

CHARACTERISATION AND ESTIMATION OF THE WIND ENERGY POTENTIAL OF THE TOWN OF MELFI IN CHAD

Abstract: -

This study characterised and estimated the wind energy potential of the town of Melfi in the Guera province of central Chad, situated at 11.06° north latitude and 17.93° east longitude at an altitude of 416 m. The data consisted of an hourly time series of wind speed and direction observed at 10 m above ground level over six years, from August 2020 to August 2026, comprising 52,536 valid data points. Monthly wind roses were produced to characterise the distribution of wind directions and intensities throughout the year. The quadratic mean method was chosen to calculate the average wind speed at the site, as it is more representative of the energy content of the wind than the simple arithmetic mean. Three independent methods were compared to extrapolate wind speed to heights of 50, 100 and 150 m: the variable-exponent power law of Justus and Mikhail, the logarithmic roughness law and the fixed-exponent power law of Hellmann. The annual wind speed was 3.50 m/s at 10 m above ground level and ranged from 4.9 to 7.1 m/s at heights of 100 to 150 m, depending on the method used. Of the three methods, that of Justus and Mikhail overestimated wind speed the most. The wind power density, calculated at 10, 50, 100 and 150 m, placed the site in Class 1 (low) at 10 and 50 m and in Class 2 at 100 and 150 m on an annual basis, with more favourable potential during the dry season.

Key words: -Wind energy, Vertical extrapolation, Justus method, Logarithmic law, Power density, Root mean square.

1. Introduction: -

Estimating wind resource potential is crucial for the implementation of a wind energy project. To this end, two complementary steps are essential: the statistical characterisation of wind speed at the available measurement height (10 m), and the extrapolation of this speed to the hub height of the wind turbines (generally between 80 and 160 m for modern turbines).

This paper has several objectives:

- To produce monthly wind rose diagrams to determine the prevailing wind directions and their seasonal variation at the site;
- To calculate the average wind speed using the root-mean-square method, which is more suitable than the arithmetic mean due to the non-linear nature of wind kinetic energy;
- To extrapolate this speed to heights of 50, 100 and 150 m using three methods recognised in the wind energy literature, and to compare the results obtained.

2. Materials and Methods: -

2.1 Data source and processing

The data used were obtained from the NASA website (Prediction of Worldwide Energy Resources), derived from the MERRA-2 atmospheric analysis (NASA Langley Research Center, 2026). This is a time series of hourly wind speed and direction data at 10 m above ground level, covering the period from August 2020 to August 2026, comprising 52,608 data points. Missing values, which occurred in 72 instances (0.14 per cent of the time series), were excluded, resulting in a total of 52,536 valid data points.

Python software was used to generate the wind rose, as well as to carry out all the statistical analyses for this study (RMS mean, vertical extrapolation, power density), using the following libraries:

- Pandas: filtering out missing values, grouping by month and performing statistical calculations by group;
- Numpy: numerical calculations of the root mean square, the cubic mean (power density), and logarithmic and power distributions (Justus, logarithmic, Hellmann);
- Matplotlib: plotting graphs (extrapolation, power density);
- Winrose for generating wind roses.

2.2 Wind rose

Wind directions were subdivided into 16 sectors of 22.5°; the monthly averages of wind speeds were categorised into six classes, as shown in Table 1; and the frequency of wind occurrences by class and by sector was calculated as a percentage of the number of valid data points for the month.

Table 1. Wind classes.

Class	1	2	3	4	5	6
Speed (m/s)	0–2	2–4	4–6	6–8	8–10	>10

2.3 Average speed using the root mean square method

The root mean square (RMS) (Justus et al., 1978) is defined by Equation 1:

$$V_{RMS} = \sqrt{\left[\left(\frac{1}{n}\right) \times \sum V_i^2\right]} \quad (1)$$

Where V_i is the instantaneous velocity and n is the number of observations.

