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# Investigation of Wind Characteristics and Estimation of Wind Power Potential of Narok County Using Weibull Distribution

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***Authors' contributions***

*This work was carried out in collaboration among all authors. All authors read and approved the final manuscript.*

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## ABSTRACT

**Aim:** To investigate wind characteristics and estimate wind power density of Narok weather station in Narok county using Weibull distribution.
**Research Design:** Historical hourly wind direction and speed data recorded by the Kenya Meteorological Department in Narok weather station was analyzed.
Place and duration: The study utilized data samples collected at Narok weather station over a period spanning from 2011 to 2021.
**Methods:** To assess the temporal characteristics, a statistical average technique was employed. The spatial aspect, specifically wind speed variation with height, was evaluated through wind speed extrapolation using the power law. The dominant wind direction was determined by plotting a polar chart based on a frequency distribution table prepared using both wind direction and wind speed data. The turbulence intensity of the wind was calculated using the turbulence intensity equation.

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The Weibull parameters were estimated using the maximum likelihood estimation method. The Weibull probability distribution was used to analyze wind speed distribution and power density. The extrapolated Weibull parameters were utilized to calculate wind power density at various heights. The accuracy of the wind regime distribution in Narok was assessed by employing the R2 technique.

**Results:** The wind regime in Narok exhibited an average annual wind speed of 4.3 m/s and a mean wind power density of 126 W/m2. Analysis of diurnal wind speed variation revealed peak wind speeds around noon, with wind speeds exceeding the cut-in wind threshold (3 m/s) between 0430hrs and 2100hrs. March and October were identified as the windiest months, exhibiting the highest wind power densities, while June and December demonstrated the lowest values. Wind speed and, consequently, wind power density increased exponentially with height. The prevailing wind directions in Narok were primarily from the East, followed by the North and North West. The wind regime in Narok exhibited turbulence, as indicated by average turbulence intensities exceeding 0.25. The wind regime in Narok was accurately described by the Weibull distribution, with an approximation accuracy of 0.94 based on the R2 error.

**Conclusion:** The wind regime in Narok is generally suitable for extracting wind power at heights above 15 m, regardless of the scale of the wind power extraction.

*Keywords: Narok; wind speed; wind power density; wind turbine; Weibull probability distribution function.*

## 1. INTRODUCTION

Kenya is one of the African countries having the fastest population and economic growth in Africa [1]. This growth is characterized by an exponential increase in energy demand which is a precursor for economic progress and industrialization of a developing country. Bulk of energy used in Kenya is derived from wood and fossil fuels supplemented with renewable energy sources [2] [3]. Currently, the country is heavily relying on non-renewable energy sources to suffice its ever-growing energy demands [4]. Wood and fossil fuels are non-renewable and are characterized by environmental pollution due the Green House Gases (GHGs) associated with them Perera F [5] which are harmful to both human health and environment. Furthermore, the reserves of the conventional energy sources have been speculated to be declining worldwide [6] [7]. These disadvantages have triggered the efforts of transiting from the conventional energy sources to renewable energy sources by the country.

Full transition can be achieved only if the concept of energy mix is fully embraced [8]. This is currently not the case since renewable energy exploitation statistics indicate that wind energy is among the least exploited in Kenya [9]. According to the energy report by the Energy and Petroleum Regulatory Authority (EPRA) of Kenya, 73% of Kenyan land experience favorable wind speeds of 6 m/s at 100 m height. In addition, $28228 km^2$ land experiences wind speeds ranging between 7.5 m/s to 8.5 m/s and about $2825 km^2$ experiences wind speeds between 8.5 m/s to 9.5 m/s [10]. The data further confirms that there is indeed colossal wind power potential in Kenya, which remains untapped. Low exploitation of wind power may be attributed to scanty information Kazimierczuk [11] on the relevant wind characteristics of most places in Kenya despite of wind regime characterization being a mandatory requirement prior to wind power extraction. Characterization of wind regime have been done for only a few areas in Kenya as reviewed in next paragraph.

