

Prediction of Wind Potential by Mathematical Methods: Application to the City of Mongo in CHAD

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Abstract

Understanding the wind power potential of a site is essential for designing an optimal wind power conditioning system. The Weibull distribution and wind speed extrapolation methods are powerful mathematical tools for efficiently predicting the frequency distribution of wind speeds at a site. Hourly wind speed and direction data were collected from the National Aeronautics and Space Administration (NASA) website for the period 2013 to 2023. MATLAB software was used to calculate the distribution parameters using the graphical method and to plot the corresponding curves, while WRPLOTView software was used to construct the wind rose. The average wind speed obtained is 3.33 m/s and can reach up to 5.71 m/s at a height of 100 meters. The wind energy is estimated to be 1315.30 kWh/m² at a height of 100 meters. The wind rose indicates the prevailing winds (ranging from 3.60 m/s to 5.70 m/s) in the northeast-east direction.

Keywords

Wind Potential, Weibull Distribution, Extrapolation Method, Power Conditioning

1. Introduction

Mongo is a town in central Chad. The study site is located at 18.82° east longitude and 12.23° north latitude, at an altitude of 495.79 meters above sea level. The site is close to the Aboutelfane mountain range, whose peak reaches an altitude of 1500 meters. The terrain is rugged and dotted with small trees typical of the region. The site experiences a regular wind flow throughout the year. Two seasons

alternate: the dry season from October to May and the rainy season from June to September. The hottest period is between March and May, with temperatures reaching 45 degrees Celsius in April. The coldest period is between November and February, with temperatures dropping as low as 15 degrees Celsius in late January.

Several factors are generally considered when estimating the wind potential of a site, including the topography of the area, variations in meteorological parameters (such as wind speed and direction, temperature and humidity) and surface roughness [1]. Anemometers installed at the site provide long-term records of meteorological parameters, allowing climatic variations to be observed and analyzed over time. Various simulation tools such as Wind Pro and WASP (Wind Atlas Analysis and Application Program) are commonly used to predict wind potential [2].

This study provides a preliminary assessment of the wind potential available at the site. The originality of this work lies in the use of accessible and effective mathematical tools and software for data processing and wind speed prediction. The analysis uses the two-parameter Weibull distribution (c and k) calculated using the graphical method [3]. The calculation of the Weibull distribution parameters and the plotting of the distribution curves are performed using MATLAB software. Hourly wind data are first processed in Microsoft Excel and then classified into wind categories based on their frequency of occurrence using WRPLOTView software to construct a wind rose.

A study of the Sahelian zone of Chad, which includes our site, was carried out using data from the National Meteorological Agency of Chad over a period of 21 years. The Weibull distribution was used to analyze the wind patterns, and the power density method was used to calculate the parameters c and k . The results obtained are similar to those of the present study, with the average wind speed in the Sahelian zone of Chad being approximately 3.25 m/s at 10 meters above ground level [4].

2. Data and Analysis Tools

2.1. Data

The hourly wind speed and direction data used in this study were obtained from satellite records available on the NASA website. These data cover an uninterrupted period of ten years (2013-2023), providing a robust dataset for analysis. This extended observation period allows variations in meteorological parameters to be considered and facilitates projections for long-term wind potential forecasting. The exclusive use of NASA satellite data is justified by the lack of ground-based meteorological data at the exact location of the study. This is the first limitation of this study, as the lack of these ground-based measurements may influence the wind resources.

2.2. Data Processing and Analysis Tools

The data processing and analysis tools used in this study are both accessible and

highly effective for handling meteorological data:

- Microsoft Excel: Used for data pre-processing and formatting files into formats compatible with MATLAB and WRPLOT View software for further analysis.
- MATLAB: Used to simulate the Weibull distribution and determine its parameters (scale parameter c and shape parameter k) using a custom-written script.
- WRPLOTView: An open-source software program used to create wind rose visualization, frequency analysis and graphs using various weather data formats. In this study it was used to generate wind rose plots from data processed in Microsoft Excel.