The root-mean-square value is a relevant indicator in wind engineering; it provides a better approximation of the available power density (proportional to the cube of the velocity, V^3) than the simple arithmetic mean, which is often less than or equal to it (Justus et al., 1978; Akdağ and Dinler, 2009; Jamil et al., 1995; Sarkar et al., 1984; Takle and Brown, 1978; Akdağ and Güler, 2015; Emeksiz, 2022; Rehman et al., 2022; Abbas et al., 2025).

2.4 Vertical extrapolation

The monthly (RMS) and annual average wind speeds at 10 m were extrapolated to heights of 50 m, 100 m and 150 m using three methods:

a) The Justus and Mikhail method (Justus and Mikhail, 1976): this is a power law with a variable exponent α , where the exponent is re-estimated from the reference wind speed and calculated using the following formula (Doran and Verholek, 1978; Peterson and Hennessey, 1978; Gualtieri and Secci, 2012; Gualtieri, 2016):

$$\alpha = 0.37 - 0.088 \times \ln V_{ref} ; V(h) = V_{ref} \times \left(\frac{h}{h_{ref}} \right)^\alpha \quad (2)$$

(b) Logarithmic law (Businger et al., 1971; Emeis and Türk, 2005): this law is based on the roughness length z_0 of the terrain at the site; the formula in Equation 3 allows the wind speed to be extrapolated:

$$V(h) = V_{ref} \times \frac{\ln\left(\frac{h}{z_0}\right)}{\ln\left(\frac{h_{ref}}{z_0}\right)} \quad (3)$$

The roughness length for agricultural land or savannah with little topographical variation is $z_0 = 0.05$ m; this value is used in the absence of on-site roughness measurement data (Troen and Petersen, 1989).

c) Hellmann's power law (Hellmann, 1916; Counihan, 1975; Touma, 1977): this is a power law with a fixed exponent, which does not depend on local conditions:

$$V(h) = V_{ref} \times \left(\frac{h}{h_{ref}} \right)^{1/7} \quad (4)$$

In all three cases, $h_{ref} = 10$ m and V_{ref} is the average speed calculated using equation (1).

3. Results: -

3.1 Monthly wind rose diagrams

Figure 1 shows the wind rose diagrams for the site for each month of the year. The site experiences consistent and strong wind activity, depending on the direction from which the wind blows: the strongest winds, with average speeds of between 5 m/s and 10 m/s, are observed from December to March – a period corresponding to the dry season and the Harmattan – whilst the weakest winds, with average speeds of less than 2 m/s, are observed during the rainy season in September.



Fig. 1. Monthly wind rose diagrams (2020–2026), 16 directional sectors, 6 wind speed classes, at 10 m.

3.2 Average wind speed at 10 m above ground level

Table 2 compares, for each month, the arithmetic mean and the root mean square (RMS) of wind speed at 10 m. The difference between the two means ranges from 0.16 m/s (November) to 0.41 m/s (March), with the difference being greater where the variability in wind speed for the month in question is higher.

Table 2. Monthly average wind speed at 10 m: comparison of the arithmetic mean and the root mean square (RMS).

Month	No. of obs.	Arithmetic mean (m/s)	RMS mean (m/s)	Difference (m/s)
January	4464	4.390	4.631	0.241
February	4056	4.656	4.976	0.320
March	4464	4.192	4.598	0.406
April	4320	3.336	3.698	0.362
May	4464	3.162	3.469	0.307
June	4320	2.959	3.224	0.265
July	4464	2.421	2.653	0.232
August	4416	2.193	2.436	0.243
September	4320	1.750	1.917	0.167
October	4464	1.973	2.127	0.155
November	4320	2.850	3.009	0.160
December	4464	3.565	3.768	0.203
Annual	52536	3.114	3.502	0.389