Cheruiyot et al. [12] characterized wind speed and estimated the wind power potential of the Kasses region in Kenya which exhibited unimodal and positively skewed characteristics using two parameter Weibull Probability Distribution Function (PDF). Their results showed that the region had mean wind speeds of 6.5 and 10.5 at 10 m and 100 m heights with a power density of 41.24 W/m$^2$ and 228.91 W/m$^2$ respectively. Similar study was done by Nyasani et al. [13] in Kisumu city, Kenya. The findings showed that wind power extraction in Kisumu city is viable from 50 m hub and beyond. The wind power density recorded at that height was 127.99 W/m$^2$. Mean wind speed at 10 m was 2.35 m/s while wind speed carrying maximum energy at the same hub height was 2.85 m/s. Laban et al. [14] conducted comparative study of wind regime in Kisii using Rayleigh and Weibull PDFs. The results suggested that Rayleigh fitted wind regime in Kisii slightly better than two parameter

Weibull based on $R^2$ best of fit judgement criterion. Similar study was conducted in the neighboring county, Nyamira by Kwamboka et al. [15]. Power densities that were obtained were 142.57 W/m$^2$ and 147 W/m$^2$ using Weibull and Rayleigh PDFs respectively. It was shown that two parameter registered low error margin compared to Rayleigh distributions. Another study was conducted in Marsabit and Garisa to determine wind power extraction feasibility in the two areas. The results showed that Marsabit had mean wind power density of 2202 W/m$^2$ with a prevalent wind speed of 11 m/s while, Garisa registered a mean wind power density of 190 W/m$^2$ with a prevalent wind speed of 3.90 m/s [16]. There other couple of studies that have assessed wind energy in other places and are well documented in [17], [18]; [19]. The wind regime characteristics of Narok county are still scanty owing to few studies that have been done on the same area even though wind energy mapping shows that Narok is lying in windy region. This work bridged the gap partially by estimating wind power potential and characterizing the wind regime of Narok using two parameter Weibull probability distribution function.

## 2. METHODS

### 2.1 Site Description and Wind Data

Narok is one of the 47 counties in Kenya which lies in the great Rift valley region. The geographical coordinate of Narok county is 1.3605°S, 35.7407°E. Narok generally have rugged terrain, trees, shrubs and a small town with storey buildings. The meteorological station where the data was collected lies in Narok north and located about 500 m from the Narok town central business district. Based on the nature of ground structures, Narok is typically having wind shear coefficient exponent ranging between 0.28-0.3 according to classification tabled by Resen et al. [20]. The data that was studied in this work was hourly wind and direction data recorded in Narok weather station for eleven years. The data was measured at 10 m height from the year 2011 to 2021.

### 2.2 Wind Direction

Wind direction was obtained by plotting polar chart from a frequency distribution table prepared using both the wind direction and wind speed data.

### 2.3 Temporal Variation of Mean Wind Speed

To gain understanding of diurnal and monthly wind speed behavior, average wind speed of each hour of the day and month of the year over the entire period was determined using equation 1 which is just a simple averaging technique.

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

Where; $\bar{v}, v$ $and$ $N$ denotes average mean wind speed, wind speed and number of observations in the considered data set respectively.

### 2.4 Extrapolation of Wind Speed with Respect to Height

Most wind speed measurements are taken at 10 m height but most wind turbines operate beyond this height. Therefore, it is reasonable to find the average wind speeds at various heights based on mean wind speeds at 10 m. This was done using equation 2. The b was chosen to be 0.3 based on the ground description in section 2.1.

$$v_z = v_0\left(\frac{z}{10m}\right)^b \quad (2)$$

$$b = 0.3.$$

### 2.5 Turbulence Intensity

Wind turbulence intensity was determined using equation 3. The wind turbulence intensity is an important aspect of wind power assessment as it determines the amount of stress that will be experienced by the wind turbines installed in the region [21].

$$I = \frac{1}{N}\left(\sum_{i}^{N} \frac{\sqrt{(\sigma_i)^2}}{\bar{v}}\right) \quad (3)$$

Where $\sigma$ & $\bar{v}$ represents standard deviation and mean wind speed, respectively, other terms bear their normal meanings.

### 2.6 Wind Speed Distribution

Wind speed regime is typically stochastic and dependent on many physical processes and features, making it almost impossible to predict wind speed at specific time and point. However, the behavior of wind speed may be described by a probability distribution function with minimal error margins. There are a number of PDFs that can be employed with the most common ones being Rayleigh, Weibull, hybrid Weibull and lognormal [22] [23]. In this work, Weibull PDF was used because of its reported success in wind speed distributions in various places around the world. The PDF is given in equation 4.

$$f(v) = \begin{cases} \frac{k}{c}\left(\frac{v}{c}\right)^{k-1} e^{-\left(\frac{v}{c}\right)^{k}}; \; v \geq 0 \\ 0 \qquad ; v < 0 \end{cases} \tag{4}$$

