

Statistical Assessment of the Wind Energy Potential in the Baktchoro Area of Chad

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Abstract

In this article, we present an assessment of the wind energy potential at the Baktchoro site based on a statistical analysis of wind speeds using the Weibull distribution, applied at various heights ranging from 10 to 100 m. The results highlight marked seasonal variability in the resource, with higher speeds during the dry season, particularly from January to May, and a significant decrease during the wet season, especially between July and October. At 10 m, average monthly speeds range from 2.30 to 4.04 m/s, indicating a weak to moderate wind regime. However, vertical extrapolation shows a significant improvement in the wind resource with altitude, with speeds reaching 7.34 m/s at 100 m, while the maximum power density reaches 424.83 W/m² in April. The Weibull parameters, with a shape factor ranging from 1.26 to 1.88, reflect significant wind variability. The annual frequency analysis reveals that 54.8% of wind speeds are below 3 m/s, highlighting the need to select wind turbines with a low start-up speed. A comparison of the turbines studied shows that the Bergey Excel 10 offers the best performance, with an estimated power output of 3.56 kW and a capacity factor of 0.36. The contribution of this study lies in the characterization of the Baktchoro wind resource, the identification of favorable wind speeds and periods, and guidance on technology selection. The results confirm the suitability of a hybrid photovoltaic-wind system for improving the site's energy stability.

Keywords

Wind Energy, Weibull Distribution, Power Density, Capacity Factor

1. Introduction

The link between rising energy consumption, improved quality of life, and economic growth is well documented in the scientific literature [1] [2]. In a global context marked by growing demographic pressure and demands for human development, access to reliable and affordable energy remains the foundation of any societal transformation. However, this growth is now coming up against the climate emergency and the need to preserve ecosystem balances [3]-[5]. To address this dual challenge, the transition of energy systems toward renewable energy sources has become a top priority, in line with the Sustainable Development Goals [6] [7]. Today, wind power is considered one of the most promising solutions for replacing fossil fuels. Given the lack of precise data at the Baktchoro site, characterizing the wind speed distribution there is essential, not only for assessing wind potential but also for the optimal sizing of power plants and the appropriate selection of wind turbines. The most well-established fitting function is the Weibull distribution, as this method provides an excellent fit for the majority of global wind regimes. With this in mind, this study aims to statistically assess the wind energy potential of the Baktchoro area using Weibull distributions, in order to estimate the exploitable electricity generation and contribute to local energy planning. This article is structured as follows: Section 2 presents the study area by describing its geographic, climatic, and topographic characteristics, as well as the data sources used, and outlines the methodology adopted for the statistical analysis, the theoretical foundations of the Weibull distribution, the methods for estimating the shape (k) and scale (c) parameters, and the selection of wind turbines. Section 3 presents the results and discussion.

2. Materials and Methods

2.1. Materials

2.1.1. Site Description, Reliability, and Limitations of Reanalysis Data

Baktchoro (the capital of the West Tandjilé subprefecture) is located 320 km south of N'Djamena in the Sudanese zone [8]. The data for this study were obtained from the NASA POWER platform (2000-2020) at a reference height of 10 m. Data validation was performed using *in situ* observations from the Kélo weather station (Chad; 9.31°N, 15.80°E; elevation: 390 m). The comparison period spans from January 1, 2000, to December 31, 2020. The NASA POWER data used correspond to monthly averages, harmonized with the station's observations at the same temporal resolution. The completeness and consistency of the data series were verified prior to statistical analysis. These data have a spatial resolution of ($0.5^\circ \times 0.5^\circ$) for statistical analysis. It should be noted that these data were compared with ground-

based measurements from the Kélo reference station to assess their reliability (see coordinates in **Table 1**), located 20 km away. **Figure 1** shows the study area.

Table 1. Geographic coordinates of the site.