3.3 Extrapolation to 50, 100 and 150 m

Table 3 and Figure 2 compare the average speeds extrapolated to 50 m, 100 m and 150 m using the three methods. The Justus method yields 5.4 m/s at 50 m, 6.37 m/s at 100 m and 7.08 m/s at 150 m, compared with 4.5 m/s, 5.02 m/s and 5.29 m/s for the logarithmic law, and 4.4 m/s, 4.87 and 5.16 m/s for Hellmann's law; the discrepancy is significant compared with an extrapolation from 50 m, as the height ratio (and therefore the effect of shear) is much greater here ($10 \rightarrow 100/150$ m versus $50 \rightarrow 100/150$ m).

Table 3. RMS velocities extrapolated to 50 m, 100 m and 150 m (m/s) according to the three methods (reference point 10 m above ground level).

Month	V10 RMS (m/s)	α Justus	V50 Justus	V50 Log	V50 Hellmann	V100 Justus	V100 Log	V100 Hellmann	V150 Justus	V150 Log	V150 Hellmann
January	4.631	0.235	6.761	6.038	5.828	7.958	6.644	6.435	8.754	6.998	6.818
February	4.976	0.229	7.191	6.487	6.262	8.426	7.138	6.914	9.246	7.519	7.326
March	4.598	0.236	6.720	5.995	5.787	7.912	6.596	6.389	8.706	6.948	6.770
April	3.698	0.255	5.574	4.822	4.654	6.651	5.306	5.139	7.376	5.589	5.445
May	3.469	0.261	5.276	4.523	4.366	6.320	4.977	4.820	7.025	5.242	5.108
June	3.224	0.267	4.955	4.203	4.057	5.962	4.625	4.480	6.643	4.872	4.747
July	2.653	0.284	4.191	3.459	3.339	5.104	3.806	3.686	5.727	4.009	3.906
August	2.436	0.292	3.895	3.176	3.066	4.768	3.495	3.385	5.366	3.681	3.587
September	1.917	0.313	3.171	2.499	2.412	3.938	2.750	2.663	4.471	2.896	2.822
October	2.127	0.304	3.468	2.774	2.677	4.280	3.052	2.956	4.840	3.215	3.132
November	3.009	0.273	4.670	3.924	3.787	5.643	4.317	4.182	6.304	4.548	4.431
December	3.768	0.253	5.664	4.913	4.742	6.751	5.406	5.236	7.481	5.694	5.548
ANNUAL	3.502	0.260	5.320	4.566	4.408	6.369	5.024	4.867	7.076	5.293	5.157

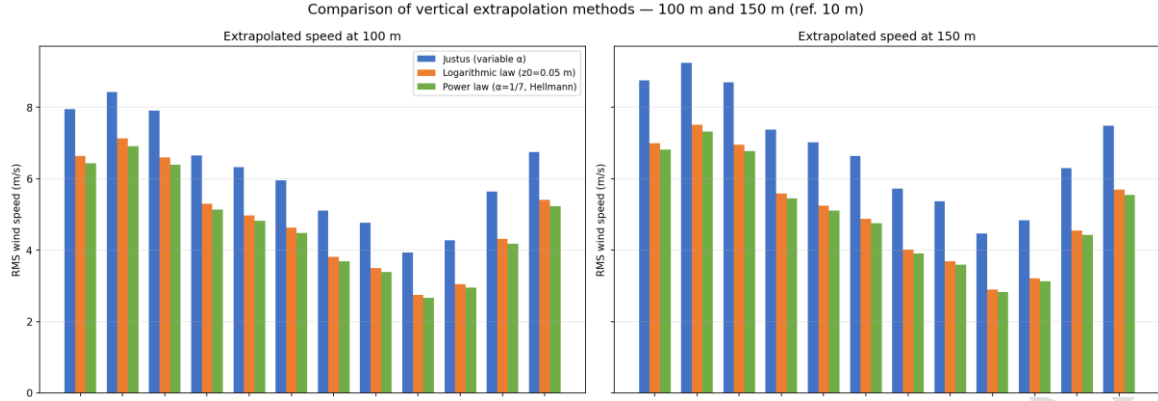


Fig. 2. Monthly comparison of the three extrapolation methods at 100 m and 150 m (10 m reference).