Equation 4 is a two-parameter traditional Weibull distribution where $c$ &$k$ are scale and shape parameters respectively. The scale and shape parameters must be obtained based on the data set observed. In this work, the parameters were obtained through Maximum Likelihood Estimate (MLE) method. The MLE is basically solving the log function of equation 4 to obtain equations 5 and 6. Equation 7 is solved numerically to find the shape parameter then substituted in equation 5 to get the scale parameter.

$$c = \left(\frac{1}{N}\sum_{i=1}^{N} v_i{}^{k}\right)^{\frac{1}{k}} \tag{5}$$

$$k = \left[\frac{\sum_{i=1}^{N} v_i{}^{k} ln v_i}{\sum_{i=1}^{N} v_i{}^{k}} - \overline{lnv}\right]^{-1} \tag{6}$$

Determination of the likelihood of a wind speed not exceeding certain wind speed was done using Weibull Cumulative Distribution Function (WCDF). The WDCF plot gives visual illustration of how well Weibull PDF describes the wind regime. However, the assessment of how well Weibull PDF fits the data was assessed using method of coefficients which is also knowns as the $R^2$ technique. WCDF and the $R^2$ equations are given in equations 7 and 8.

$$F(v) = \begin{cases} 1 - e^{-\left(\frac{v}{c}\right)^{k}} \qquad ; \; v \geq 0 \\ 0 \qquad ; v < 0 \end{cases} \tag{7}$$

$$R^2 = 1 - \left(\frac{\sum_i^N |y_i - \widehat{y_i}|^2}{|y_i - \bar{y}_i|^2}\right) \tag{8}$$

### 2.7 Wind Power Density

Mean Wind Power Density (WPD) is very key when assessing wind energy resource of an area. WPD gives the available wind power in a wind regime at a specific height. Wind power variation at different heights can assessed through extrapolation using equation 9 but with extrapolated values of c and k as shown in equations 10 and 11 respectively. WPD was determined using equation 10.

$$\bar{P} = \frac{1}{2}\rho c^3 \Gamma\left(\frac{k+3}{k}\right) \tag{9}$$

$$c_z = c_{10}\left(\frac{z}{10m}\right)^{b} \tag{10}$$

$$c_z = \frac{k_{10}}{1 - 0.088 \ln{(z/10)}} \tag{11}$$

## 3. RESULTS AND DISCUSSION

### 3.1 Wind Direction

Predominant wind direction of the wind regime in Narok is from the east (E). Fig. 1. indicates that about 25% of the time, wind was blowing from the E direction. Other predominant wind direction includes North West (NW), North (N) and West North West (WNW) corresponding to 15%, 7% and 5% respectively. Fig. 1. also shows that most arms of the Wind Rose are lying in the quadrant bounded by West and North directions. Therefore, wind turbines will generally face this quadrant (NW direction). Turbines with the ability to yaw will tap most of the power in this region since wind direction is not constant.

### 3.2 Temporal Wind Speed Variation

Fig. 2. displays diurnal behavior of wind speed. The maximum wind speed (6.5 m/s) occurs at about noon while the minimum (~2.7 m/s) wind speed occurs at midnight. The profile is almost symmetric about the midday hour. The most suitable hours of wind power generation at 10 m height are between 0430hrs to 2100hrs. During these hours, most wind speeds are above 3.0 m/s which corresponds to cut-in wind speeds of most wind turbines. Outside these hours of the day, wind turbines will most likely stall or just run without power generation because of wind speeds are lower than 3 m/s which is the cut-in wind speed for most turbines.

Fig. 3 on the other hand suggests that wind speed varies between about 3.7 m/s to about 5.8 m/s over the entire year. The profile of Fig. 3 also suggests that wind regime over the year has two peaks which occur in the months of March and October. These months are the windiest months of the year whereas wind speed is lowest in January, June and December. This suggests that the most suitable time of annual turbine maintenance is during any of the stated months since power output would be lowest. Monthly variation of wind speed over the year and the annual mean wind speed (4.3 m/s) suggest that the wind regime is mostly gentle breeze at 10 m height since most wind speeds lie in the range 3.5 m/s to 5 m/s.

