

Assessment and Analysis of the Technical and Economic Feasibility of Wind Energy Potential in Chad: A Case of the Guéra Region

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Abstract

Located between 10° and 13° North latitude, the Guéra region lies in central Chad; it covers an area of 61,279 km² and has Mongo as its administrative capital. Its terrain is predominantly rugged and mountainous, dominated by the Guéra Massif, which reaches an elevation of 1800 meters and is geologically characterized by granites and dolerite dykes. Administratively, the region is divided into four departments: Mongo, Barh Signaka, Bitkine, and Mangalmé. Actual data for the study area, covering a 15-year period (January 1, 2010, to December 31, 2025), were obtained from Chad's National Meteorological Agency (ANAM) and processed using the Python programming language. The proposed methodology relies on using Weibull distribution parameters and directional wind speed analysis (fitting speed data to this distribution to model probability), analyzing wind roses to identify dominant directions and flow variability, estimating the capacity factor to select a suitable turbine, and conducting a more in-depth techno-economic analysis. The results demonstrate the feasibility of this assessment based on actual ANAM data. They highlight a promising resource characterized by low wind speeds but excellent consistency, an ideal profile for water pumping or hybrid solar-wind systems, although this rules out large-scale industrial wind power. Application of the wind shear model shows that raising masts from 10 to 18 meters increases average wind speeds by 15.8%, thereby generating a massive 56% gain in gross energy output across the entire area. From an economic standpoint, a clear difference distinguishes the sites studied: Mangalmé, Bitkine, and Mongo prove to be highly profitable, thanks to an annual output of 12.5 GWh, low energy costs (€0.06 per kWh), and a rapid payback period of six years. Conversely, Barh Signaka proves less advantageous due to more intermittent op-

eration and low output (4.1 GWh/year); this drives the cost of electricity up to €0.14 per kWh and extends the payback period to 14 years. Furthermore, this work serves as a valuable decision-support tool for experts and researchers in the wind energy sector. Finally, this research paves the way for future studies, particularly a techno-economic analysis of hybrid systems designed for areas with low wind potential.

Keywords

Wind Resource, Wind Roses, Weibull Distribution, Wind Speed, Guéra Region, Techno-Economic

1. Introduction

1.1. Context and Justification of the Study

The transition to renewable energy has become a global priority due to climate imperatives and the depletion of fossil fuel resources [1]. In this context, wind energy plays a pivotal role thanks to its low environmental impact and sustainability [2]. In sub-Saharan Africa, Chad faces limited access to electricity, estimated at less than 10% [3]. However, harnessing local wind resources offers a strategic opportunity for establishing wind farms [4]. Such implementation requires precise knowledge of the resources, as is the case in the Guéra region of central Chad [5] [6]. To address this critical energy shortage, we evaluate the energy output and profitability of a wind turbine at four sites in Guéra. This article examines a model whose accuracy relies on detailed input data and significant computational resources [7]-[9]. Conversely, Weibull distributions serve as an effective statistical tool for specifically analyzing temporal wind variability [10]-[12]. The wind potential analysis identifies Mangalmé, Bitkine, and Mongo as the most profitable sites, with an annual output of 12.5 GWh and a low energy cost of €0.06/kWh, enabling a return on investment within six years. In contrast, the Barh Signaka site shows low profitability, with an output of 4.1 GWh/year, a cost of €0.14/kWh, and a payback period extending to 14 years.

1.2. Background and Prospects of Wind Energy

The distribution of electricity generation sources worldwide, illustrated in **Figure 1**, demonstrates an energy transition driven by the limited availability of fossil fuels and their greenhouse gas emissions during combustion. This has accelerated the development of renewable energies, making it a global necessity. Among these sustainable alternatives, wind energy is experiencing remarkable growth, representing 8.8% of global production in the first half of 2023 and positioning itself as the fifth largest source of electricity globally [13]. This growth aligns with international commitments, including the objective of tripling renewable energy capacity, as set at COP28 [14] [15].

In the Chadian context, the Guéra province presents considerable wind power potential with very remarkable average speeds, and is promising for renewable energies in general [16]. However, this potential faces a major challenge, namely the lack of precise and reliable data, which hinders investment in provincial renewable energies.

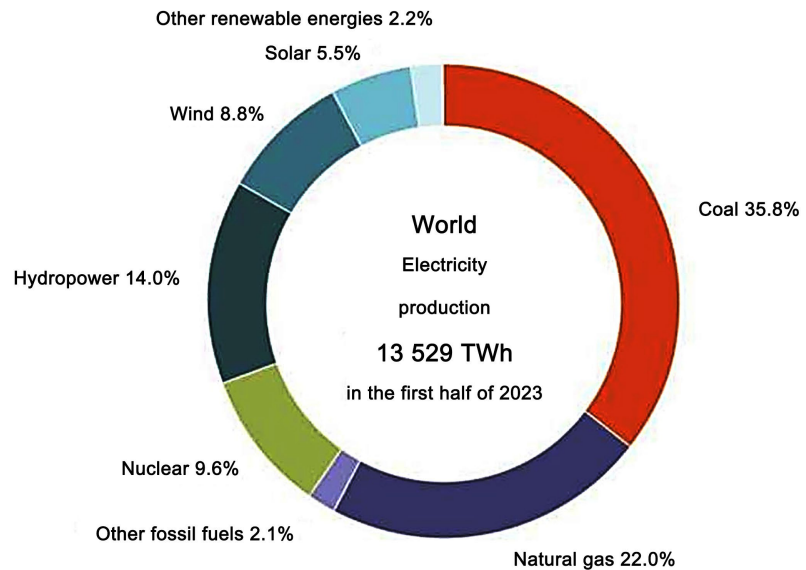


Figure 1. Distribution of electricity production sources in the world in 2023 [17].

Overall, wind power generation capacity has seen remarkable expansion, reaching nearly 900 GW by the end of 2022, as shown in **Figure 1**. Consequently, several countries worldwide have promoted the development of renewable energy, with a particular focus on wind power [18].

This steady growth in annual wind power generation capacity reflects a global commitment to reducing carbon and greenhouse gas emissions to improve energy independence [19].

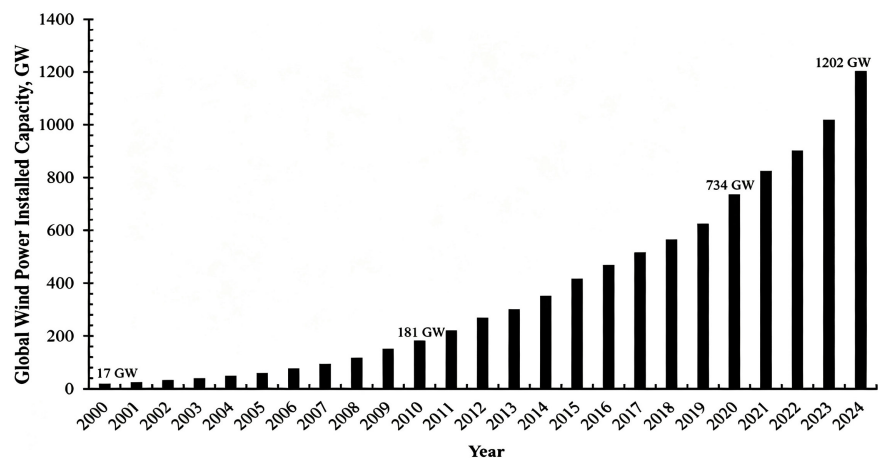


Figure 2. Evolution of installed wind energy capacity in the world [20].

