibull distribution (Zhou *et al.*, 2006) using Eqn. 15.

$$P(v_a < v < v_b) = e^{\left[-\left(\frac{v_a}{c}\right)^k\right]} - e^{\left[-\left(\frac{v_b}{c}\right)^k\right]} \quad (15)$$

F. *Wind power density estimates*

Wind power per unit area is called wind power density (WPD). The WPD is critical in the analysis of wind energy availability of a prospective wind farm site. Wind turbine industries for decades have adopted the Weibull distribution for assessing the time series wind data of a site. The distribution has been proved reliable than mean wind speed value by integrating the wind speed data over time (Ditkovich & Kuperman, 2014). Eqn. 16 gives the WPD using the Weibull parameter method.

$$WPD = \frac{1}{2}\rho c^3 \Gamma\left(1 + \frac{3}{k}\right) \quad (16)$$

Classification of the evaluated WPD has also been worked out by National Renewable Energy Laboratory (NREL). Wind power class shows the range, quality and corresponding mean wind speed of wind power densities that can be possibly harnessed at a particular site (Islam *et al.*, 2013; Kalmikov, 2017).

III. RESULTS AND DISCUSSION

Figure 2 shows the maximum and minimum points of the variation of the mean annual wind speed at hub-heights: 10, 30, 50, 70 and 90 m used for the evaluation. The two decades' wind characteristics analysis done by this study showed that the mean annual wind speed possible in this study area at hub-height of 10 m is 2.89 m/s, 30 m is 4.50 m/s, 50 m is 4.30 m/s, 70 m is 6.95 m/s, and 90 m is 7.68 m/s. It is obvious from this study that none of the mean wind speeds is up to the conventional wind turbine rated maximum capacity wind speed which is 11 or 12 m/s and the turbine cut-out wind speed which is 25 m/s. Although, wind turbine installed in this area might not generate power up to its maximum capacity, but the performance safety of the machine is ascertained until the date of its decommissioning.

Figure 3 shows the 2021 monthly wind speed at 10 m hub-height. The atmospheric weather condition during the daytime and night-time have influences on the vertical wind profiles. The daytime wind is always fresh while night-time wind is calm (Emeis, 2004). Plotting the mean wind speed of both day and night-time against hub-heights have been used to find "crossover height or reversal height". Lokoshchenko *et al.* (2009) and Emeis *et al.* (2007) have worked on the determination of crossover height for Moscow city, Russia and Hannover, Germany respectively. The term crossover height has been embraced in this work to estimate the prospective and investment hub-height for the experimental site. Figures 4 and 5 show the graphical evaluation of February and May 2021 diurnal wind variation which were the months with minimum and maximum mean wind speed respectively. The diurnal wind variations and wind speeds for these months were studied at different hub-heights. The wind pattern for the day and night analysis shows nonsymmetric pattern but similar trends for all hub-heights except 50 m altitude with an inexplicable slight distortion for both months of February and May.

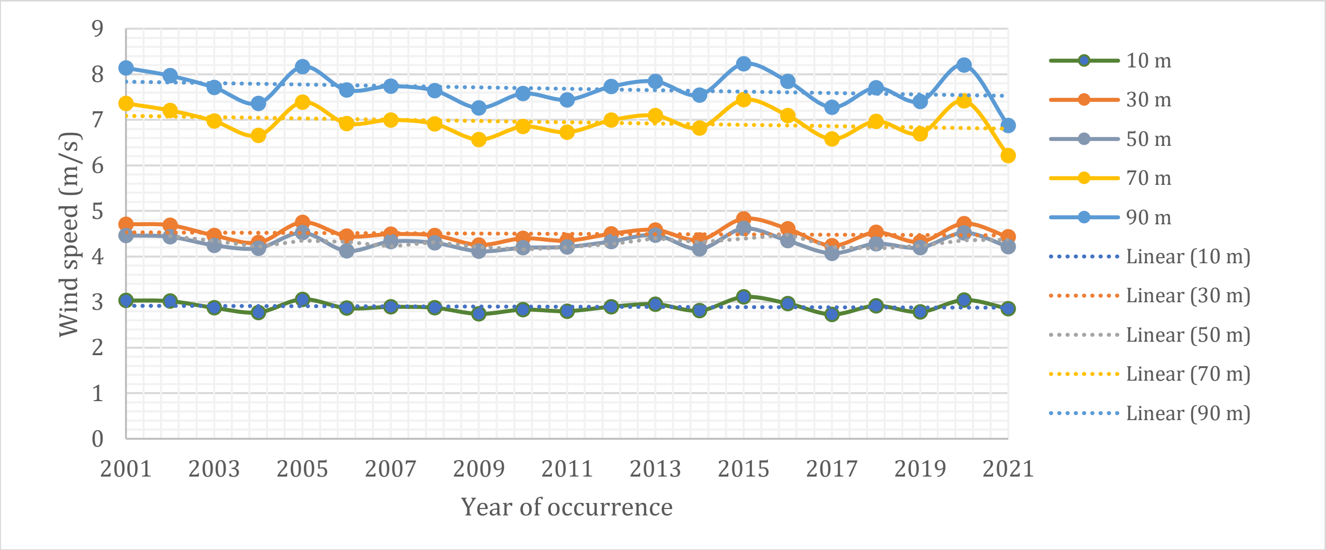


Figure 2: Mean annual wind speed at different hub-height.