### 3.3 Wind Speed Variation with Height

Fig. 4. shows mean wind speed extrapolated at various heights. From the figure, wind speed is increasing exponentially with height and the maximum wind speed is occurring at 100 m height. The figure is quite similar to surface-layer wind profile, as expected, and consistent with the results obtained by Boming et al who concluded that wind speeds have an exponential relationship with turbine heights [24]. The lower layers of wind experience a deceleration due to the stationary surface of the Earth, which remains fixed relative to the moving wind. Additionally, the layers above the lower layers are also subject to a certain degree of deceleration caused by the lower layers, although the magnitude of this deceleration is not as significant as the deceleration caused by the Earth's surface. This rend leads to the profile seen in figure 4. The observation suggests that it's more desirable for wind turbine heights to exceed 10 m for more power extraction since wind power is directly proportional to the cube of wind speed.

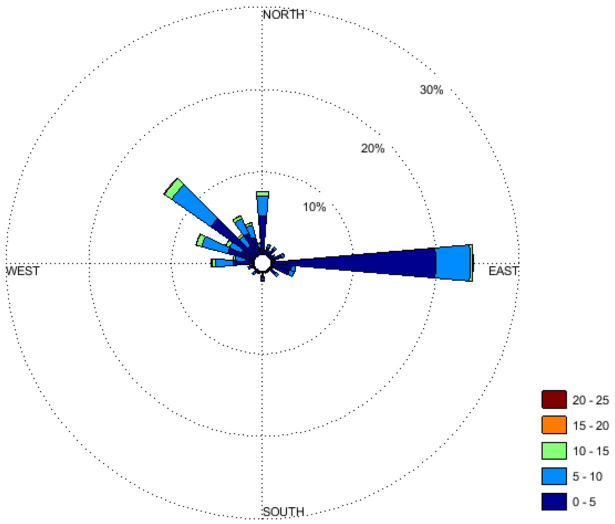


**Fig. 1. Wind-rose demonstrating wind directions over different wind speed ranges**

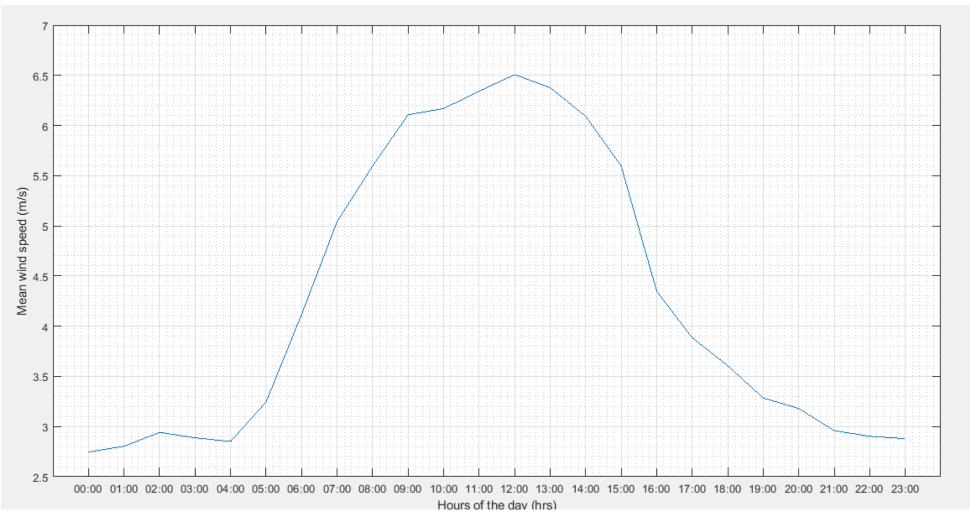


**Fig. 2. Evolution of mean wind speed with respect to the hour of the day**

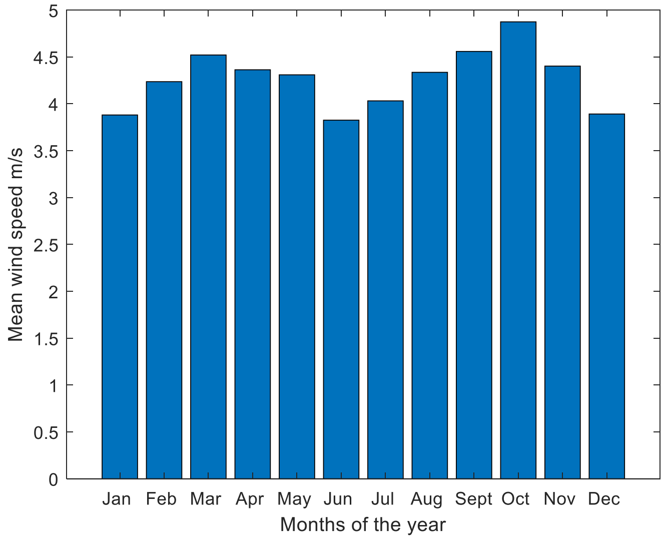


**Fig. 3. Mean wind speed variation over the months of the year**

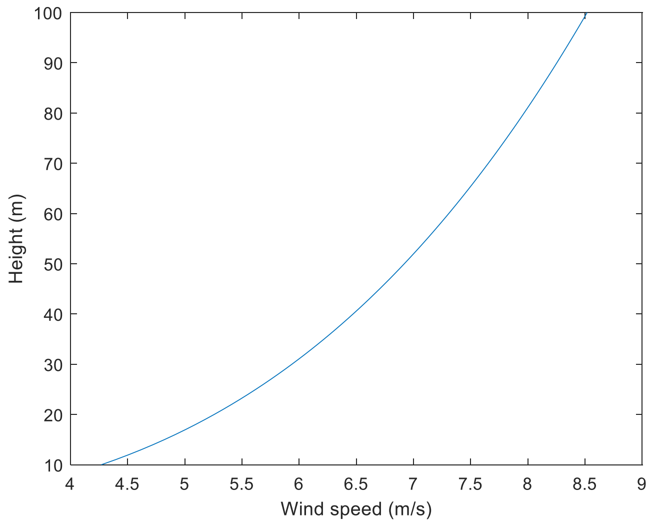


**Fig. 4. Mean wind speed variation with respect to hub height**

## 3.4 Wind Turbulence Intensity

Wind regime in Narok is mostly turbulent over the entire day. This is because all turbulence intensities recorded were above 0.25 Twidell and Weir [25] as observed in Fig. 5. The figure also suggests that wind is mostly turbulent during the hours when the wind speed is low which is consistent with the results published by Sheng-Lun *et al*. According to their findings, low wind speeds are often associated with high wind turbulence intensity [26]. The high turbulence intensities can be attributed to generally rough ground surface since the area is associated with rugged terrain, vegetation and buildings. The high turbulence intensities might also be attributed to shear-generated turbulence due to drag. The upper layer is dragged by the lower layer at the boundary separating the two layers due to the difference in speed. This causes wind shear which in turn creates wind turbulence. Another reason that might have contributed to generally high turbulence is the fact that most wind speeds at 10 m height lie in the range 0-5 m/s, work reported by Stefan showed that turbulence intensity rapidly changes within this