Figure 2 shows the continuous exponential growth of installed global wind power capacity between 2000 and 2024.

1.3. Wind Power in Chad

According to the International Renewable Energy Forum held in N'Djamena in 2012, Chad was identified as a country with significant potential for the development of renewable energies, particularly solar and wind power. The northern and central regions of the country, with their mountain ranges, possess substantial wind resources [21]. The first wind farm was commissioned in 2022 with an installed capacity of 1 MW, following the model of wind power installations in other areas of the country [22]. **Figure 3** presents the wind energy potential in Africa and Chad in particular.

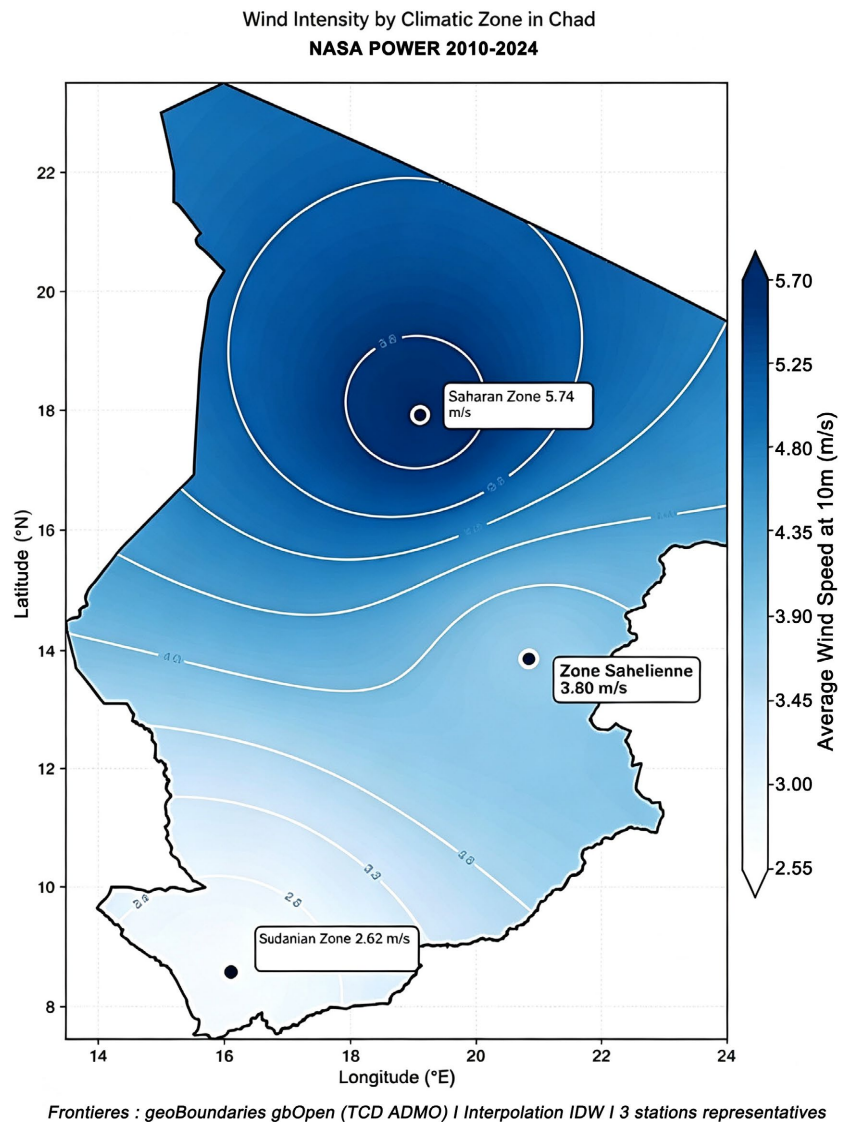


Figure 3. Wind resource supply in Chad.

Figure 3 shows wind intensity in Chad increasing progressively from south to north. The northern Saharan zone records the highest average speed of 5.74 m/s, the central Sahelian zone shows an intermediate average speed of 3.80 m/s, and the Sudanian zone exhibits the lowest average speed of 2.62 m/s.

1.4. Wind Power in the Guéra Region

The Guéra region, in the center of the country, has remarkable wind power potential for electricity generation, thanks to average wind speeds of around 4 m/s. **Figure 4** illustrates the spatial distribution of wind speeds in the Guéra province of Chad.

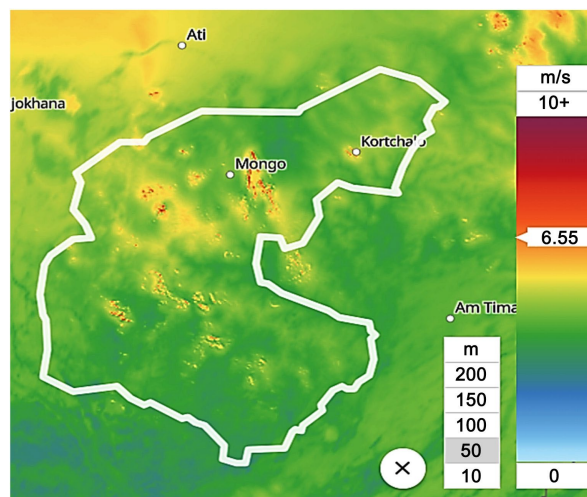


Figure 4. Spatial distribution of mean wind speed in the Guéra region at 10 m.

1.5. Problem Statement

Chad's growing energy deficit is often attributed to a lack of reliable data on wind energy potential, which hinders investment in wind power in the Guéra region. It is therefore essential to develop a master plan to estimate the area's wind potential in order to guide energy policies and contribute to the deployment of renewable energy. This involves assessing generation capacity based on observed wind patterns and conducting a techno-economic study based on meteorological variables and environmental factors.

1.6. General Objective

In this context, the overall objective is to assess the production capacity based on observed wind patterns and the potential profitability of the Guéra region through a techno-economic study. This will enable the formulation of recommendations for integrating wind energy into local development strategies and decentralized systems.

1.7. Hypothesis

This approach aims to assess production capacity and estimate average wind speed

at wind turbine hub height. A techno-economic study demonstrates sufficient profitability to justify the installation of wind energy systems from both technical and economic standpoints.

1.8. Plan Structure

Section 2 provides a global overview and outlines the general outlook for wind energy, before focusing on the specific context of the Guéra province in Chad. Section 3 describes the study area in terms of its geography and climate, then details the methodological approach—analytical, technical, and evaluative—used to estimate wind potential based on Weibull distribution parameters. Section 4 presents a detailed statistical analysis of wind speeds and directions at various heights, highlighting spatial variations in the wind resource across the region. Section 5 outlines the techno-economic assessments conducted for various sites in the Guéra region. Section 6 presents the study's results and analysis. Finally, the conclusion establishes a solid scientific foundation for creating a reliable wind potential map. It serves as a valuable decision-making tool for public and private stakeholders, with the ultimate goal of transforming an underestimated potential into a genuine opportunity for sustainable development in Chad. Our analyses confirm the vital importance of this endeavor through several regional studies.