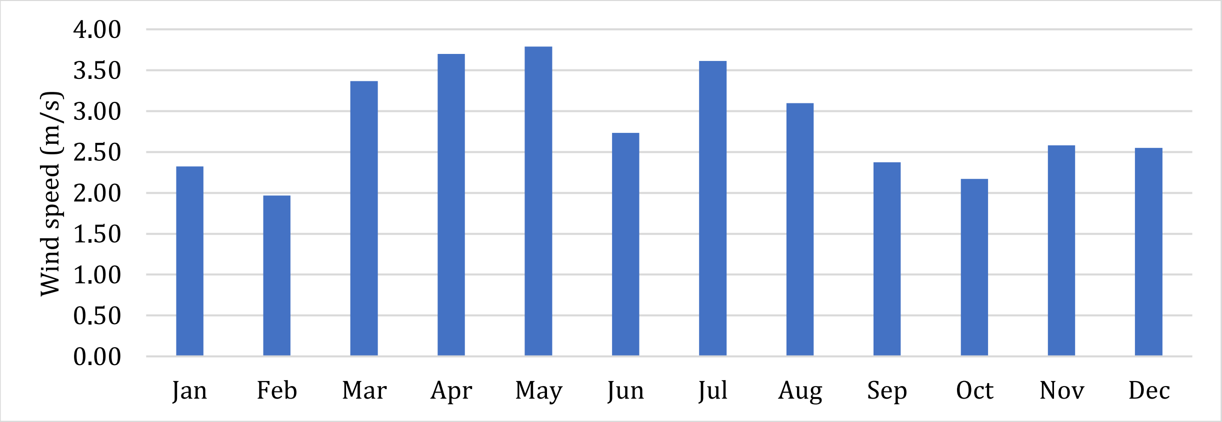


Figure 3: 2021 monthly mean wind speed at 10 m hub-height

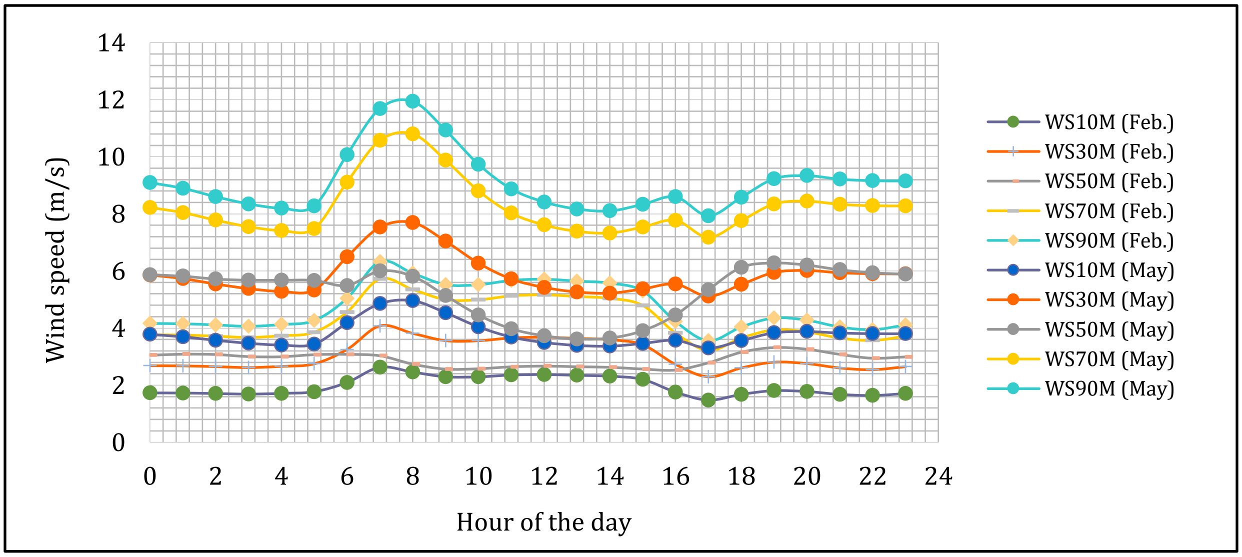


Figure 4: Diurnal wind variation for February and May 2021

The study area is exposed to two seasonal conditions, the dry and rainy seasons. These seasons range from October to March for dry and from April to September for rainy season. These seasons influence the wind characteristics in this area (Ohunakin, 2011). The seasons in the study area were responsible for the lowest wind speed in the month of February and highest for month of May in the year 2021 as shown in Figure 3. The diurnal variations of wind profile for these months were studied to estimate the crossover height of the site. It is found that the prospective hub-height is within the frame of 35 to 45 m while the investment hub-height stretches from 60 to 70 m as depicted in Figure 5.

power obtained from this evaluation from 10 to 50 m hub-heights were less than 100 W/m^2. This simply implied that the value of wind power density from these hub-heights were in poor categories. The values of wind power density at 70 and 90 m hub-heights were greater than 100 W/m^2 but less than 400 W/m^2. Adopting NREL's classification, this indicated that the wind power density at these hub-heights ranged between marginal and fair resource potential.

The Weibull distribution frequency plots for all the elevations were shown in Figure 8. The values of the mean wind power density were the average power density for the 21 years' assessment carried out in this study.