Site	Latitude	Longitude	Altitude (m)
Baktchoro	9.505°N	15.814°E	370.97

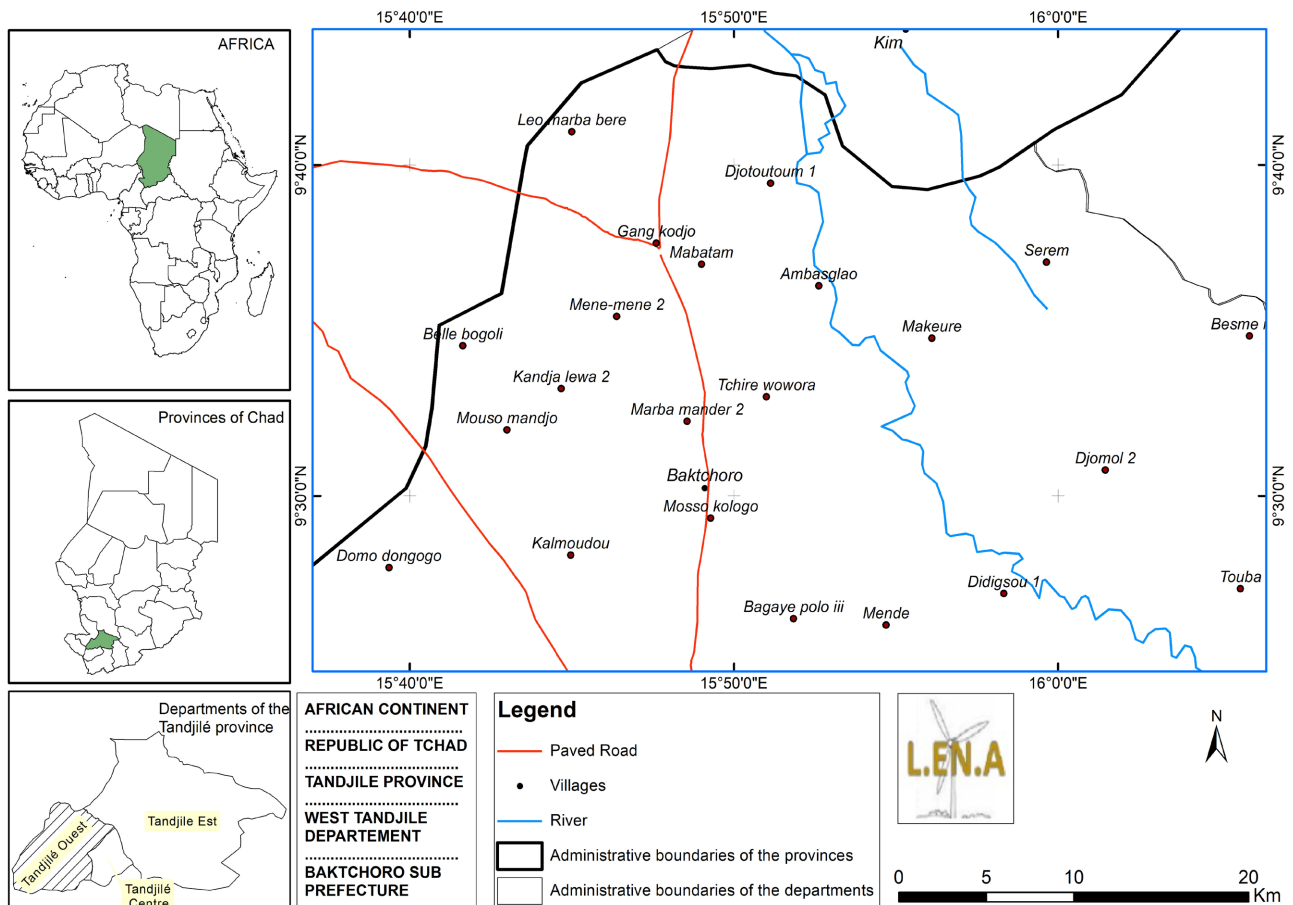


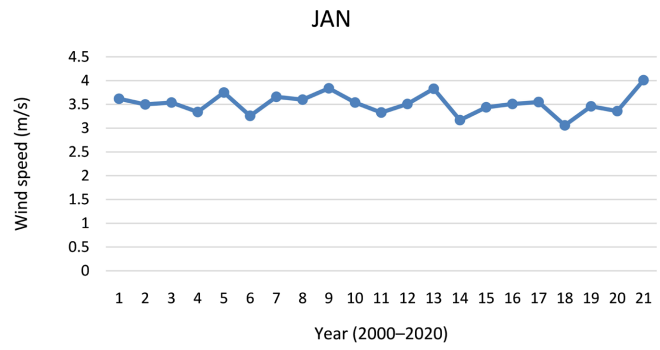
Figure 1. Map showing the location of Baktchoro.