2. Previous Work on Wind Turbines

The study by [23] analyzes the effectiveness of small wind turbines for water pumping in the Sahara Desert of Chad, specifically in Kouba Olanga. The authors demonstrate the technical viability of low-power wind turbines in arid environments but highlight that actual performance is heavily dictated by extreme desert climatic conditions and the accumulation of sand on the equipment.

In a complementary approach, [24] evaluates wind-powered electric water pumping in northeastern Chad. Their work validates the feasibility of coupling a wind turbine with an electric pump for water supply, while underscoring the system's critical dependence on the seasonal wind speed fluctuations characteristic of this Saharan zone.

Further west, [25] examines rural water supply via mechanical wind pumping around the Lake Chad floodplains. The authors base their work on a wind resource assessment to size direct mechanical systems, demonstrating their high utility for rural communities but note that the long-term viability of these installations is hampered by the lack of precise resource mapping at the micro-local scale.

Finally, the study by [26] offers a statistical assessment of wind energy potential in the Baktchoro region of Chad. Using statistical distribution methods, the authors characterize the local resource; however, their analysis remains a static, point-based assessment that lacks continuous spatial projection and mapping dynamics.

Existing literature limits its scope regarding wind energy use for water pumping systems to specific geographic areas, such as desert environments or hydrological

basins. Furthermore, these studies rely solely on localized, point-based statistical assessments, without ever offering continuous spatial modeling or an energy map. This is why we are interested in evaluating and analyzing the technical and economic feasibility of wind energy potential in Chad, specifically in the Guéra region.

3. Material and Method

3.1. Location of the Study Area

The Guéra province is located between the 10th and 13th degrees of North latitude and the 17th and 20th degrees of East longitude, with an area of 61,279 km² [27]. This area is characterized by a Sahelian climate with an average annual temperature of approximately 28.4°C and low rainfall, ranging from 300 to 800 mm. **Figure 5** presents the study area and its characteristics.

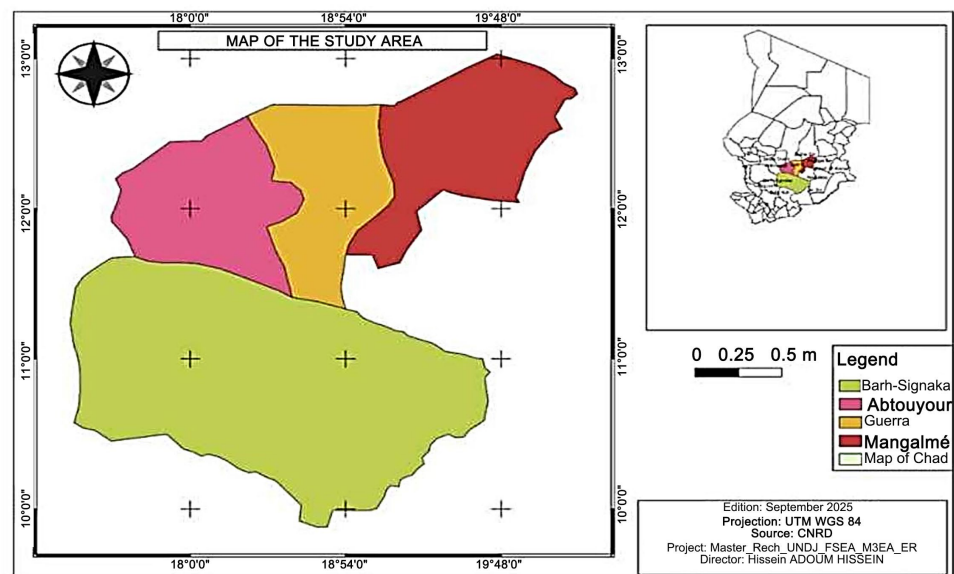


Figure 5. Location of the study area.

3.2. Data Collection

The National Meteorology and Aviation Agency (ANAM) facilitated data collection in the study area located in the Guéra region, specifically in Mongo, Barh Signaka, Bitkine, and Mangalmé. **Figure 6** shows the location map of the various stations in Guéra province, as well as the Mongo weather station [28]. Wind speed and direction, measured at a height of 10 meters, constitute the primary parameters obtained from the aforementioned databases. This dataset covers a 14-year period from January 1, 2010, to December 31, 2024 to ensure robust analysis and statistical efficiency.

3.3. Data Processing

Statistical data were processed and analyzed using Python. The Weibull distribution provided its parameters and allowed for the simulation of the wind rose. 2D/3D

modeling and visualization tools such as Surfer and QGIS were used to interpolate point data and generate Digital Elevation Models (DEMs) for the production of wind data maps.

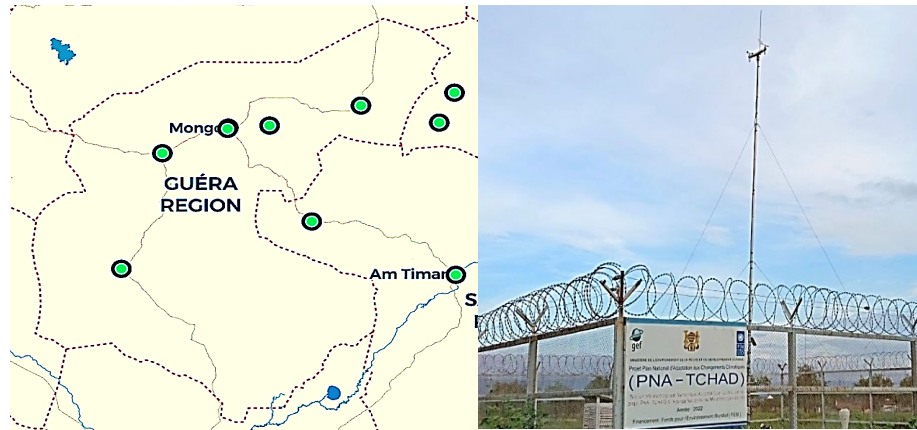


Figure 6. Location of the different meteorological stations in the province of Guéra.

3.4. Wind Potential Estimation

1) Mean wind speed distributions using Weibull distribution

The mean wind speed distribution of the potential wind speed is modeled using the Weibull distribution and parameter estimation. This wind speed distribution is characterized by the Weibull probability distribution, which is an exponential function with two parameters (c and k). The parameter c indicates the average wind speed characteristic of the site, while the parameter k indicates the degree of peaking of the distribution [29]. Equation (1) gives the mathematical formula for the probability density function $f(V)$ and the cumulative Weibull distribution function $F(V)$ corresponding to Equation (2).

$$f(V) = \frac{k}{c} \left(\frac{V}{c} \right)^{k-1} \exp \left[- \left(\frac{V}{c} \right)^k \right] \quad (1)$$

where:

- $f(V)$ is the frequency of occurrence of wind speeds;
- k is the shape parameter (unitless);
- c is the scale parameter ($\text{m}\cdot\text{s}^{-1}$).

$$F(V) = \int f(V) dV = 1 - \exp \left[- \left(\frac{V}{c} \right)^k \right] \quad (2)$$

where:

- $F(V)$ is the cumulative Weibull distribution function;
- V is the average speed (m/s).