range then stabilizes at wind speed greater than 5 m/s [27]. The same can be seen figure 5. In Figure 5, turbulence intensities tend to be less varying between 0700-1400hrs which are characterized with wind speeds greater than 5 m/s. The same high turbulence intensities are observed in the monthly variation as seen in Fig. 6. From the figure, it can be deduced that worst month of power generation is the month of December since it has the highest turbulent intensity with the low mean wind speed (see Fig. 3). This makes the month of December the best month for annual wind turbine maintenance.

### 3.5 Weibull Parameters

Weibull parameters of every month has been summarized in table 1. Table 2 displays the mean Weibull scale and shape parameters over the entire sampling period. The highest scale parameter was registered in the month of October (5.4 m/s), followed by March and September both at 5 m/s. On the other hand, the least scale parameters occurred in the month of June and December. Therefore, wind speeds distributions in the months with higher scale parameters are more stretched out and right-skewed as compared to the months with less scale parameters. This is because higher scale parameters shift the peak of the distributions to the right while the height reduces due to stretching as illustrated in figure 7 The results indicate that during October, March and September, wind speeds are more varied and cover a wider range. This wider range of wind speeds suggests that there are more occurrences of higher wind speeds compared to other months of the year, resulting in higher average wind speeds. Therefore, the average wind speed values in these months will typically be higher as confirmed in figure 3. On the other hand, the least scale parameters occurred in the months of June and December hence monthly mean wind speeds are least since wind speed range coverage is least during these months.

There is little variation in shape parameters over the months of the year, shape parameter ranges from 1.4 to 1.7 and the standard deviation of the shape parameters is ~0.09 which corresponds to a coefficient of variation of ~0.059. Therefore, there's only ~5.9% variation of the monthly shape parameters from the mean shape parameter. All the shape parameters are lying within the range $1<k<2$. This observation implies that, in all the months, there's high probability of low wind speeds occurring. Any mean wind speed <5.5 m/s is considered low since moderate wind speeds starts from 5.5 m/s. This affirmation is consistent with monthly mean wind speeds seen earlier in figure 3 which showed that there was no single that that hand mean wind speed greater than 5.5 m/s.