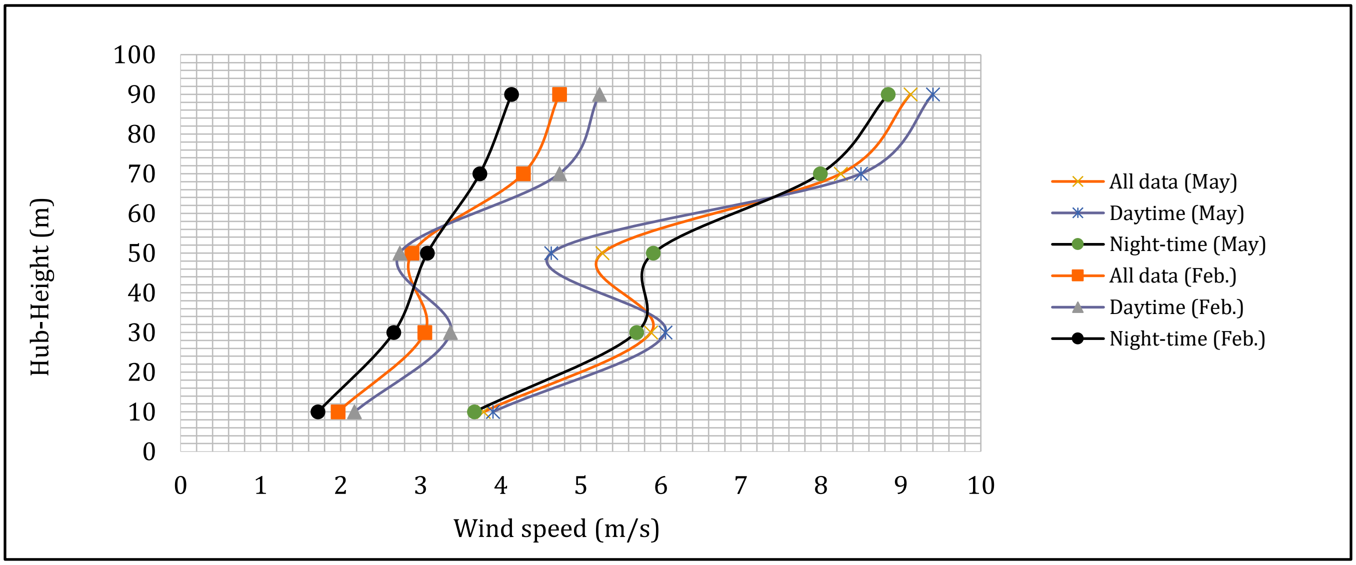


Figure 5: Wind vertical profile for February and May 2021

Figures 6 and 7 show the wind directions of the experimental site at turbine hub-height 10 and 50 m, respectively. They showed that the highest occurrence wind flux is from the South-West direction and there is no wind from the Northern direction. The southern direction also illustrates a considerable wind flow while remaining cardinal directions only indicate a specks quantity of wind flow. Since this study only evaluated wind characteristics of a site, it is assumed that the wind direction is invariant with height. The wind direction of the site is skewed with the prevailing wind originating from south-west. This is largely because of the site location on the globe. The rarest wind track is from the northern direction. The southern direction comes next to the prevailing wind direction and north-east direction also exhibit a trace of wind availability.

Table 1 shows the scale factors, c (m/s) and shape factors, k for the estimators. The scale factors for empirical methods of Justus (EMJ) and power density method (PDM) are approximately equal while the empirical method of Lysen (EML) is the lowest for all the hub-heights.

Table 2 provides the wind power densities limits for the wind speed at 10, 30 and 50 m hub-heights, respectively for the wind power density classification established by National Renewable Energy Laboratory (NREL), USA. The values of wind power density from this assessment were also ranked according to the NREL's classification. The value of wind

These were also considered with respect to the Weibull parameters estimators and the hub-heights. It is obvious from the charts that the average wind speed with respect to each height increases with the hub-height but the occurrence time decreases. The least occurrence rate at an average wind speed of 7 m/s was at 90 m hub-height. The most frequent average wind speed of 3 m/s was achieved at 10 m hub-height. This simply implied that an electric generator of 2.5 m/s cut-in wind speed is appropriate for this location and the significance of hub-height above 30 m may not be pronounced.

The prominent wind speeds occurrence at the hub-heights are as shown in Table 1. The results shown in Table 4 are compared with the viable wind speed occurrence in Table 1. The viable wind speed match appropriately with the most probable wind speed in the study area with slight difference to maximum energy wind speed. It was also observed that the probability for a low cut-in speed wind turbine to function in this region is 98% for all the estimators when the cut-in wind speed is 2 m/s and a value of 95% for cut-in wind speed of 2.5 m/s while 88% was observed for 3 m/s cut-in wind speed. The probability results considered were for hub-height of 30 m and above.

The wind power density results over the 21 years of appraisal at the experimental hub-heights are presented in Table 5. The wind power density as evaluated using empirical method of Justus (EMJ) and power density method (PDM)