The mean velocity and the mean cubic velocity are essential for evaluating wind potential. According to [30], Equation (3) gives the weighted mean velocity.

$$\bar{V} = \int_0^\infty V f(V) dV \quad (3)$$

where:

- $\bar{V}$ is the weighted average speed;
- V is the average speed (m/s).

2) Evaluation of Weibull parameters

The modified maximum likelihood method allows the Weibull parameters (k and c) to be determined from the site wind data for the wind potential. These parameters are calculated using Equations (4) and (5) [31]. They are implemented in FORTRAN 90 until the numerical value of K converges, and this value is then used explicitly to find that of C .

$$k = \left(\frac{\sum_{i=1}^n V_i^k \times \ln(V_i) \times f(V_i)}{\sum_{i=1}^n V_i^k \times f(V_i)} - \frac{\sum_{i=1}^n \ln(V_i) \times f(V_i)}{F(v \geq 0)} \right)^{-1} \quad (4)$$

$$c = \left(\frac{1}{F(v \geq 0)} \times \sum_{i=1}^n V_i^k \times f(V_i) \right)^{\frac{1}{k}} \quad (5)$$

where:

- V_i is the midpoint of the speed interval i ;
- $f(V_i)$ is the frequency for which the wind speed falls within the interval i ;
- $F(v \geq 0)$ is the probability that the wind speed is greater than or equal to zero;
- n is the number of intervals.

3.5. Wind Energy Modeling

1) Roughness

The terrain roughness length, denoted Z_0 , is often parameterized by obstacles seen from a distance, or a set of very small obstacles considered on the wind scale. A simple empirical relationship between roughness elements and roughness length has been formulated by Equation (6) [32].

$$Z_0 = 0.5(h \times S) / A_H \quad (6)$$

where:

- h is the height of the roughness element (m);
- S is the cross-sectional area facing the wind (m²);
- A_H is the average horizontal area (m²).

2) Wind energy density

Considering the air density, air velocity, and area swept by the wind turbine blades, the power available in a wind flow is obtained from the relationship in Equation (7). This power depends directly on the air density and the area swept by the wind turbine blades.

$$P = \frac{1}{2} \rho \times A \times V^3 \quad (7)$$

where:

- ρ is the air density (kg/m³);
- A is the swept area of the wind turbine blades (m²).

Thus, by expressing the wind flux per unit area, Equation (8) gives us the avail-

able power.

$$P_V = \frac{1}{2} \rho \times V^3 \quad (8)$$

The fraction of time for which the average speed prevails in the system is given by the probability distribution function $f(v)$. Thus, the total energy supplied by all possible average speeds of the wind regime, available per unit area and per unit time, can be expressed as in Equation (9) [33].

$$E_D = \int_0^\infty P_V \times f(v) \times dV \quad (9)$$

4. Processing of Statistical Data

1) Calculation of the arithmetic mean of the velocities

$$\bar{V} = \frac{1}{n} \times \sum_{i=1}^n V_i \quad (10)$$

2) Calculation of the weighted arithmetic mean of the speeds or the average power.

$$V = \sum_{i=1}^n V_i \times f(V_i) \quad (11)$$

3) Calculation of average power per unit area (energy density) [34].

$$\langle V \rangle = \frac{\sum_{i=1}^n P(V_i) \times f(V_i)}{\sum_{i=1}^n f(V_i)}; P(v_i) = \frac{1}{2} \times \rho \times v_i^3 \quad (12)$$

$$\langle V \rangle = \frac{1}{2} \times \frac{\sum_{i=1}^n v_i^3 \times f(V_i)}{\sum_{i=1}^n f(V_i)} \quad (13)$$

Wind comfort is defined as the probability of exceeding a discomfort threshold over a period of approximately one year. It is estimated using Equation (14), which calculates a weighted sum of the contribution of each wind direction to exceeding a discomfort threshold (v).

4) The probability that the speed exceeds the onset threshold

$$P(V \geq V_0) = \exp \left[- \left(\frac{V_0}{e} \right)^k \right] \quad (14)$$

5) The power curve $P(V)$ with the Weibull distribution.

Annual energy is calculated by integrating the turbine's power curve $P(V)$ with the Weibull distribution.

$$E_{\text{annual}} = \int_0^\infty P(V) f(V) dV \times 8760 \quad (15)$$

where $f(V)$ is the Weibull density.

5. Techno-Economic Feasibility: Economic Indicators (LCOE/NPV/Payback) [35]

1) The LCOE represents the average cost of generating one kilowatt-hour (kWh) of electricity over the total lifespan of the wind power installation.

$$LCOE = \frac{\sum_{t=0}^N \frac{CAPEX + OPEX}{(1+r)^t}}{\sum_{t=1}^N \frac{E_t}{(1+r)^t}} \quad (16)$$

2) The NPV determines the intrinsic financial profitability of the investment. Net Present Value (NPV).

$$VAN = \sum_{t=1}^N \frac{R_t - OPEX_t}{(1+r)^t} - CAPEX_0 \quad (17)$$

3) The payback period estimates the number of years required for the cumulative, discounted earnings from the installation to fully recoup the initial capital investment (CAPEX₀).

$$CAPEX_0 = \sum_{t=1}^T \frac{R_t - OPEX_t}{(1+r)^t} \quad (18)$$

6. Results and Analysis

6.1. Analysis of the Variation in Average Wind Speed

These curves (**Figure 7**) represent the wind speed probability distributions for the various departments of the Guéra region, as illustrated in the figures below. The figures show that higher density corresponds to higher wind speeds. Each curve is characterized by parameter k , which describes the shape of the distribution, and parameter c , which is linked to the characteristic wind speed; the higher this speed (c), the more the distribution shifts toward higher speeds. A value of k greater than or equal to 2 indicates a more steady wind, meaning fewer fluctuations, whereas a value of k less than or equal to 2 indicates a more unstable, or variable, wind.

Figure 7(a) shows the wind pattern described by the Weibull distribution for the Mongo department. It presents a shape parameter k of 4.833, well above 2 and a scale parameter c of 3.839 m/s, representing the actual mean wind speed simulated by the distribution. The curve in **Figure 7(a)** is relatively broad, indicating that the wind is fairly stable.

The Weibull distribution in **Figure 7(b)** shows a shape parameter k of 5.061 well above 2 and a scale parameter c of 3.992 m/s; while the wind is slightly more variable than at Mongo, the average speed is slightly higher. **Figure 7(b)** represents the most promising site among those analyzed, as it offers the best potential.

Figure 7(c) shows a shape parameter k of 5.177 well above 2 and a scale parameter c of 3.945 m/s; the high shape factor indicates very stable wind conditions, while the distribution yields a simulated mean speed of 3.63 m/s. The wind in this locality is quite steady, making it the second-ranked site after Mangalmé in terms of wind speed.

Figure 7(d) illustrates the wind characteristics in this department, showing a shape parameter k of 5.139 well above 2 and a scale parameter c of 3.524 m/s. The actual mean wind speed simulated for the site is 3.24 m/s. **Figure 7** indicates that this department is the least ideal of the three, as it exhibits low wind speeds.