2.1.2. Depiction of Monthly Variations in Wind Speeds at the Site at a Height of 10 Meters above Ground Level

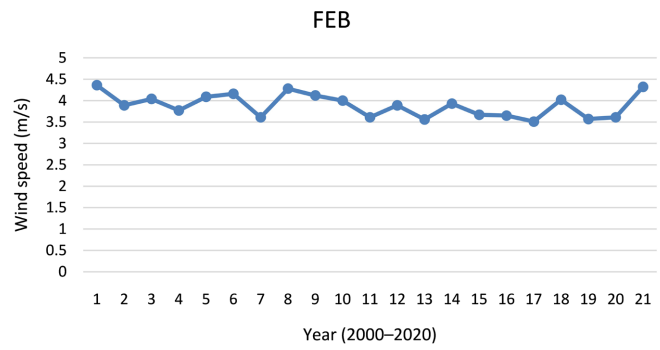
- **Year-over-year change in average wind speed observed at the site**

The graphs of the monthly evolution of wind speed at 10 m, shown in **Figure 2** for Baktchoro (2000-2020), highlight a strong seasonal variability. At the beginning of the year (January-February), wind speeds are moderate and relatively stable, under the influence of dry conditions. An increase, accompanied by more pronounced variability, appears in March-April, corresponding to a transition period.

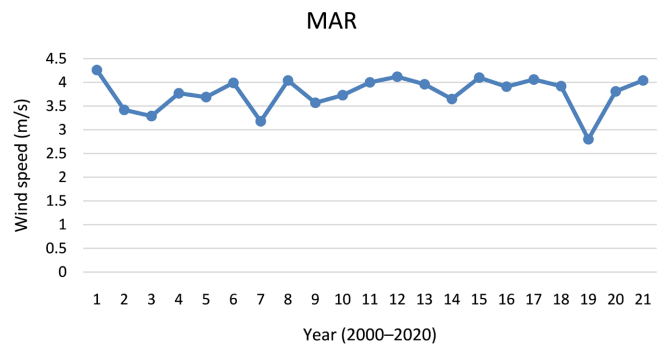
From May onward, a gradual decrease sets in, becoming more noticeable in June, and reaching a minimum in July-August during the rainy season, when winds are weak and less variable.



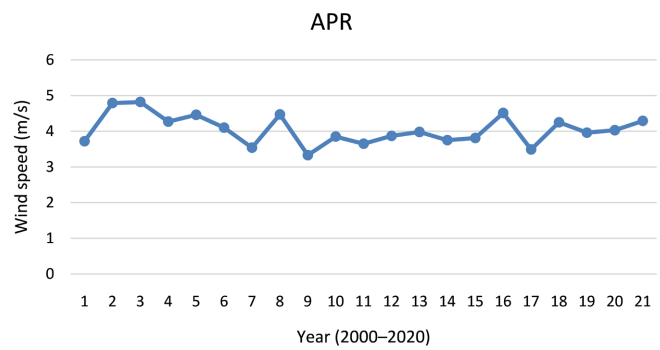
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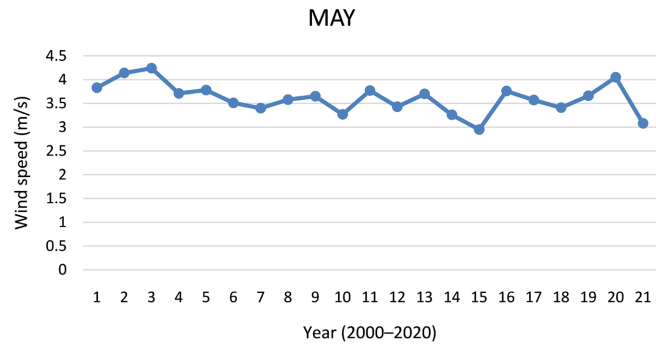
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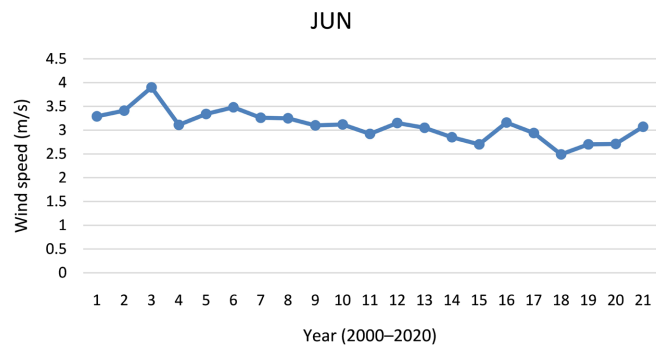
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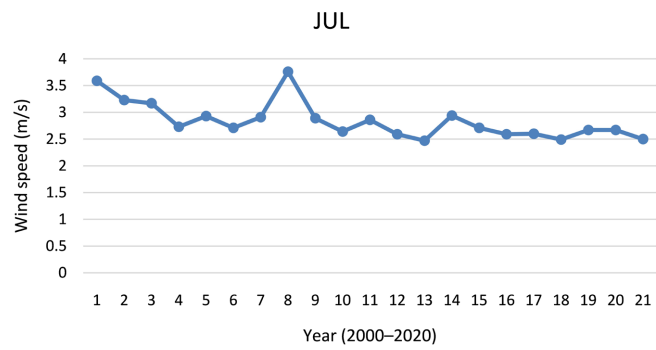
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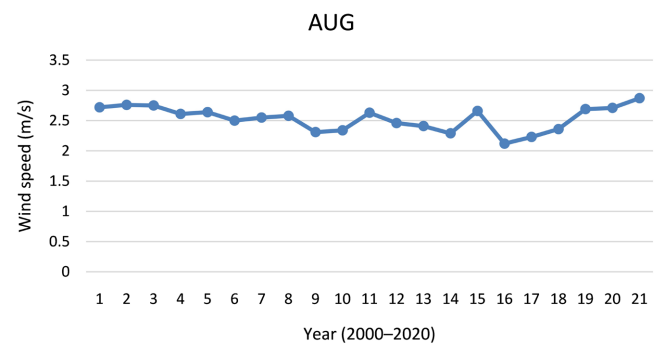
(e)