Table 1: Hub-heights shape and scale factors

	10 m hub-height					**30 m hub-height**						**50 m hub-height**				**70 m hub-height**					**90 m hub-height**				
Year	**K (EMJ)**	**K (PDM)**	**C (EMJ)**	**C (EML)**	**C (PDM)**	**K (EMJ)**	**K (PDM)**	**C (EMJ)**	**C (EML)**	**C (PDM)**	**K (EMJ)**	**K (PDM)**	**C (EMJ)**	**C (EML)**	**C (PDM)**	**K (EMJ)**	**k (PDM)**	**C (EMJ)**	**C (EML)**	**C (PDM)**	**K (EMJ)**	**K (PDM)**	**C (EMJ)**	**C (EML)**	**C (PDM)**
2001	5.70	4.00	3.28	2.81	3.35	5.70	4.00	5.09	4.36	5.20	6.68	4.16	4.78	4.17	4.91	2.96	2.82	8.25	6.57	8.26	2.96	2.82	9.12	7.26	9.14
2002	6.36	4.11	3.25	2.81	3.33	6.36	4.11	5.04	4.37	5.16	8.08	4.30	4.71	4.18	4.87	4.06	3.49	7.94	6.54	8.01	4.06	3.49	8.78	7.23	8.86
2003	5.94	4.03	3.10	2.67	3.17	5.94	4.03	4.81	4.14	4.92	6.73	4.14	4.55	3.97	4.68	2.96	2.81	7.81	6.22	7.83	2.96	2.81	8.64	6.88	8.66
2004	5.34	3.90	3.01	2.56	3.06	5.34	3.90	4.67	3.97	4.76	6.80	4.16	4.48	3.91	4.60	3.41	3.15	7.41	5.98	7.44	3.41	3.15	8.19	6.61	8.22
2005	5.30	3.91	3.32	2.82	3.38	5.30	3.91	5.16	4.38	5.25	6.25	4.10	4.86	4.21	4.98	3.11	2.95	8.26	6.61	8.28	3.11	2.95	9.13	7.31	9.15
2006	5.11	3.88	3.12	2.64	3.17	5.11	3.88	4.84	4.09	4.92	6.25	4.10	4.44	3.84	4.54	3.07	2.94	7.74	6.19	7.76	3.07	2.94	8.56	6.84	8.58
2007	5.09	3.86	3.15	2.66	3.20	5.09	3.86	4.89	4.13	4.96	5.71	4.00	4.68	4.01	4.77	2.99	2.87	7.84	6.25	7.85	2.99	2.87	8.67	6.91	8.68
2008	6.42	4.12	3.09	2.68	3.17	6.42	4.12	4.79	4.16	4.92	7.21	4.22	4.59	4.03	4.73	3.55	3.21	7.67	6.22	7.71	3.55	3.21	8.49	6.88	8.53
2009	7.24	4.22	2.93	2.57	3.02	7.24	4.22	4.54	3.99	4.68	8.09	4.30	4.37	3.88	4.52	3.88	3.38	7.26	5.94	7.31	3.88	3.38	8.03	6.57	8.09
2010	4.91	3.81	3.09	2.60	3.14	4.91	3.81	4.80	4.04	4.87	5.56	3.96	4.54	3.88	4.63	2.97	2.86	7.68	6.12	7.69	2.97	2.86	8.49	6.76	8.50
2011	5.26	3.90	3.04	2.58	3.09	5.26	3.90	4.72	4.01	4.80	5.55	3.97	4.56	3.89	4.65	3.35	3.13	7.49	6.04	7.52	3.35	3.13	8.29	6.68	8.31
2012	5.26	3.90	3.15	2.67	3.20	5.26	3.90	4.89	4.15	4.97	6.01	4.05	4.67	4.02	4.77	3.14	2.98	7.81	6.26	7.83	3.14	2.98	8.64	6.92	8.66
2013	6.96	4.17	3.16	2.76	3.25	6.96	4.17	4.90	4.29	5.05	8.40	4.31	4.74	4.22	4.91	3.63	3.23	7.87	6.40	7.92	3.63	3.23	8.70	7.07	8.75
2014	5.20	3.88	3.06	2.59	3.11	5.20	3.88	4.74	4.02	4.82	6.13	4.07	4.48	3.87	4.59	2.87	2.77	7.65	6.08	7.66	2.87	2.77	8.46	6.72	8.47
2015	6.55	4.15	3.34	2.90	3.43	6.55	4.15	5.18	4.50	5.32	6.96	4.19	4.93	4.32	5.08	3.90	3.41	8.22	6.74	8.28	3.90	3.41	9.09	7.45	9.16
2016	5.14	3.87	3.23	2.73	3.28	5.14	3.87	5.01	4.24	5.09	6.53	4.14	4.66	4.05	4.79	3.62	3.30	7.87	6.40	7.91	3.62	3.30	8.71	7.07	8.75
2017	5.39	3.92	2.96	2.52	3.02	5.39	3.92	4.60	3.91	4.68	6.59	4.14	4.37	3.80	4.48	3.21	3.02	7.34	5.90	7.37	3.21	3.02	8.12	6.52	8.14
2018	4.59	3.71	3.19	2.67	3.23	4.59	3.71	4.96	4.14	5.02	5.82	4.02	4.62	3.97	4.72	3.48	3.24	7.75	6.27	7.77	3.48	3.24	8.56	6.93	8.60
2019	5.57	3.96	3.01	2.57	3.07	5.57	3.96	4.68	3.99	4.77	6.11	4.07	4.52	3.90	4.62	3.33	3.10	7.46	6.01	7.49	3.33	3.10	8.25	6.65	8.28
2020	4.92	3.81	3.32	2.79	3.37	4.92	3.81	5.15	4.34	5.23	5.52	3.96	4.90	4.18	4.99	2.65	2.57	8.35	6.59	8.35	2.65	2.57	9.23	7.29	9.24
2021	5.12	3.85	3.11	2.63	3.16	5.12	3.85	4.82	4.08	4.90	6.04	4.05	4.54	3.91	4.65	5.12	3.85	6.76	5.72	6.88	5.12	3.85	7.48	6.33	7.60
Average	**5.59**	**3.95**	**3.14**	**2.68**	**3.20**	**5.59**	**3.95**	**4.87**	**4.16**	**4.97**	**6.52**	**4.11**	**4.62**	**4.01**	**4.74**	**3.39**	**3.10**	**7.74**	**6.24**	**7.77**	**3.39**	**3.10**	**8.55**	**6.90**	**8.59**