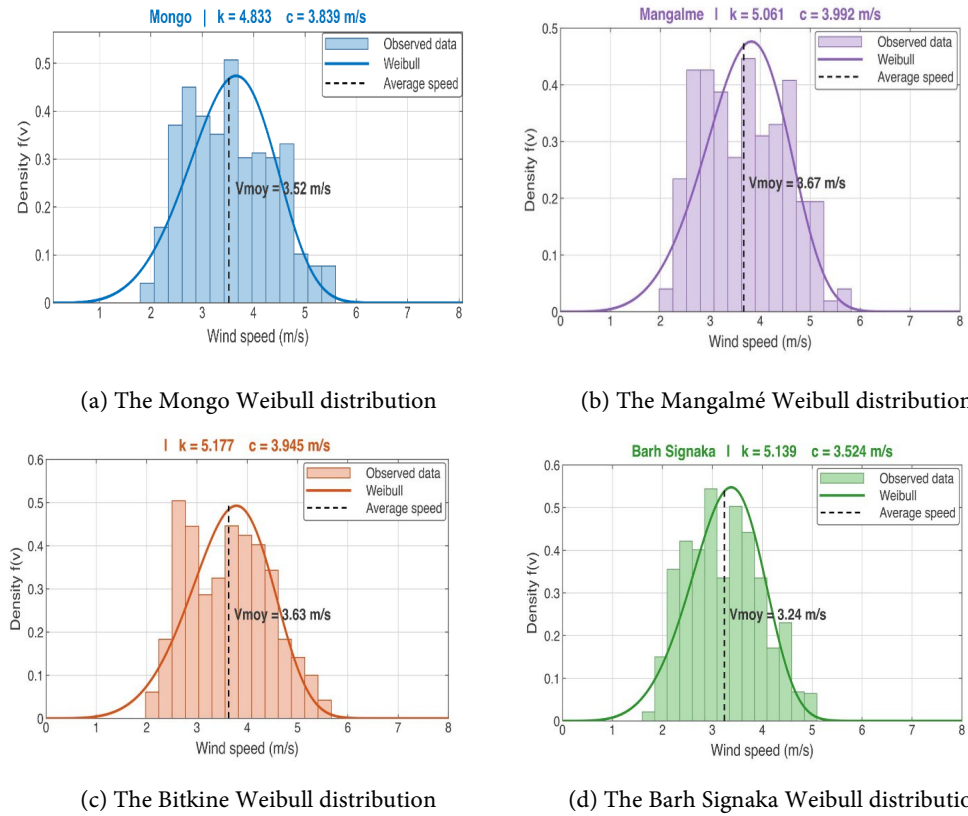
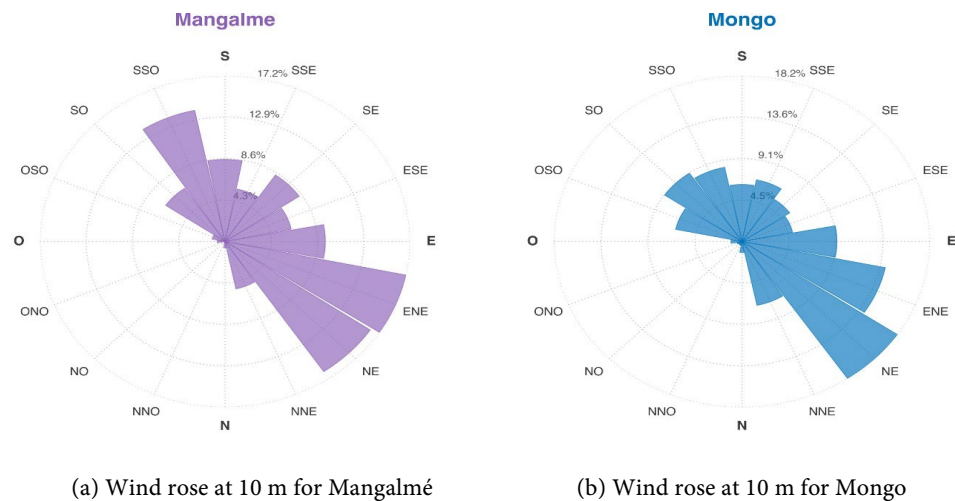
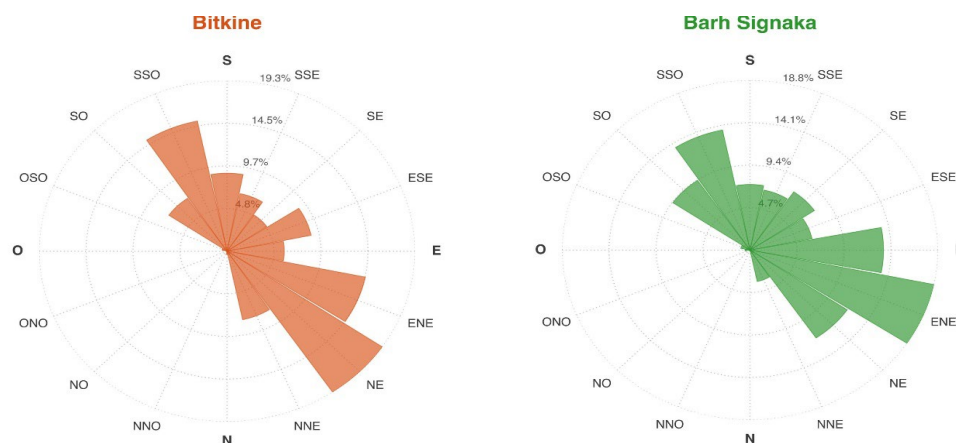


Figure 7. Wind speed frequency model fitted to the Weibull distribution. Weibull distribution results for the departments of (a) Mongo, (b) Mangalmé, (c) Bitkine and (d) Barh_Signaka.

6.2. Wind Frequency Estimation and Wind Turbine Orientation at 10 m Altitude

The quantification of wind frequency and the orientation of wind turbines for the different sites studied is analyzed using wind roses at 10 m altitude, as illustrated in **Figure 8**. These wind roses allow for the precise determination of the prevailing wind regime and direction for optimal wind turbine placement.





(c) Wind rose at 10 m for Bitkine

(d) Wind rose at 10 m for Barh Signakha

Figure 8. Analysis of wind direction and average speed at 10 m altitude. Wind rose results for the departments of (a) Mangalmé, (b) Guéra, (c) Bitkine and (d) Barh_Signakha.

The wind roses provide an overview of wind frequencies and directions for the different sites at 10 m altitude.

Figure 8(a) shows that the wind blows primarily from the East (E), Northeast (NE), and East-Northeast (ENE) directions, with the latter exhibiting the highest frequency peaks in the area, at approximately 0.17 (17% of the time). Notable wind patterns are also observed from the South (S) and South-Southwest (SSW), whereas winds from the West, Northwest, and West-Northwest are virtually absent. Few obstacles are found in these directions.

In **Figure 8(b)**, the prevailing winds blow from the east and northeast, reaching a peak frequency of approximately 0.13 to 0.18 (representing a maximum of 18.2% of the time); the Southwest (SW) and Southeast (SE) directions are significant secondary sources, accounting for a frequency of 0.10, while other directions such as West, northwest, and north show a near-zero frequency.

Figure 8(c) shows that the prevailing winds are from the Northeast (NE) and East-Northeast (ENE); frequencies in these dominant directions range from approximately 0.17 to 0.19 (representing 19% of the time). Significant wind activity is also observed from the East (E) and South-Southwest (SSW). Conversely, there are sectors with low or negligible frequency, such as the South-Southeast (SSE) with values of 0.4 to 0.6 and the West (W), Northwest (NW), and West-Northwest (WNW), where frequencies are virtually non-existent (below 0.3).