### 3.6 Wind Speed Probability and Cumulative Distribution Densities

Fig. 8 displays the comparison between the actual (histogram) and estimated (line curve) wind speed probability distribution densities. The similarity between the predicted wind speeds and actual wind speed based on method of $R^2$ is 0.942. Therefore, Weibull distribution satisfactorily describes the wind probability distribution of Narok. It can be deduced from Fig. 9. that the probability of wind speed not exceeding the cut-in wind speed range (2-3m/s) for most wind turbines is in the range 0.25-0.35. This imply that 65%-75% of the wind speeds blowing over Narok will most likely exceed the cut-in wind speed. Therefore, most wind turbines installed in the area will generate power most of the time.

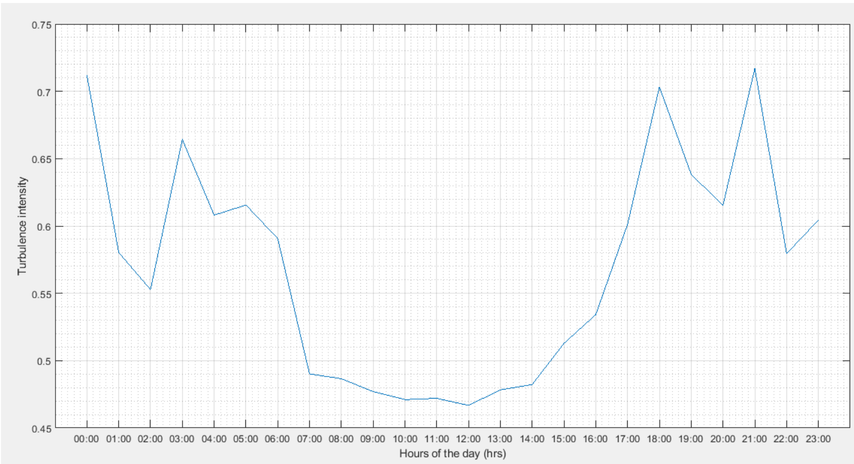


**Fig. 5. Wind turbulence intensity over the hours of the day**

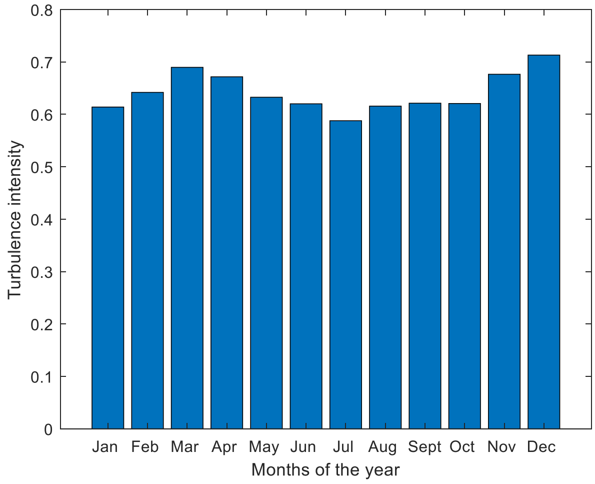


**Fig. 6. Turbulence intensity evolution over the year**

**Table 1. Weibull Parameters c and k over the months of the year**

| Month | c (m/s) | K |
|---|---|---|
| Jan | 4.3 | 1.6 |
| Feb | 4.7 | 1.6 |
| Mar | 5 | 1.4 |
| Apr | 4.8 | 1.4 |
| May | 4.8 | 1.5 |
| Jun | 4.2 | 1.6 |
| Jul | 4.5 | 1.7 |
| Aug | 4.8 | 1.6 |
| Sept | 5 | 1.6 |
| Oct | 5.4 | 1.6 |
| Nov | 4.8 | 1.4 |
| Dec | 4.2 | 1.4 |