3.4 Wind power density

Wind power density (in W/m²) is used to determine the energy available per unit area swept by the rotor. It is calculated using the following formula:

$$E_c = \frac{1}{2} \times \rho \times V^3 \quad (5)$$

Where ρ is the density of air and V^3 is the cubic mean of the wind speed, calculated directly from the hourly data at 10 m and then extrapolated to different heights using the following equation:

$$V^3(h) = V^3(h_{ref}) \times \left(\frac{h}{h_{ref}} \right)^{3\alpha} \quad (6)$$

Where α is Justus's exponent.

The density has been corrected for the site's altitude (416 m) using the standard barometric formula, giving a density of $\rho = 1.177 \text{ kg/m}^3$.

Table 4 summarises the power densities at heights of 10 m, 50 m, 100 m and 150 m. The annual density ranges from 34 W/m² at 10 m, 120 W/m² at 50 m, 204 W/m² at 100 m and 280 W/m² at 150 m, which places the site in class 1 (<200 W/m²) at 10 and 50 m, but in class 2 (200–300 W/m²) at 100 and 150 m on an annual basis; wind potential is significantly greater at higher altitudes. At 100 m, a comparison of the three methods yields 204 W/m² (Justus), 100 W/m² (logarithmic law) and 91 W/m² (Hellmann) on an annual basis: the discrepancy

between the different methods, which is very significant at higher wind speeds, is greatly amplified by cubing.

Table 4. Monthly wind power density (W/m^2) at 10, 50, 100 and 150 m (Justus method, reference height 10 m).

Month	α Justus	PD 10 m (W/m^2)	PD 50 m (W/m^2)	PD 100 m (W/m^2)	PD 150 m (W/m^2)
January	0.235	67.2	209.0	340.8	453.7
February	0.229	85.4	257.9	415.0	548.2
March	0.236	71.5	223.1	364.2	485.2
April	0.255	38.6	132.0	224.2	305.7
May	0.261	31.0	109.0	187.3	257.2
June	0.267	24.5	88.9	154.9	214.4
July	0.284	13.9	54.8	99.0	139.9
August	0.292	11.4	46.6	85.5	121.9
September	0.313	5.3	24.2	46.3	67.7
October	0.304	6.9	29.9	56.1	81.2
November	0.273	18.6	69.3	122.3	170.5
December	0.253	36.6	124.3	210.4	286.3
Annual	0.260	34.0	119.1	204.4	280.3