In **Figure 8(d)**, the prevailing winds are predominantly from the Northeast (NE) and East (E), with frequencies ranging from 0.14 to 0.18 (representing 18% of the time). Other directions show significant frequencies, such as South (S) at 0.10 - 0.12, and South-Southwest and Southwest at 0.08 - 0.11. Certain directions show lower frequencies, specifically Northeast, Southeast, and South-Southeast at 0.05 - 0.07, while the frequency is very low (less than 2%) from the West.

Analysis of the Weibull parameters (**Table 1**) reveals that the Guéra province

possesses a low-speed wind resource characterized by excellent consistency and high temporal stability, as evidenced by very high shape factors ($k > 4.8$). Mangalmé stands out for having the highest average wind speed (3.67 m/s), while Bitkine offers the greatest energy potential with the highest scale factor ($c = 3.992$ m/s), making these two locations the top performers in terms of productivity. Conversely, Mongo experiences the most consistent and predictable winds in the study ($k = 5.177$)—a major advantage for minimizing mechanical wear on equipment—whereas Barh Signaka is the least favorable site, showing the lowest speed and scale indicators, which limits its utilization to low-power applications such as water pumping for irrigation.

Table 1. Weibull parameters derived using the energy factor method.

Sites	Speeds (m/s)	k	c (m/s)
Mangalmé	3.67	4.833	3.839
Bitkine	3.63	5.061	3.992
Mongo	3.52	5.177	3.945
Barh Signaka	3.24	5.139	3.524

6.3. Power Output

1) Estimation of the capacity factor for the turbine

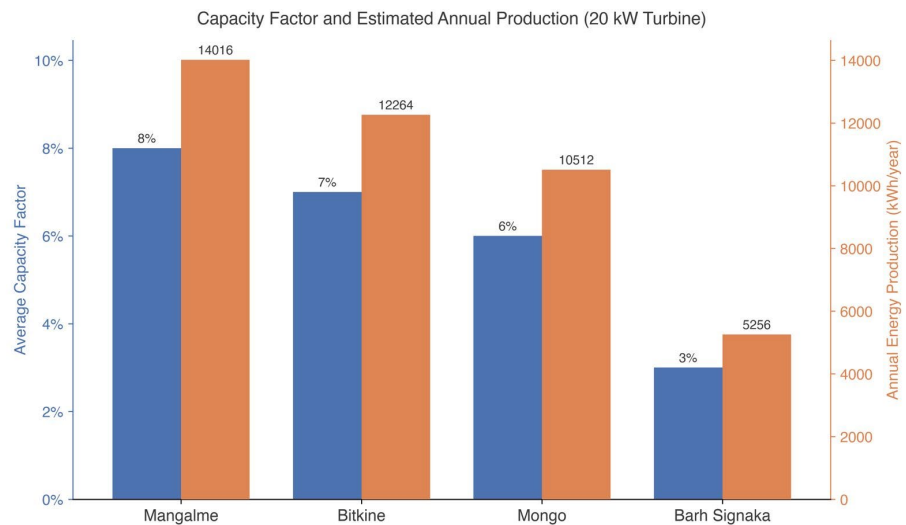


Figure 9. Average wind speed versus turbine performance.

Figure 9 shows a direct correlation between the extrapolated average wind speed and turbine performance. Although these capacity factors remain low, typical of areas with low wind speeds, Mangalmé and Bitkine stand out as the only technically viable sites for installing the 20-kW turbine. Conversely, Barh Signaka should be considered for very small, direct-drive hydraulic pumps.

2) The performance gap

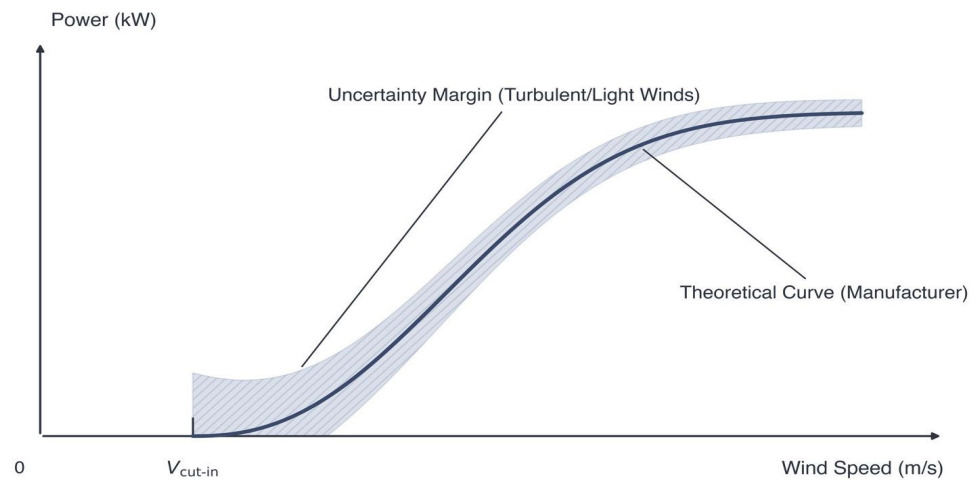


Figure 10. The gap between a wind turbine's theoretical electricity generation and its actual performance in the presence of disturbances.

Figure 10 illustrates the gap between a wind turbine's theoretical electricity generation and its actual performance in the presence of disturbances. The manufacturer's theoretical curve predicts a clean start at the cut-in speed. However, the margin of uncertainty reflects a tangible drop in efficiency. Low wind speeds disrupt airflow, reducing the energy captured by the blades. Ultimately, actual output remains below ideal estimates in this transition zone.

3) An assessment of the probability

Table 2 shows that the Mangalmé, Bitkine, and Mongo sites are above the cut-in speed and thus technically viable; conversely, the Barh Signaka site remains below the threshold, which reduces its profitability.

Table 2. Qualitative probabilities by location (for $V = 3$ m/s).

Location	Estimated probability	Qualitative assessment
Mangalmé	0.78 - 0.79	High
Bitkine	0.78 - 0.79	High
Mongo	0.75 - 0.76	Slightly lower
Barh Signaka	0.66	Significantly lower

Table 3, showing the systematic application of the wind shear model for rough terrain ($\alpha = 0.25$), demonstrates that raising the mast height from 10 to 18 meters increases average wind speeds by 15.8% across all Guéra sites, bringing speeds to 4.25 m/s in Mangalmé, 4.20 m/s in Bitkine, 4.08 m/s in Mongo, and 3.75 m/s in Barh Signaka. Due to the proportional relationship between available power and the cube of wind speed (V^3), this increase yields a substantial and uniform 56% gain in gross energy for all locations. This improvement significantly enhances the

technical viability of the study, as even the least exposed site—Barh Signaka—now comfortably exceeds the critical 3 m/s cut-in speed, thereby reducing turbine downtime and optimizing overall performance.

Table 3. Results of vertical extrapolation (10 m $\rightarrow$ 18 m) with roughness exponent $\alpha = 0.25$, rough terrain.