3. Mathematical Modeling of Wind Frequency Distribution

The wind potential of a given site is typically estimated from the distribution of mean wind speeds. If wind measurement data are available, they can be visualized as a histogram showing the variation in the relative frequency of wind speeds.

The Weibull distribution is the most widely used method for predicting wind potential. It is defined by two parameters: the scale parameter c and the shape parameter k . This distribution is a probability density function expressed as follows [5]:

$$f(v) = \left(\frac{k}{C}\right) \left(\frac{v}{C}\right)^{k-1} e^{-\left(\frac{v}{C}\right)^k} \quad (1)$$

where v is the wind speed, $f(v)$ is the probability of v occurring, k is the shape parameter and c is the scale parameter.

The mean wind speed can be determined by integrating the probability density function of the Weibull distribution. It is calculated as:

$$v_{\text{moy}} = \int v f(v) dv \quad (2)$$

The Weibull distribution can facilitate many calculations required to analyze wind data.

Other methods can also be used to estimate the average wind speed represented by a scalar function that varies with time [6]. One such approach is to use a Fourier series representation to model the wind. In this case, the wind speed is expressed as a signal consisting of the superposition of several harmonic components. The Fourier series representation is given by [7]:

$$v_v = A + \sum_{n=1}^i [a_n \sin(b_n \omega_v t)] \quad (3)$$

where A is the mean wind speed, a_n is the amplitude of the n th order harmonic, $b_n \omega_v$ is the pulsation of the n th order harmonic and i , is the rank of the last harmonic retained in the wind profile calculation.

3.1. Determination of Weibull Parameters

There are several methods for determining the scale (c) and shape (k) parameters from a given wind distribution [3]:

$$c = \frac{1.125V_{moy}}{(1-B)} \quad (4)$$

$$k = 1 + 0,483(v_{moy} - 2)^{0,51} \quad (5)$$

$$B = 1 - 0.81(v_{moy} - 1)^{0.089} \quad (6)$$

The graphical method used in this article involves the linearization of cumulative distributions. This is done by applying a logarithmic transformation to the distribution function $F(v)$:

$$\ln[-\ln(1-F(v))] = k \ln v - k \ln c \quad (7)$$

And by posing:

$$Y = \ln[-\ln(1-F(v))] \text{ et } X = \ln v \quad (8)$$

We obtain a linear function of X :

$$Y = aX + b, k = a \text{ et } b = -k \ln c \quad (9)$$

The scale parameter c is worth:

$$c = e^{\frac{b}{a}} \quad (10)$$

If the mean velocity and variance of a site are known (otherwise they can be determined from the statistical distribution), the shape parameter k is determined using the following approximation [4]:

$$k = \left(\frac{\sigma}{v}\right)^{-1.086} \quad (11)$$

We can deduce the scale parameter:

$$c = \frac{v}{\Gamma\left(1 + \frac{1}{k}\right)} \quad (12)$$

3.2. Extrapolation of Weibull Parameters

Estimating the wind potential at the height of the wind turbine tower, which is considered meters above the ground, requires the transformation of the Weibull parameters. The following equation is used to estimate the coefficient at a different height:

$$\frac{C_2}{C_1} = \left(\frac{z_2}{z_1}\right)^{m''} \quad (13)$$

For any heights, Mikhail gave the expression for the exponent m'' considering the roughness of the site as follows [8]:

$$m'' = \frac{1}{\ln\left(\frac{z_g}{z_0}\right)} + \frac{0.0881(1 - \ln C_1)}{1 - 0.0881 \ln\left(\frac{z_1}{10}\right)} \quad (14)$$

With z_0 , the roughness, defined as the height from which the friction speed

slows down the wind speed.