**Table 2. Mean scale and scale and shape parameters over the entire sampling period**

| c (m/s) | K |
|---|---|
| 4.7 | 1.5 |

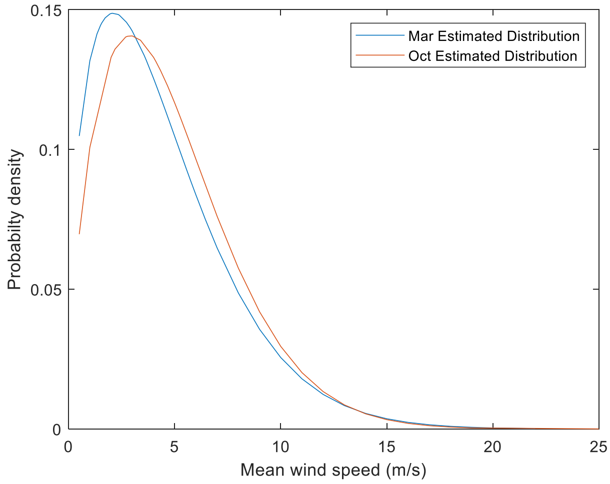


**Fig. 7. Wind speed probability distribution for months of March and October**

### 3.7 Wind Power Density

Mean wind power density (at 10 m height) of each month of the year has been summarized in figure 10. Nearly all the months have wind power density exceeding 100 W/m$^2$ except in the months of January, June and July. Annual mean wind power density at the same height was found to be 126 W/m$^2$. Since the annual wind power density and most of the monthly power densities lie between 100 W/m$^2$ and 160 W/m$^2$, the wind regime in Narok is classified as class 2 at 10 m. The results imply that wind power extraction at 10 m height might be uneconomical especially the utility-scale (wind farms with installed wind turbines exceeding 100 kW) wind farms. However, upon extrapolation, as illustrated in Fig. 11. (mean wind power density extrapolation), the wind power density exceeds 200 W/m$^2$ which is the recommended power density for economical wind power extraction. It can be deduced that economical wind power starts at hub height of about 15 m according to Fig. 10. At this height, the wind power densities exceed the threshold wind power density.