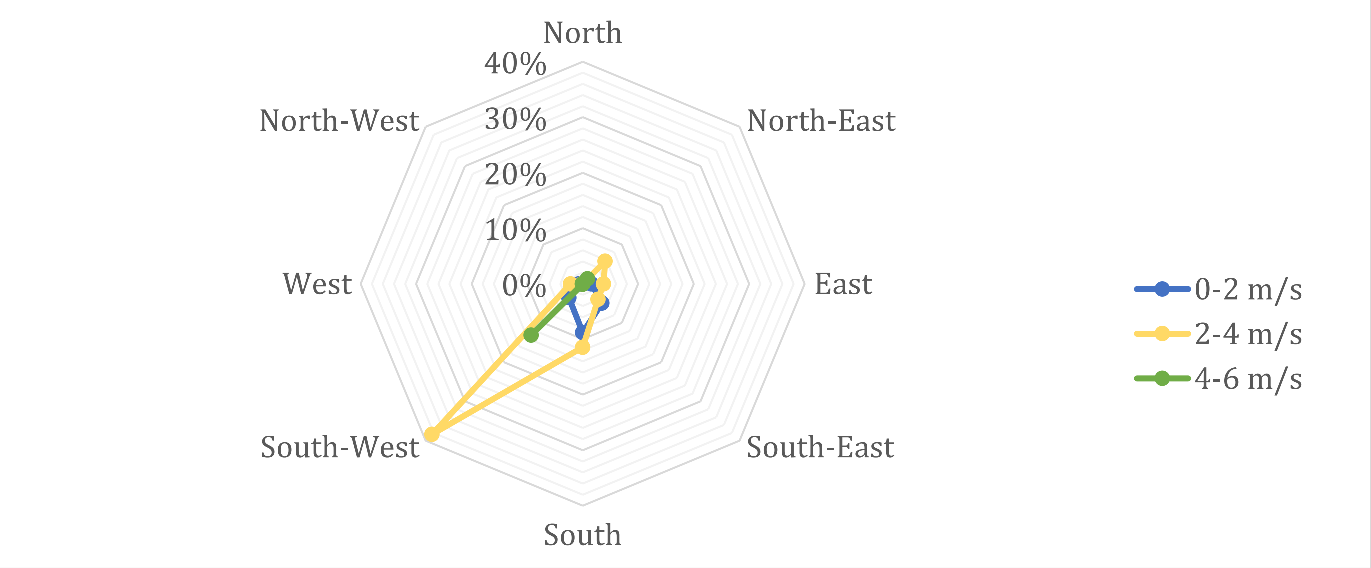


Figure 6: Wind directions at 10 m hub-height

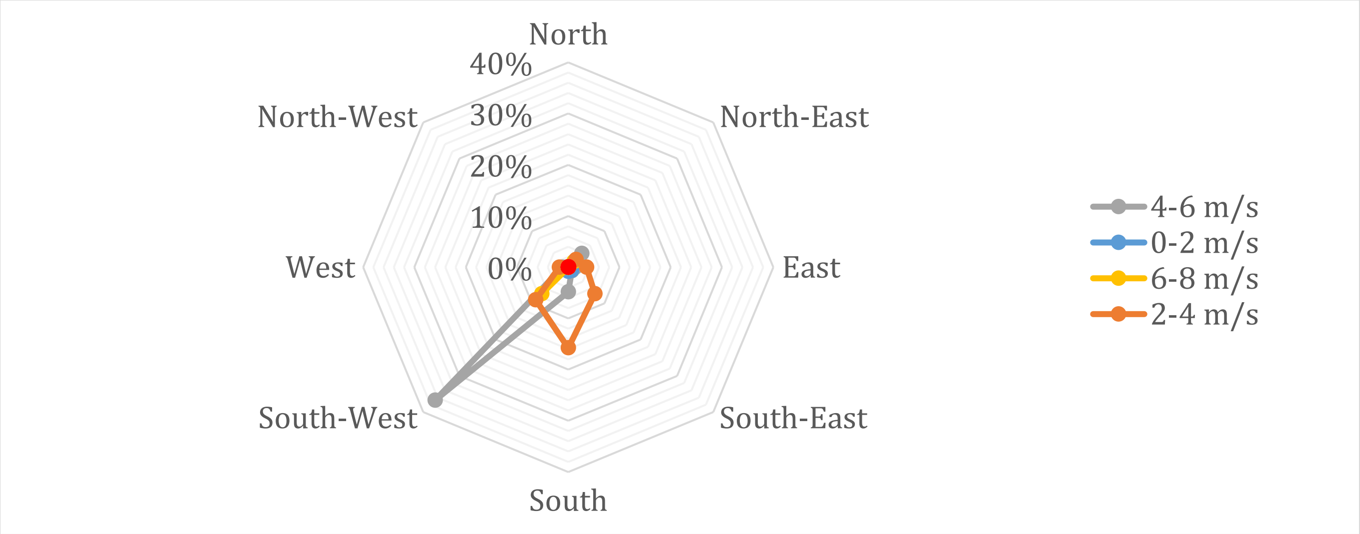