The geometric mean of z_0 is z_g and determined by the following relation:

$$z_g = \sqrt{z_1 z_2} \quad (15)$$

Thus, the expression for the exponent m'' becomes:

$$m'' = \frac{1}{\ln\left(\frac{\sqrt{z_1 z_2}}{z_0}\right)} + \frac{0.0881(1 - \ln C_1)}{1 - 0.0881 \ln\left(\frac{z_1}{10}\right)} \quad (16)$$

3.3. Vertical Extrapolation of Wind Speed

Wind speed varies with height above the ground. This phenomenon is called vertical wind shear. Over flat terrain and with neutral atmospheric stratification, the logarithmic wind profile provides a good approximation of the vertical shear. The logarithmic profile is derived from the ratio of the vertical wind profile and is given by the following expression:

$$v_2 = v_1 \frac{\ln \frac{h_2}{z_0}}{\ln \frac{h_1}{z_0}} \quad (17)$$

where h_1 is the height of the mast, v_1 is the speed measured at the level of the mast and v_2 is the speed we want to determine.

The roughness length z_0 is defined relative to the type of terrain. For the present work, we considered a very uneven terrain whose roughness length z_0 is theoretically defined to be equal to 0.4 m [8].

The power law of Justus and Mikhail gives a good extrapolation for higher altitudes, the wind speed $v(z_2)$ at the desired altitude z_2 is expressed as follows [9]:

$$v(z_2) = v(z_1) \times \left(\frac{z_2}{z_1}\right)^\alpha \quad (18)$$

The formula for estimating the coefficient of friction α to plot the vertical profile and thus allow instantaneous extrapolation of wind speeds is written in the following form:

$$\alpha = a + b \times \ln(v_1) \quad (19)$$

where a and b are constants whose values depend on the height of the anemometer, given by:

$$a = \frac{0.37}{1 - 0.088 \times \ln \frac{z_1}{10}} \quad (20)$$

$$b = \frac{-0.008}{1 - 0.088 \times \ln \frac{z_1}{10}} \quad (21)$$

$$\alpha = \frac{0.37 - 0.088 \times \ln v_1}{1 - 0.088 \times \ln \frac{z_1}{10}} \quad (22)$$

Both profiles are commonly used to represent the vertical distribution of wind speed: the logarithmic law applied in this work gives a good extrapolation of wind speed for altitudes less than or equal to 100 meters. The power law is adapted to higher altitudes (≥ 200 m).

3.4. Wind Energy Estimation

Wind measurements can be used to calculate the wind energy available at a given site. In practice, the annual wind energy, expressed in kWh/m², is calculated using the BETZ limit, written as [3]:

$$E_B = 3.56 \sum f_i v_i^3 \quad (23)$$

where f_i is the frequency corresponding to the speed v of the wind of class i .

This calculation can be done using the Weibull distribution, we obtain the following expression:

$$E_B = 3.56 C^3 \Gamma \left(1 + \frac{3}{k} \right) \quad (24)$$

3.5. Wind Rose

It provides information on the prevailing wind directions. The wind frequencies are distributed over 360°, divided into 12 sectors of 30°. A frequent but very weak wind will have a small share of the energy of the wind rose. This rose therefore makes it possible to identify the directions that contain the most energy, *i.e.* strong and frequent winds. The frequency distribution of wind speeds according to their direction is summarized in **Table 1**.

Table 1. Frequency distribution.

Wind Classes (m/s)	0.50 - 2.10	2.10 - 3.60	3.60 - 5.70	5.70 - 8.80	8.80 - 11.10	≥ 11.10	Total
Sub-Total	24%	39%	29%	7%	0%	0%	99%
Calms						0.00796	0.00796
Missing/ incomplete						0.00001	0.00001
Total						1	100%

4. Results and Discussions

4.1. Wind Potential of the Site at the Collection Height

The series of hourly wind speed measurements over ten years show that winds with speeds of approximately ± 3 m/s are dominant and consistent throughout all years of measurement. **Figure 1** shows the variations in the time series of wind speeds at the site. The data from the hourly wind speed measurements are grouped by wind class together with their frequency of occurrence. **Table 1** summarizes this information and shows the percentage of time the wind is blowing within each speed interval.