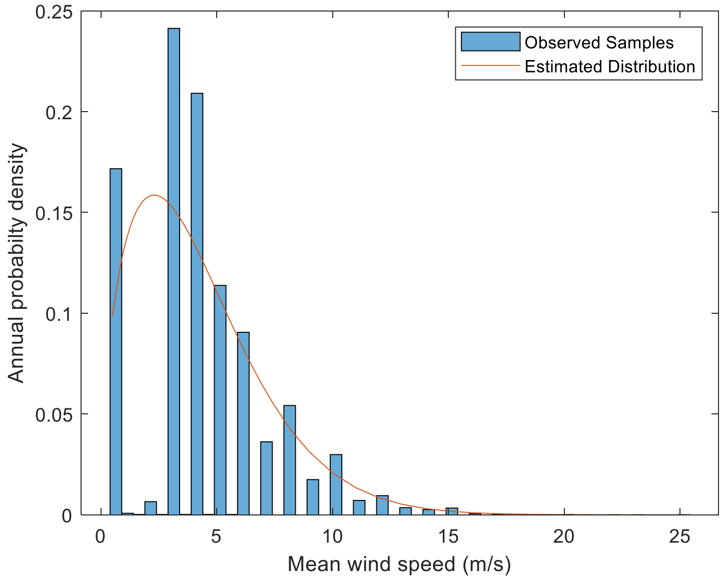


**Fig. 8. Mean wind speed probability distribution**

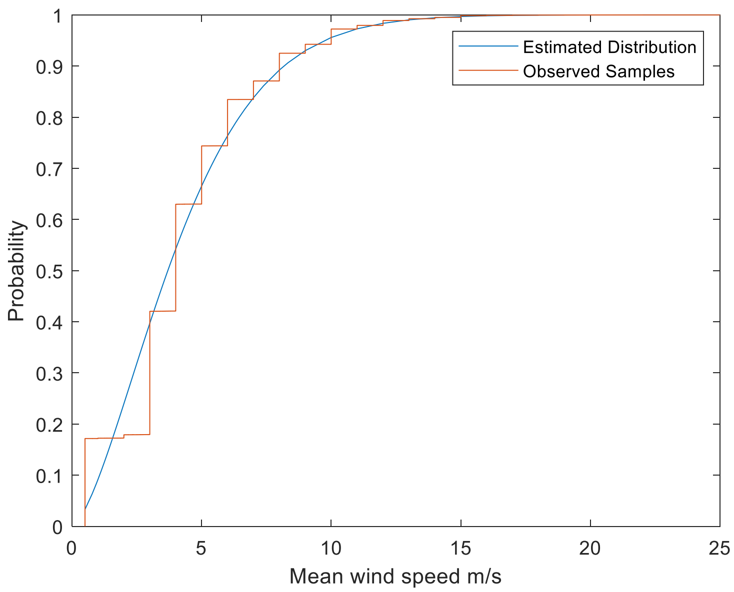


**Fig. 9. Mean wind speed cumulative probability distribution**

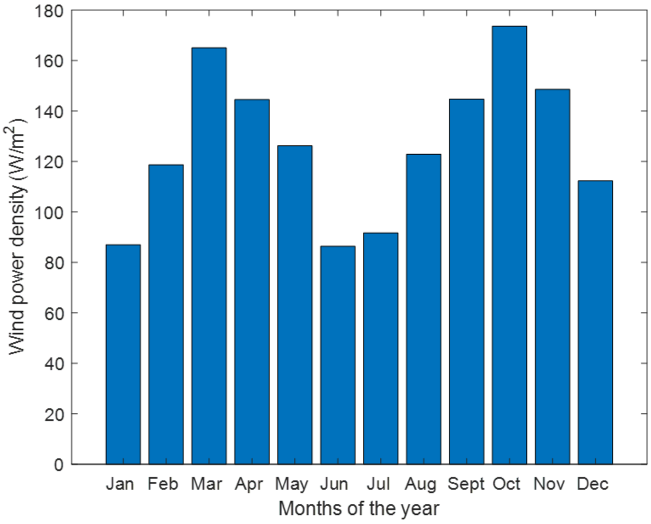


**Fig. 10. Mean wind power density over the months of the year**

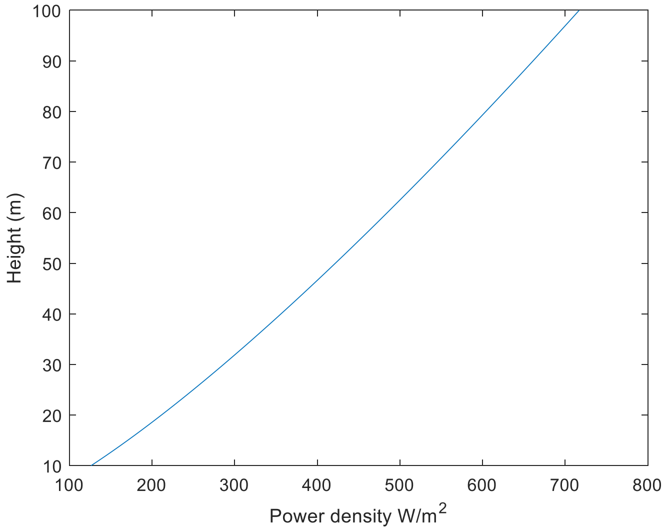


**Fig. 11. Annual wind power density variation with height**

## 4. MAJOR CONTRIBUTIONS OF THE STUDY

The major contributions of the study include;

1. The study has successfully characterized the wind regime in Narok county (specifically Narok weather station and its environs) in terms of predominant wind direction, wind speed (both temporal and spatial wind speed variation), and wind turbulence intensity all of which are vital wind energy and other applications.
2. The study has also demonstrated that Weibull PDF describes wind speed distribution with satisfactory accuracy and therefore can be used to predict wind speeds likely to occur in Narok.
3. Wind power density variation over the months of the year and at various turbine heights has been availed. As a result, it has been shown that wind power extraction in the area is viable based on the findings.

All the above contributions were previously absent in the mainstream literature.

## 5. CONCLUSIONS

Wind regime in Narok is predominantly blowing from the East direction. The directions of the wind regime lie in the upper two quadrants of the Windrose chart bound by East and West directions. The wind is mostly turbulent since all the wind turbulence intensities are greater than 0.25. The annual wind speed of the wind regime occurring in Narok is about 4.3 m/s. The wind regime blowing over Narok at 10 m height can be classified as gentle breeze since most wind speed lie in the range 3.5 m/s to 5 m/s. The wind regime in Narok generally follows Weibull probability distribution. The function describes the wind regime with an average accuracy of 0.94 based of $R^2$ best of fit analysis criteria. The available wind power density at 10 m height was found to be 126 W/$m^2$ which is classified as class II wind power. Narok is a viable region for wind power extraction at 15 m height for both domestic and utility scale wind power installations.

## COMPETING INTERESTS

Authors have declared that no competing interests exist.

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