(f)



(g)



(h)

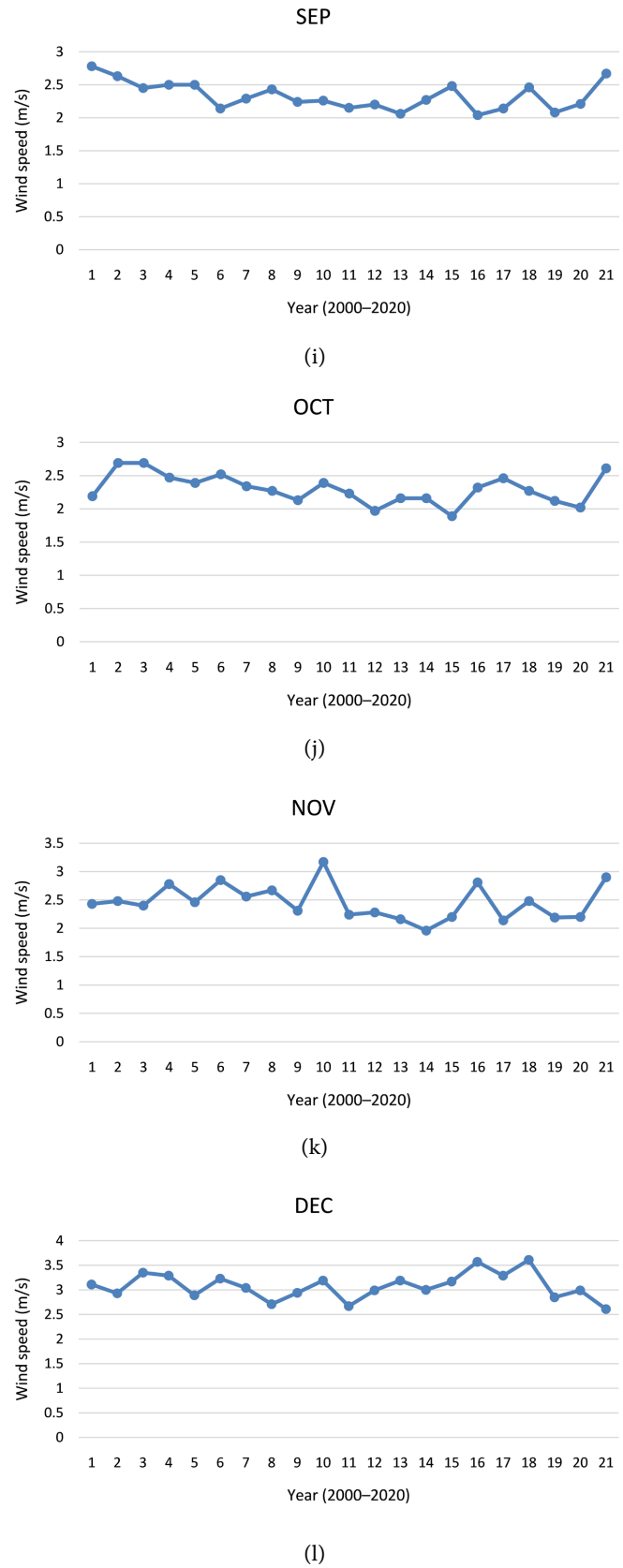


Figure 2. Year-over-year trend in wind speed (2000–2020).

From September, wind speeds gradually recover, with a more marked increase in October. The months of November and December once again record high and regular wind speeds, associated with the return of dry conditions dominated by the Harmattan.

Overall, a period of strong winds can be identified from November to April, a period of weak winds from July to September, and intermediate transition phases that are essential for assessing the wind energy potential.

2.2. Methods

2.2.1. The Weibull Distribution Function

The Weibull distribution, the Weibull parameters were estimated based on the monthly average wind speeds over the 2000-2020 period, comprising 240 observations. For each month, the shape (k) and scale (c) parameters were calculated from 20 observations, while the annual parameters were determined from the full set of 240 observations. This method allows for the description of the statistical behavior of the wind and its variation over the course of the year at the study site, defined by Equation (1), is a two-parameter distribution: the scale parameter c (expressed in m/s) and the shape parameter k (dimensionless). It allows for the precise modeling and characterization of the properties of the wind speed distribution as a function of these two variables [8]-[10]:

$$f(v) = \left(\frac{k}{c}\right) \cdot \left(\frac{v}{c}\right)^{k-1} \cdot \exp\left(-\left(\frac{v}{c}\right)^k\right) \quad (1)$$

where:

- $f(v)$: Wind speed frequency,
- v : Wind speed,
- k : Shape factor (dimensionless), which describes the regularity of the wind regime (the larger k is, the more stable the wind speed);
- c : Scale parameter (in m/s), which corresponds approximately to a wind speed.