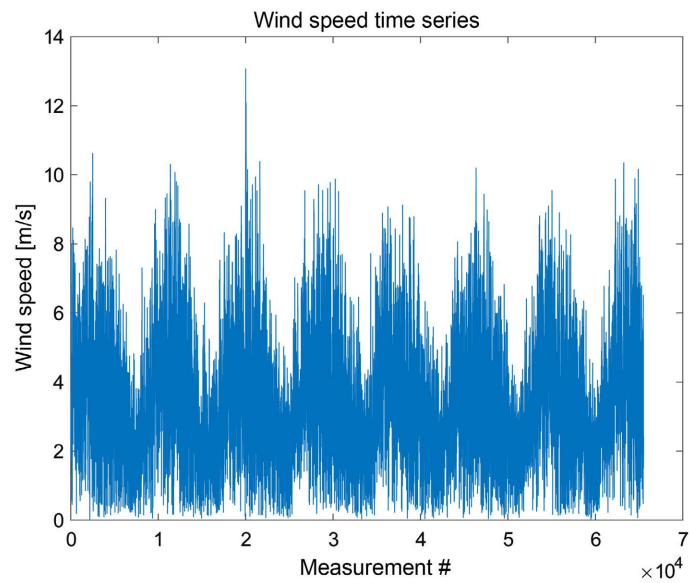


Figure 1. Wind speed time series.

The Weibull parameters of the frequency distribution are a shape factor $k = 2.2$ and a scale factor $c = 3.76$ m/s. These values of k and c were obtained by logarithmic transformation of the distribution function, as shown in **Figure 2**. The relatively high value of the Weibull shape parameter k indicates that the distribution is tightly centred around the mean, suggesting that the prevailing winds are relatively constant with minimal variability. The probability density and cumulative probability density of the distribution are plotted for the obtained values of c and k . In **Figure 3**, the frequency distribution derived from the time series measurement data is shown in red, while the Weibull distribution is plotted in blue. The mean wind speed calculated from the Weibull distribution is 3.33 m/s.

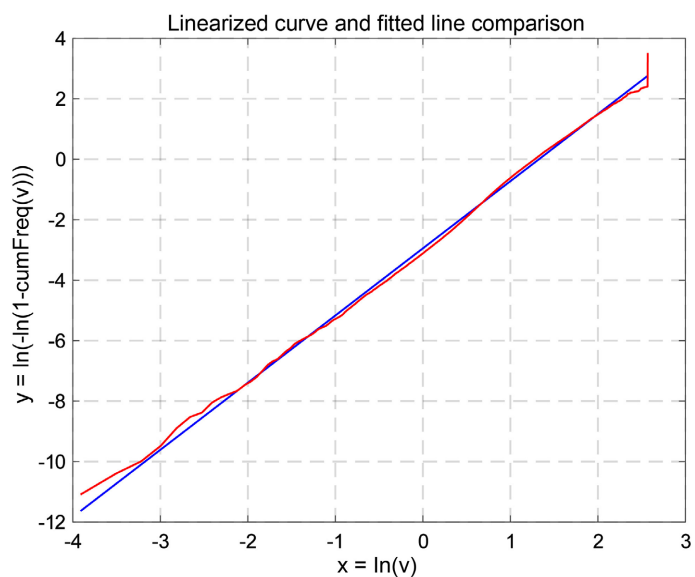


Figure 2. Linearized curve and fitted line comparison.