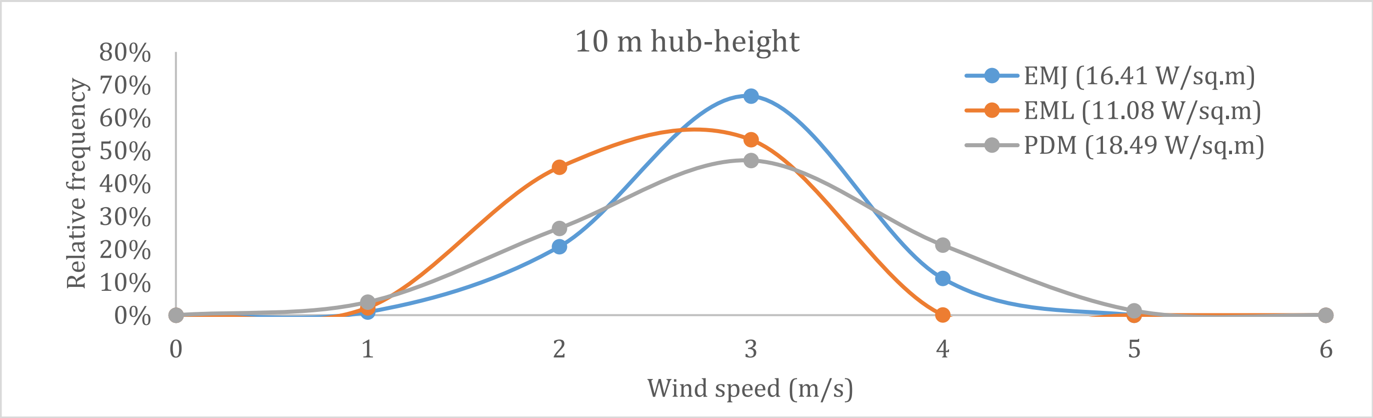
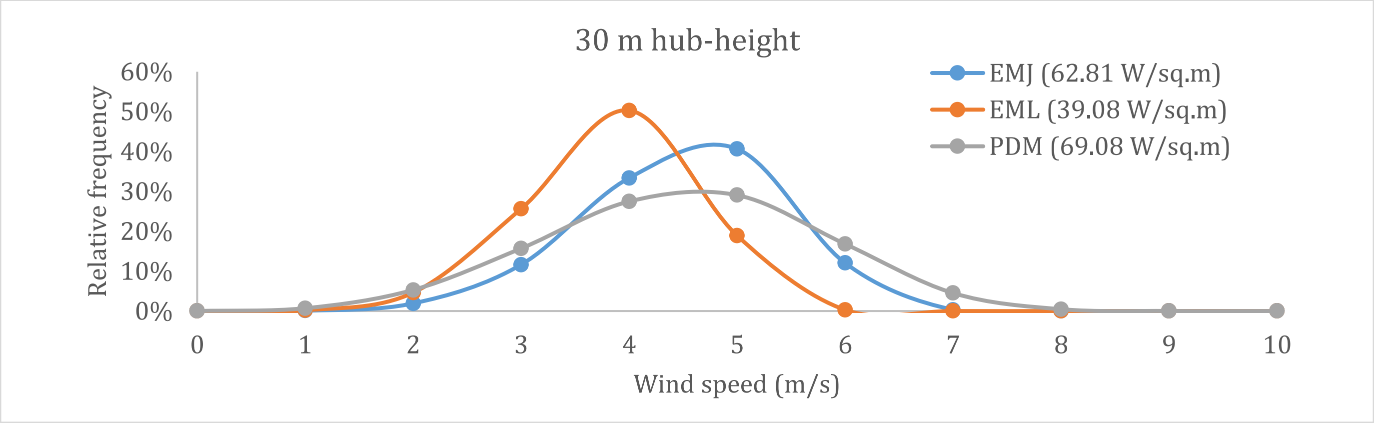


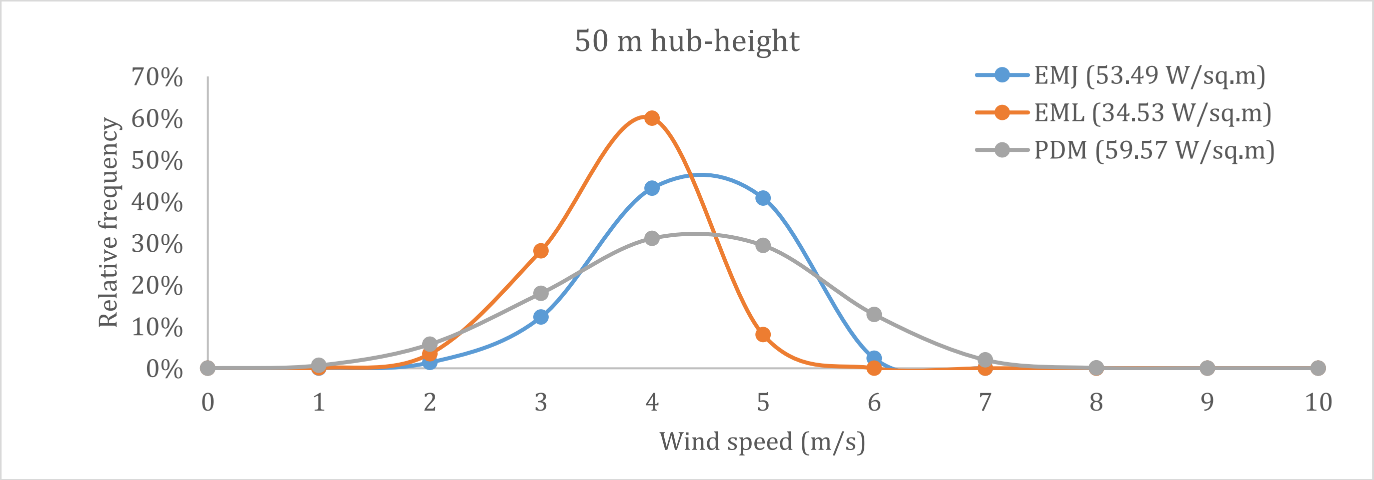
Figure 7: Wind directions at 50 m hub-height