2.2.2. Evaluation of Weibull Parameters by the Method of Mean Wind Speed and Variability

This empirical approach consists of estimating k , from the variability of the wind and the average wind speed, whereas c can be calculated from Equation (3). Previous studies (Justus et al., 1976b) have shown that there is a general trend between Weibull k values and standard deviation (or variance in the distribution of wind speeds) as well as mean wind speed. Mathematically, these expressions can be expressed for sites with low (10th percentile), medium, and high (90th percentile) variability. In order to model the behavior of K under different flow regimes, a piecewise approach was chosen, segmenting the evolution of the velocity V into three distinct intervals. This empirical relationship allows us to estimate k under conditions of low, moderate, or high variability.

$$k = \begin{cases} 1.05v_m^{0.5} & \text{if } v < 3 \\ 0.94v_m^{0.5} & \text{if } 3 < v < 4 \\ 0.83v_m^{0.5} & \text{if } v > 4 \end{cases} \quad (2)$$

$$\text{where: } v_m = \frac{1}{n} \sum_{i=1}^n v_i$$

$$c = \frac{v_m}{\Gamma\left(1 + \frac{1}{k}\right)} \quad (3)$$

where:

- v_m : average wind speed (m/s);
- n : total number of observations;
- i : index number of each wind speed observation;
- v_i : wind speed observed during the i^{th} measurement (m/s);
- Γ : represents the gamma function.

2.3. Estimation of Average Wind Power Density

The available energy of a wind with velocity v passing through a surface area S is given by [11]:

$$\bar{P}_d = \frac{1}{2} \rho \bar{v}^3 \quad (4)$$

where:

$$\bar{v}^3 = c^3 \Gamma\left(1 + \frac{3}{k}\right) \quad (5)$$

$$\bar{P}_d = \frac{1}{2} \rho c^3 \Gamma\left(1 + \frac{3}{k}\right) \quad (6)$$

where:

- $\bar{P}_d$: wind power density at the site (in W/m²);
- $\bar{v}^3$: average speed;
- ρ : density (in kg/m³) is approximately 1.225 kg/m³;
- Γ : Gamma function.