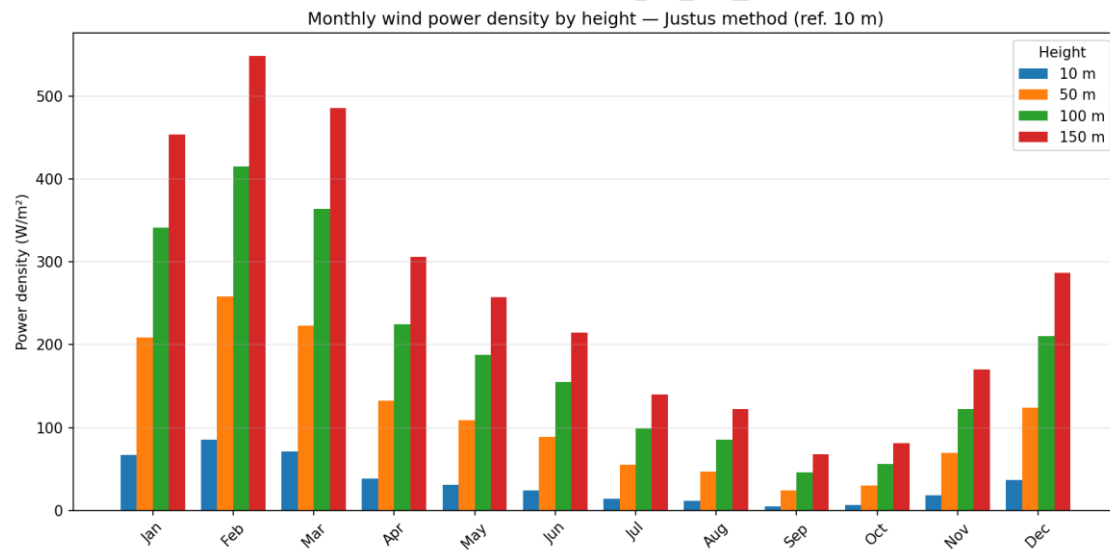


Fig. 3. Monthly wind power density by height (Justus method).

4. Discussion:-

The three methods agree on seasonal variations (strong winds in the dry season, light winds in the rainy season) but differ markedly in the extent of the extrapolation. This is due to the considerable difference between the standard measurement height (10 m) and the target heights (50, 100 and 150 m). Justus's method, in which the exponent α decreases as the reference wind speed increases, explains a lower vertical shear in strong winds. Nevertheless,

it yields a generally higher exponent (annual $\alpha \approx 0.26$) than that assigned to roughness in the logarithmic law and Hellmann's fixed exponent ($1/7 \approx 0.143$), which explains its significant and systematic upward bias (Justus approximately 27 per cent above the logarithmic law and 31 per cent above Hellmann's method, at both 100 m and 150 m) (Justus and Mikhail, 1976; Gualtieri and Secci, 2012; Gualtieri, 2016).

The roughness value adopted for the logarithmic law corresponding to the semi-arid savannah terrain type is close to Hellmann's law (less than 4 per cent deviation); this is consistent with the assumed roughness value. The significant discrepancy with Justus when extrapolation is based on a standard measurement height (10 m) highlights the known limitation of this method: as it is suited to moderate differences in height, it tends to overestimate the resource when extrapolated over a large height ratio, and this must be taken into account for any feasibility study based on data measured at 10 m (Emeis and Türk, 2005; Gualtieri, 2019).

Calculating power density considerably increases the discrepancies between the various extrapolation methods, due to the fact that speed is raised to the power of three (the Justus/Hellmann discrepancy increases from ~31 per cent for speed to more than double that for power density at 100 m); the objective is an energy estimate rather than an average speed, hence the crucial importance of the methodological choice.

Two main limitations emerge from this study. The data source is an atmospheric reanalysis (MERRA-2) rather than in situ measurements; a local measurement campaign (using a mast), ideally at several heights, would enable these results to be verified and calibrated, in particular the roughness length used in the logarithmic law and the validity of Justus's method over such a range of heights. Furthermore, the velocity extrapolation was applied to the monthly mean velocity rather than to each hourly time step (except for the production estimate, which was processed on an hourly basis); a generalised hourly application would capture the intra-monthly variability of vertical wind shear in greater detail.

5. Conclusion:-

The site under study exhibits wind conditions that vary significantly between seasons, with RMS wind speeds at 10 m ranging from 1.9 m/s (September) to 5.0 m/s (February). Extrapolation to modern hub heights (100–150 m) confirms this seasonality and shows an annual RMS potential of between 4.9 and 7.1 m/s depending on the extrapolation method used — a significant difference which highlights the sensitivity of the estimates to the choice of methodology when the reference measurement height is low (10 m). The annual power density at 100 m (204 W/m² using the Justus method) places the site in class 2. Validation through local measurements, particularly at intermediate heights, is recommended before any investment decision is taken, in order to ensure the suitability of the extrapolation method and the roughness assumptions used for the design of a wind farm at this site.

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