Mangalmé	The average speed increases from 3.67 m/s to 4.25 m/s (a 56% gain in gross energy).
Bitkine	The average speed increases from 3.63 m/s to 4.20 m/s (a 56% gain in gross energy).
Mongo	The average speed increases from 3.52 m/s to 4.08 m/s (a 56% gain in gross energy).
Barh Signaka	The average speed increases from 3.52 m/s to 3.75 m/s (a 56% gain in gross energy).

6.4. Techno-Economic Feasibility

Financial trends based on site productivity

Table 4 demonstrates a direct correlation between the wind energy potential of the sites and their financial profitability, thereby establishing a clear hierarchy to support decision-making. The three sites, Mangalmé, Bitkine, and Mongo, emerge as priority investment areas due to high annual output, which lowers the Levelized Cost of Energy (LCOE), maximizes Net Present Value (NPV), and ensures a rapid return on capital. Conversely, the Barh Signaka site proves far less attractive; its poor energy performance drives up production costs and significantly extends the payback period.

Table 4. Showing the electricity generation performance alongside key financial indicators (LCOE, NPV, payback period) and identifying specific profitability risks, highlighting the least exposed site.

Sites	Annual production level (E_{annual})	Levelized Cost of Energy (LCOE)	Net present value (VAN/NPV)	Return on investment period (Payback)
Mangalmé, Bitkine and Mongo	High production volume	Weaker	Higher	Shorter
Barh Signaka	Low production	Higher	Weaker	Longer

6.5. Wind Map of the Guéra Province

Wind mapping of the Guéra area

Figure 11 shows the average wind speed at a height of 10 meters above ground level (WS10M) in the Guéra region (Chad) for the 2010-2025 period, based on ANAM data; this method, Inverse Distance Weighting (IDW) interpolation, allows for the estimation of values between stations using data from measurement points.

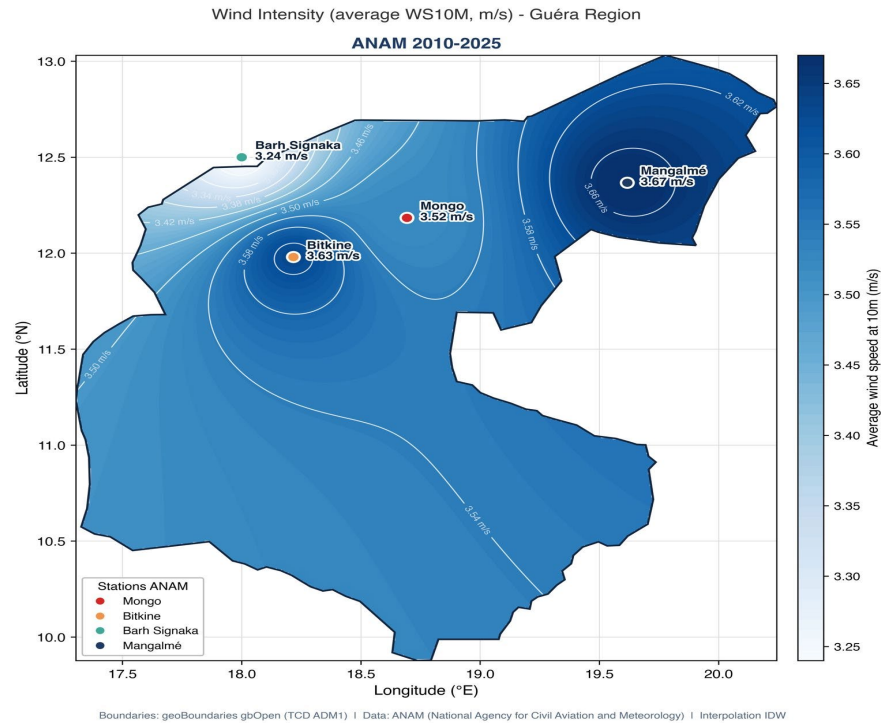


Figure 11. Map of the average annual wind speed (m/s) at 10 m altitude of the Guéra province.

The colored dots in **Figure 11** represent reference stations characterizing wind dynamics across the Guéra zone:

The green color in **Figure 11** represents Barh Signaka, the western part of the Guéra zone, where the average wind speed is approximately 3.24 m/s. The red color represents Mongo, the central part of the Guéra zone, with an average wind speed of 3.52 m/s. The yellow color represents Bitkine, located in the Guéra zone, where the average speed is 3.63 m/s. The very dark blue color represents Mangalmé, located in the Guéra zone, where the average speed is 3.67 m/s.

6.6. Discussions

The Guéra region possesses a wind resource characterized by low average wind speeds (3.24 to 3.67 m/s) but excellent consistency, as evidenced by high shape factors ($k > 4.8$). Mangalmé stands out with the highest average speed ($V = 3.67$ m/s), while Bitkine ($V = 3.63$ m/s) shows the best overall energy potential with a scale factor (c) of 3.992 m/s; both offer optimal performance, with a very high probability (79%) of exceeding the cut-in speed (3 m/s). Mongo (75% - 76%) exhibits the most stable winds ($k = 5.177$). Conversely, Barh Signaka is the least viable site, with only a 66% probability of operation; the turbine would frequently remain idle there, severely limiting economic viability compared to the other three locations. Indeed, while these conditions rule out the use of high-capacity industrial wind turbines, the resource is suitable for water pumping or solar-wind hybrid systems. Applying a wind shear model for rugged terrain ($\alpha = 0.25$) shows that raising the mast height from 10 to 18 meters increases average speeds by 15.8%

across all Guéra sites, bringing speeds to 4.25 m/s in Mangalmé, 4.20 m/s in Bitkine, 4.08 m/s in Mongo, and 3.75 m/s in Barh Signaka. Given the proportional relationship between available power and the cube of wind speed (V^3), this increase yields a massive, uniform 56% gain in gross energy output for all locations. Analysis of the wind energy potential reveals a clear difference in profitability among the studied areas, identifying Mangalmé, Bitkine, and Mongo as the most promising sites. With an annual output of 12.5 GWh, these three locations achieve cost optimization, resulting in a low energy price of €0.06 per kWh. This translates into excellent long-term profitability, featuring a Net Present Value (NPV) of €4.2 million and a rapid project payback period of six years. Conversely, the Barh Signaka site proves far less advantageous: its low output (4.1 GWh/year) drives the energy cost up to €0.14 per kWh, thereby limiting financial returns (NPV of €0.3 million) and extending the payback period to 14 years. These conclusions align with trends reported in the literature and highlighted by Oung-zetna *et al.* (2025) [23] [24] in the study titled Efficiency of Small Wind Turbines for Water Pumping in the Chadian Desert at Kouba Olanga.

6.7. Wind Turbine Selection

Table 5 shows that the small-scale wind category actually encompasses a highly diverse range of technologies, extending from systems suited to individual households to machines capable of powering larger sites. A distinction is made for “micro-wind” systems—turbines with a capacity of less than 1 kW designed to meet very low energy needs. Next comes “small-scale” wind power proper, covering machines with capacities between 1 kW and 36 kW intended for self-consumption or small-scale installations. Finally, the term “medium-scale” wind power applies to turbines ranging from 36 kW to 250 kW; although they fall outside the scope of industrial wind power, they are closer to semi-collective energy solutions. Thus, this classification primarily reflects changes in scale regarding power output, application, and equipment sizing.

Table 5. Specifications of the RW Energy 20 kW low-wind-speed wind turbine [28].