2.3.1. Extrapolation of Wind Speed at Different Heights

To obtain good usable power output. Wind speed increases with altitude. Wind speed at different altitudes is extrapolated using the following expression (Justus et al., 1976) [12] [13]:

$$v(z_1) = v(z_0) \times \left(\frac{z_1}{z_0}\right)^\alpha \quad (7)$$

where:

- $v(z_0)$: wind speed measured at the reference height z_0 (m/s);
- $v(z_1)$: speed extrapolated to the target altitude z_1 (m/s);
- z_0 : measurement height;

- z_1 : height of the wind turbine hub;
- α : terrain roughness coefficient.

$$\alpha = \frac{0.37 - 0.088 \ln(v_{z_0})}{1 - 0.00881 \ln\left(\frac{z_0}{10}\right)} \quad (8)$$

There are several approaches to modeling how wind speed varies with height: the modified power law.

$$k_z = \frac{k_{z_0}}{1 - 0.00881 \ln\left(\frac{z}{10}\right)} \quad (9)$$

where:

- k_z : Weibull shape parameter at height z ;
- k_{z_0} : shape parameter measured at 10 m;
- z : new height (m);
- The coefficient 0.00881 is empirical and is derived from statistical studies on the vertical variation of atmospheric turbulence [14].

$$c_z = c_{z_0} \cdot \left(\frac{z}{z_0}\right)^n \quad (10)$$

where:

$$n = \left[0.37 - 0.088 \ln(c_0)\right] \quad (11)$$

where:

- c_z : scale parameter at height z ;
- c_{z_0} : Scale parameter at the reference height z_0 ;
- z_0 : measurement height (often 10 m);
- z target height,
- n : (a factor related to the vertical profile of the wind, often equated with the roughness coefficient α).

2.3.2. Power of a Wind Turbine

1) Modeling of average usable power

Given the variability of wind speed and the characteristics of a wind turbine as a function of its start-up speed v_1 , nominal speed v_n , and shutdown speed v_s , the usable power of a wind turbine is given by Equation (12) [15][16]:

$$\langle P_u \rangle = \frac{1}{2} \rho A \langle v_u^3 \rangle \quad (12)$$

where:

- $\langle P_u \rangle$: average usable power;
- $\langle v_u \rangle$: wind speed at height v_u (m/s);
- ρ : density $\rho = 1.225 \text{ kg/m}^3$;
- A : area swept by the blades.

The speed v_u is derived from the curve representing the Weibull distribution within the machine's operating limits. The lower limit is represented by the starting speed. Only speeds greater than the starting speed v_i are taken into account in the calculation. In the second case, when the nominal speed v_n is reached, an increase in wind speed has no effect on the impeller's operating speed. Finally, when the stopping speed v_s is reached, the system is automatically braked, and speeds higher than this do not factor into the calculation of v_u [13]. The mathematical expression for the usable power density is given by Equation (13):

$$\langle P_u \rangle = \begin{cases} 0 & \text{for } v < v_i \\ \frac{1}{2} \rho \langle v^3 \rangle & \text{for } v_i \leq v \leq v_n \\ \frac{1}{2} \rho v_n^2 & \text{for } v_n \leq v \leq v_s \\ 0 & \text{for } v > v_s \end{cases} \quad (13)$$

The average usable cubic velocity (Equation (14)) is obtained by integrating the cubic velocity weighted by the probability function, using the limits specified by the turbine manufacturer as the integration bounds [17][18].

$$\langle v_u^3 \rangle = \int_{v_i}^{v_n} f(v) v^3 dv + v_n^3 \int_{v_n}^{v_s} f(v) dv \quad (14)$$