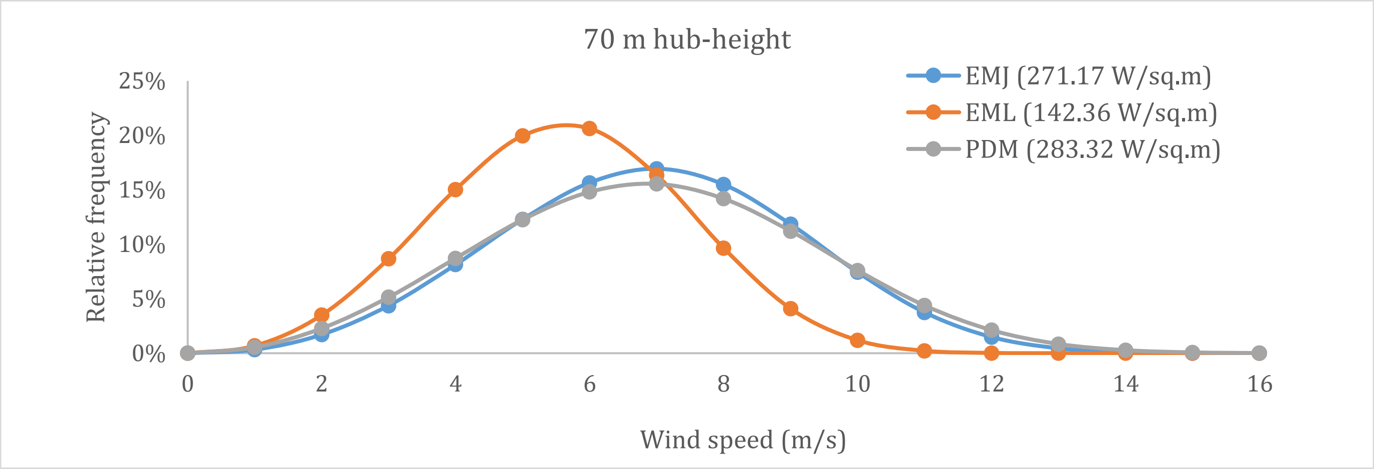
Table 2: Wind power density class

Wind power class	10 m Hub-height		30 m Hub-height		50 m Hub-height		Resource potential
	WS (m/s)	WPD (W/m^2)	WS (m/s)	WPD (W/m^2)	WS (m/s)	WPD (W/m^2)	
1	< 4.4	< 100	< 4.9	< 243	< 5.6	< 200	Poor
2	4.4 – 5.1	100 – 150	4.9 – 6.9	243 – 378	5.6 – 6.4	200 – 300	Marginal
3	5.1 – 5.6	150 – 200	6.9 – 7.5	378 – 500	6.4 – 7.0	300 – 400	Fair
4	5.6 – 6.0	200 – 250	7.5 – 8.1	500 – 616	7.0 – 7.5	400 – 500	Good
5	6.0 – 6.4	250 – 300	8.1 – 8.6	616 – 748	7.5 – 8.0	500 – 600	Excellent
6	6.4 – 7.0	300 – 400	8.6 – 9.4	748 – 978	8.0 – 8.8	600 – 700	Outstanding
7	> 7.0	> 400			> 8.8	> 800	Superb


10 m hub-height
EMJ (16.41 W/sq.m)
EML (11.08 W/sq.m)
PDM (18.49 W/sq.m)
Relative frequency
80%
70%
60%
50%
40%
30%
20%
10%
0%
0
1
2
3
4
5
6
Wind speed (m/s)


30 m hub-height
EMJ (62.81 W/sq.m)
EML (39.08 W/sq.m)
PDM (69.08 W/sq.m)
Relative frequency
60%
50%
40%
30%
20%
10%
0%
0
1
2
3
4
5
6
7
8
9
10
Wind speed (m/s)


50 m hub-height
EMJ (53.49 W/sq.m)
EML (34.53 W/sq.m)
PDM (59.57 W/sq.m)
Relative frequency
70%
60%
50%
40%
30%
20%
10%
0%
0
1
2
3
4
5
6
7
8
9
10
Wind speed (m/s)


70 m hub-height
EMJ (271.17 W/sq.m)
EML (142.36 W/sq.m)
PDM (283.32 W/sq.m)
Relative frequency
25%
20%
15%
10%
5%
0%
0
2
4
6
8
10
12
14
16
Wind speed (m/s)