Rotor diameter (m)	10.0
Blade material and number	Fiberglass-reinforced (3 blades)
Rated power/maximum power	20/25 kW
Rated wind speed (m/s)	11
Cut-in wind speed (m/s)	3
Operating wind speed (m/s)	3 - 25
Survival wind speed (m/s)	45
Rated rotational speed (rpm)	200
Operating voltage	DC 240 V/360V/480V
Generator type	Three-phase, permanent magnet
Charging method	Constant current with voltage regulation

Continued

Speed regulation method	Yawing + Automatic brake
Weight	1150 kg
Tower height (m)	18
Suggested battery capacity	80 units of 12 V/200Ah deep-cycle batteries
Service life	15 years

6.8. Interpretation of the RW Energy 20 kW Low-Wind-Speed Wind Turbine

The RW Energy 20 kW low-wind-speed wind turbine generation begins at a minimum speed of approximately 2 m/s; power output then rises rapidly and continuously as the wind strengthens, reflecting the increase in available kinetic energy. The turbine reaches its optimal peak output of 25,000 watts at a wind speed of 15 m/s, before the power output drops slightly beyond this peak.

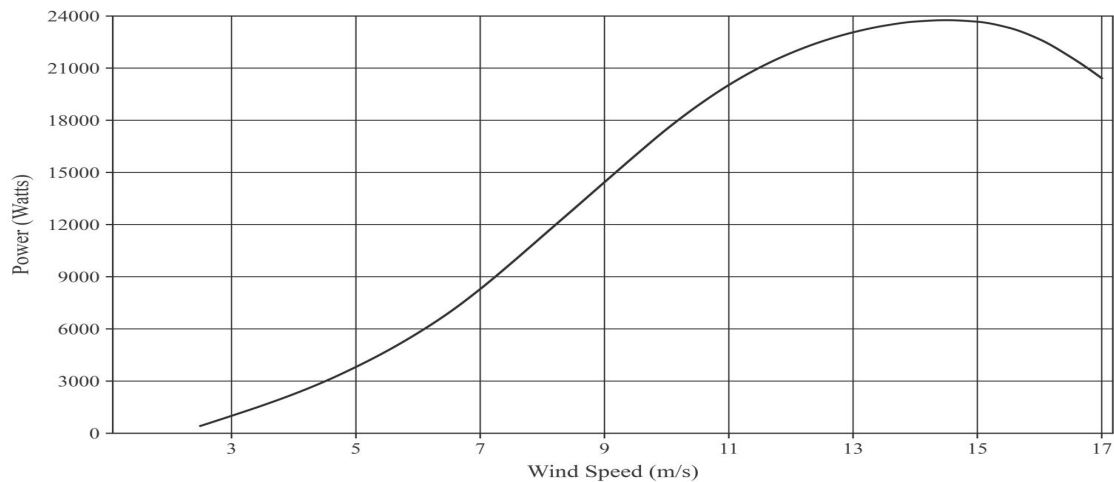


Figure 12. Maximum power as a function of wind speed for a small wind turbine with a power output of 20 kW [36].

Figure 12 shows the power curve of a wind turbine, illustrating how its electricity generation varies with wind speed: it begins producing energy at a minimum cut-in speed of 2.5 m/s, sees its power output rise rapidly following an exponential trend as the wind strengthens, then levels off at its maximum rated power to protect mechanical components, before shutting down completely during storms as a safety measure.

7. Conclusions

Renewable energy is a key driver of Chad's national energy development program. However, certain areas, such as the Sahel region, suffer from a significant energy deficit. This study employed numerical modeling to assess and analyze the technical feasibility of harnessing wind energy potential in the Guéra region. The ob-

jective is to help improve access to electricity and meet the area's sustainable development needs. Assessing the wind potential involved using Weibull distribution parameters, analyzing wind speed and direction (via a wind rose), and conducting a techno-economic evaluation for the Guéra region. Actual data for the study area, covering a 15-year period (from January 1, 2010, to December 31, 2025), were obtained from Chad's National Meteorological Agency (ANAM) and processed using Python.

The results reveal significant wind energy potential, with average wind speeds ranging from 3.24 to 3.67 m/s at a height of 10 meters across all four sites; this indicates a low-wind regime characteristic of mountainous areas where obstacles and terrain roughness limit available energy that is suitable for the installation of small-scale domestic wind turbines. The wind potential analysis identifies Mangalmé, Bitkine, and Mongo as the most cost-effective sites, boasting an annual output of 12.5 GWh and a low energy cost of €0.06/kWh, allowing for a return on investment within six years. In contrast, the Barh Signaka site shows low profitability, with an output of 4.1 GWh/year, a cost of €0.14/kWh, and a payback period extending to 14 years. Strategic recommendations advise focusing initial investments on the Mangalmé-Bitkine axis, identified as the most profitable wind corridor due to its minimal Levelized Cost of Energy (LCOE) and high Net Present Value (NPV). To optimize this potential, it is essential to install turbines on towers at least 18 to 24 meters high to capture wind shear and to deploy a hybrid wind-solar system coupled with battery storage, ensuring service continuity despite seasonal wind variations and the region's intense heat. Finally, given its insufficient financial viability, the Barh Signaka site should be repurposed for direct agricultural water pumping applications. These results are significant and highly favorable for wind energy deployment, from both scientific and practical perspectives. This work provides public policymakers and private investors with a valuable decision-support tool for regional energy planning. The generated wind maps, combined with site-specific analyses, make it possible to optimize future installations while reducing technical and financial uncertainties.

Author Contributions

Yacoub Nassian Nimir was responsible for data collection, study design, methodology, simulation execution, result analysis, and manuscript drafting. **Hissein Adoum Hissein** also participated in data collection and the interpretation of results. **Moussa Ahmat** contributed to the development, programming, and validation of the results. **Jean Benjamin Bidias** supervised the research while actively contributing to the methodology and validation. Finally, all authors contributed to the interpretation of the data as well as the review and approval of the final version of the text.

Conflicts of Interest

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

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Acronyms and Abbreviations

A	Area swept by the wind turbine blades (m^2)
A_H	Average horizontal surface area (m^2)
ANAM	National Meteorological Agency
c	The Weibull parameter, provides information on the average wind speed
$^{\circ}\text{C}$	Degrees Celsius
CFD	Computational Fluid Dynamics Models
COP28	28th Conference of the Parties
ER	Renewable Energies
$F(V)$	Weibull cumulative distribution function
$f(V)$	Probability density function
$F(v=0)$	Probability that the wind speed is greater than or equal to zero
$f(V_i)$	Frequency for which the wind speed falls within the interval i
GW	Gigawatt
GWEC	Global Wind Energy Council
h	Height of the roughness element (m)
HAWT	Horizontal Axis Wind Turbines
K	The Weibull parameter, indicates the more or less sharpness of the distribution
km^2	Square kilometer
kW	Kilowatt
EMN	Digital elevation models
MW	Megawatt
n	Number of intervals
P	Weighted arithmetic mean of velocities
S	Cross-sectional area facing the wind (m^2)
GIS	Geographic Information Systems
$\bar{V}$	Weighted average velocity
V_i	Midpoint of velocity interval i
V	Average velocity (m/s)
VAWT	Vertical axis wind turbines
WAsP	Wind Atlas Analysis and Application Program
ρ	Air density (kg/m^3)