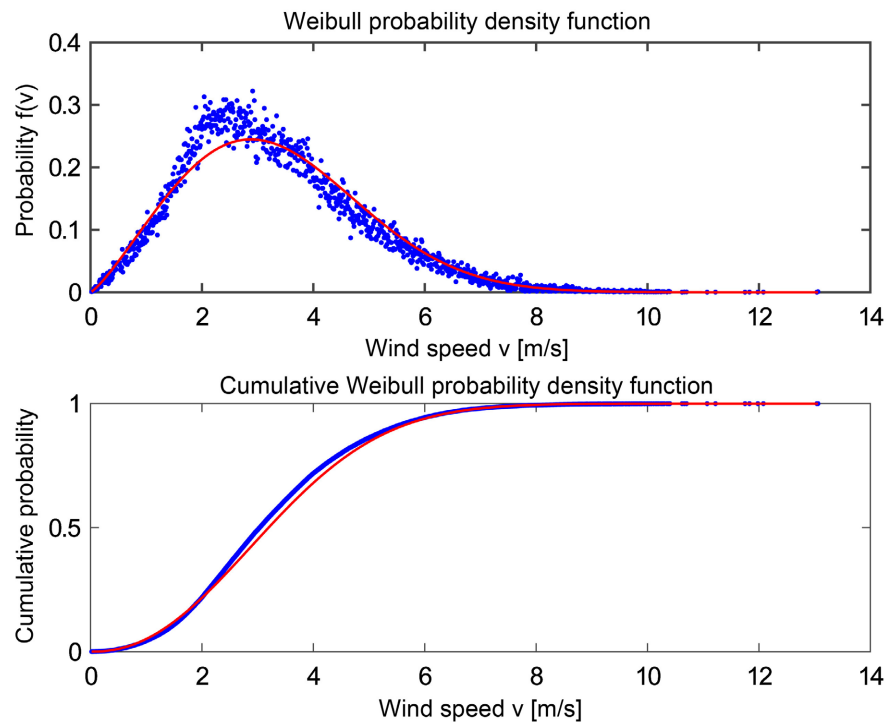


Figure 3. Weibull probability function.

4.2. Wind Speed Extrapolation

Wind resources are generally exploited at heights above 10 meters, which is the height of the measurement mast. Wind turbines are generally installed at a height of around 100 meters to maximize the kinetic energy of the wind. It is therefore essential to extrapolate wind speeds vertically. **Table 2** shows a significant increase in the amount of energy produced as a function of height z (m). At a height of 100 meters, the average wind speed is 5.71 m/s, which corresponds to a generated energy of 1315.30 kWh/m². This represents a 59% increase in the energy produced at a height of 10 meters.

Table 2. Extrapolation of mean wind speed (v) and scale parameter (c).

Altitude (m)	Wind speed (m/s)	Shape scale (m/s)	Energy (kWh/m ²)
10.00	3.33	3.73	222.70
20.00	4.05	4.67	436.87
30.00	4.47	5.21	606.70
40.00	4.76	5.59	748.11
50.00	5.00	5.88	869.89
60.00	5.18	6.11	977.25
70.00	5.34	6.30	1073.51
80.00	5.48	6.47	1160.93
90.00	5.60	6.62	1241.13
100.00	5.71	6.74	1315.30

These results, obtained using the logarithmic method, are valid for altitudes below 100 meters and can be a prerequisite for more detailed studies of the wind potential of the site.

Analysis of the wind statistics shows that the predominant winds come from the north-north-east, east-north-east and south-west directions, represented by sectors 1, 2, 3 and 8 of the wind rose in **Figure 4**. The other sectors correspond to areas with lower average wind speeds. A wind sensor should be oriented towards the direction of the most dominant winds, with a preference for sector 2, *i.e.* the north-north-east direction, as indicated in **Table 3**.