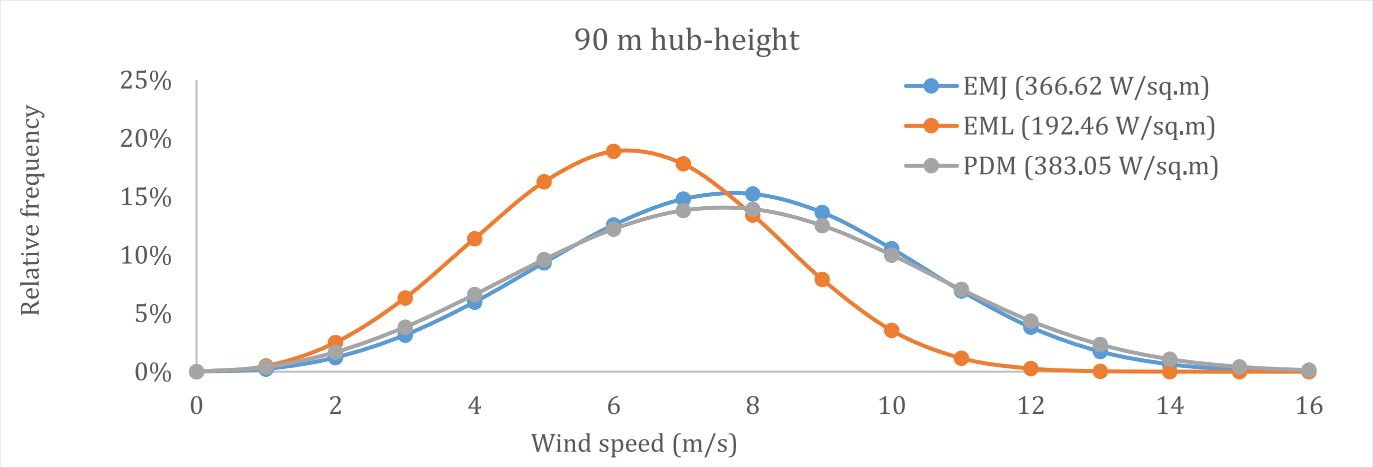


Figure 2: Weibull distribution frequency plots and mean wind power density

Table 1: Prominent wind speed occurrence

	EMJ		**EML**		**PDM**	
Hub-height (m)	Mean wind speed (m/s)	Occurrence (%)	Mean wind speed (m/s)	Occurrence (%)	Mean wind speed (m/s)	Occurrence (%)
10	3	67	3	53	3	47
30	5	41	4	50	5	29
50	4.5	41	4.5	60	4.5	30
70	7	16	6	21	7	16
90	8	15	7	18	8	14.5

Table 2: Most probable and maximum energy wind speed

	EMJ		**EML**		**PDM**	
Hub-height (m)	v_{mp}(m/s)	$v_{max.E}$	v_{mp}(m/s)	$v_{max.E}$	v_{mp}(m/s)	$v_{max.E}$
10	3.02	3.32	2,58	2.83	2.97	3.55
30	4.69	5.15	4.01	4.40	4.61	5.51
50	4.50	4.82	3.90	4.18	4.43	5.22
70	6.92	8.94	5.59	7.21	6.82	9.16
90	7.66	9.89	6.18	7.97	7.54	10.13

were closely related. However, the method of Lysen (EML) depicted a large discrepancy which is less than mid percentile for the power density. Generally, the production time of wind turbine operating in this location will be more than 50% of the daytime. This invariably also offers value for investment.

IV. CONCLUSION

Wind energy as environmentally friendly energy source has been regarded as class one renewable energy resource to combat the menace of fossil fuel emissions in the world. However, a thorough assessment of technical potential of wind energy resource in site of interest is required before the deployment of wind energy system. This study appraised technical potential of wind energy resource of Ilorin city for 21 years from 2001 to 2021. The study evaluated mean annual wind speed, diurnal wind variation to determine prospective hub-height, wind direction, wind turbines operational probability, most probable wind speed, maximum energy wind speed, and wind power density using Weibull distribution unction. Two parameters Weibull distribution function and three Weibull parameter estimators were used for analysis at 10, 30, 50, 70 and 90 m respectively. The significant conclusions derived from this appraisal were as follows:

i. The study location is not exposed to gust wind since the mean annual wind speed of the site varied from 2.89 m/s at 10 m hub-height to 7.68 m/s at 90 m hub-height. Hence, the turbine may operates below cut-out wind speed but optimal operation of the turbine at the rated output is not feasible.

ii. The major prevailing wind direction in this region is from south-west while the rarest wind direction is from the north.

iii. The Weibull parameters, scale and shape factors determined by empirical method of Justus and power density method were approximately equal, empirical method of Lysen.

iv. The operational probability of wind turbine in this location has a value of 98% for 2 m/s, 95% for 2.5 m/s and 88% for 3 m/s cut-in wind speed. Therefore, wind turbines with low cut-in wind speed will have a higher productivity chance in the study area;

v. The most probable wind speed calculated from the study match the prominent wind speed extracted from the Weibull wind distribution plots; and

vi. The wind power density at 10, 30, 50 m hub-heights were classified as poor while the wind power density at 70 and 90 m hub-heights, qualified for marginal and fair, respectively.

LIMITATION

The MERRA-2 wind data used in this study is a remote sensed data. Thus, the data might not perfectly agree with in situ measurement. Therefore, these distinctions normally will have minimal misrepresentation on the analysis results.

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AUTHOR CONTRIBUTIONS

Yahaya T.: Conceptualization and Ph.D. student on this research. **Ajimotokan H. A.:** Literature review. **Adebisi J. A.:** Data analysis. **Ahmed I. I. and Ajiboye T. K.:** Drafting of the methodology. **Abdulkareem S.**: Reviewing while **Ajao K. R.**: Supervisor.

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