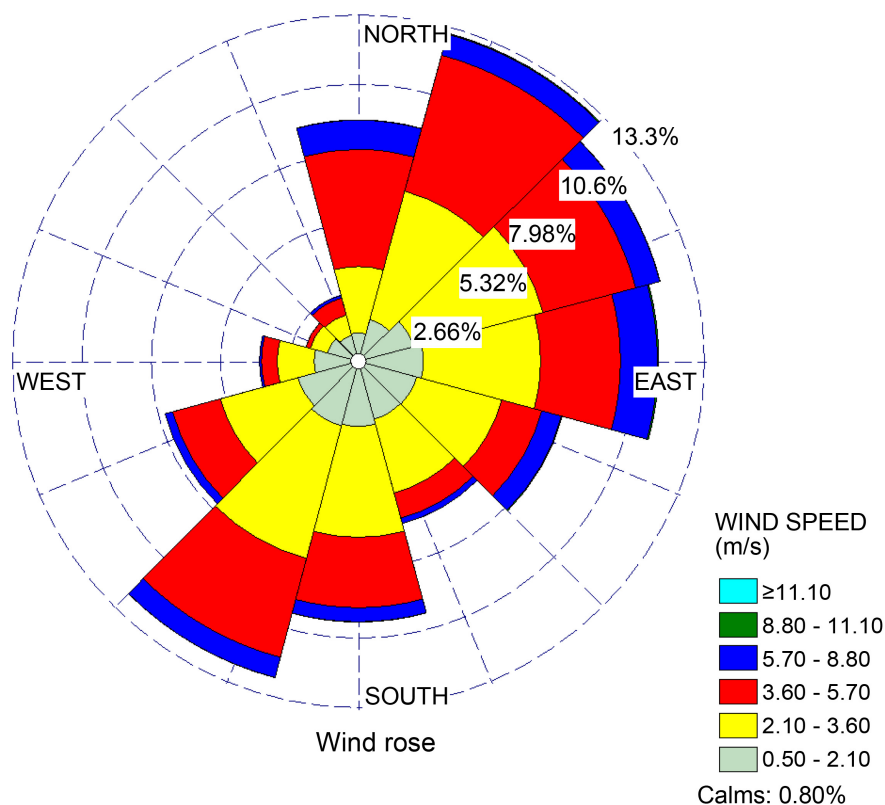


Figure 4. Wind rose at the Mongo site.

Table 3. Frequency account.

Secteur	Directions/ Wind Classes (m/s)	0.50 - 2.10	2.10 - 3.60	3.60 - 5.70	5.70 - 8.80	8.80 - 11.10	≥11.10	Total
1	345 - 15	984	2219	3926	973	11	0	8113
2	15 - 45	1480	4457	4719	729	31	8	11,424
3	45 - 75	1938	4497	3218	835	12	0	10,500
4	75 - 105	2213	3931	2670	1240	49	0	10,103
5	105 - 135	2056	2952	1394	678	30	0	7110
6	135 - 165	2039	2569	869	189	3	0	5669

Continued

7	165 - 195	2209	3721	2356	474	7	0	8767
8	195 - 225	2270	4588	3428	702	6	0	10,994
9	225 - 255	2137	2697	1658	263	3	0	6758
10	255 - 285	1526	1233	524	72	0	0	3355
11	285 - 315	1106	599	155	5	0	0	1865
12	315 - 345	930	709	580	96	0	0	2315
	Sub-Total	20,888	34,172	25,497	6256	152	8	86,973
	Calms							698
	Missing/ Incomplete							1
	Total							87,672

5. Conclusions

The method used is the two-parameter Weibull distribution of wind speed. This mathematical tool, widely used in the field of wind energy, allowed us to calculate the average wind speed, predict wind behavior and provide the frequency distribution of wind speeds at the site. The speeds were then extrapolated to different heights using the logarithmic method. At a height of 100 meters, the average wind speed is 5.71 m/s and the energy is estimated to be 1315.30 kWh/m².

The wind rose of the site shows the prevailing wind directions, with winds of 3.60 m/s to 5.70 m/s from the north-north-east being the most dominant. A wind turbine oriented in this direction would maximize the energy captured by the blades and optimize energy production. The validation of the prediction method is supported by the relatively close values between the measured data and the statistically calculated results using the Weibull approximation. **Figure 1** and **Figure 2** show the shapes of the curves from the measurements (in blue) and those from the calculations (in red), which are closely aligned.

The results obtained in this work provide an overview of the wind potential of the Mongo site, but a more detailed study is required for a wind project. The topography of the site, measurement of surface roughness, identification and measurement of obstructions will need to be considered in order to select the most appropriate wind speed extrapolation method. The collection of meteorological data using anemometers installed at the exact location of the site will allow the observed differences to be considered when assessing the wind potential. An environmental impact study is required for a viable wind project.

Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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