Either by integration using the normalized gamma distribution:

$$\begin{aligned} \langle \overline{v_u^3} \rangle = & \left[\Gamma_n \left(\left(\frac{v_n}{c} \right)^k, 1 + \frac{3}{k} \right) - \Gamma_n \left(\left(\frac{v_i}{c} \right)^k, 1 + \frac{3}{k} \right) \right] \overline{v^3} \\ & + v_n^3 \left[\exp \left(- \left(\frac{v_n}{c} \right)^k \right) - \exp \left(- \left(\frac{v_s}{c} \right)^k \right) \right] \end{aligned} \quad (15)$$

where:

$$\Gamma(n) = \int_0^{+\infty} e^{-t} \cdot t^{n-1} \cdot dt \quad (16)$$

2) Wind Turbine Output Power and Capacity Factor

Each wind energy conversion system is designed to operate at maximum efficiency within the limits of the rated wind speed and power. Therefore, once the Weibull scale and shape parameters are estimated, the performance of a wind turbine at a given location can be easily calculated using the average power and the capacity factor. In this work, the electrical power of a model wind turbine is simulated using

Equation [19] [20].

$$P_e = \begin{cases} 0 & (v < v_d) \\ P_{en} \frac{v^k - v_d^k}{v_n^k - v_d^k} & (v_d \leq v \leq v_n) \\ P_{en} & (v_n \leq v \leq v_c) \\ 0 & (v_c < v) \end{cases} \quad (17)$$

where:

- P_{en} : rated electrical power;

- v_d : the wind turbine's start-up speed;
- v_n : rated speed;
- v_c Cutting speed.

The power generated by a wind turbine is given by Equation (18):

$$P_u = C_f P_n \quad (18)$$

where:

$$C_f = \left[\frac{e^{-\left(\frac{V_d}{c}\right)^k} - e^{-\left(\frac{V_n}{c}\right)^k}}{\left(\frac{V_n}{c}\right)^k - \left(\frac{V_d}{c}\right)^k} - e^{-\left(\frac{V_a}{c}\right)^k} \right] \quad (19)$$

Thus, the output power of a wind turbine can be expressed as:

$$P_u = \left[\frac{e^{-\left(\frac{V_d}{c}\right)^k} - e^{-\left(\frac{V_n}{c}\right)^k}}{\left(\frac{V_n}{c}\right)^k - \left(\frac{V_d}{c}\right)^k} - e^{-\left(\frac{V_a}{c}\right)^k} \right] P_n \quad (20)$$

C_f is the capacity factor, which plays a very important role in the evaluation of a wind farm site. The capacity factor can be estimated based on Weibull parameters and the various operating speeds provided by the turbine manufacturer. The rated power P_n of a wind turbine is provided by the manufacturer. Knowing the useful power produced by a wind turbine, we can calculate the energy produced by a wind turbine over a given period.

2.4. Statistical Validation Metrics

To assess the reliability of NASA POWER wind speed data relative to *in situ* measurements, three statistical indicators were used. These parameters allow for an analysis of the accuracy and discrepancies between satellite data and ground-based observations [21]. **Table 2** presents the various indicators along with their mathematical expressions.

Table 2. Statistical criteria for validating NASA POWER data against meteorological station measurements.

N°	Indicators	Relationship	Settings
1	RMSE (Root Mean Square Error)	$RMSE = \sqrt{\frac{1}{n} \sum_{i=1}^n (S_i - M_i)^2}$	S_i : Satellite values M_i : Measured values (<i>in situ</i>) n : Total number (Observer)
2	RRMSE (Relative Root Mean Square Error)	$RRMSE = \frac{\sqrt{\frac{1}{n} \sum_{i=1}^n (S_i - M_i)^2}}{\frac{1}{n} \sum_{i=1}^n M_i}$	S_i : Satellite values M_i : VMeasured values (<i>in situ</i>) n : Total number (Observer)
3	X^2 (Test du khi-deux)	$X^2 = \frac{1}{n} \sum_{i=1}^l \sum_{j=1}^c \frac{(O_{ij} - T_{ij})^2}{T_{ij}}$	O_{ij} : Observed counts T_{ij} : Theoretical counts l, c : Number of rows and columns

Data Validation

Data from NASA were compared with *in situ* (local) data to validate their reliability. Analysis of **Table 3** shows a strong overall correlation between locally observed and satellite wind speeds, with very similar annual averages (3.12 m/s versus 2.94 m/s). Over the course of the year, the model demonstrates solid accuracy, as evidenced by an overall root mean square error (RMSE = 0.29 m/s) and a low relative error (RRMSE = 9.42%), with the chi-square value reaching an average of 0.3346, attesting to the reliability of the data.

Table 3. Error calculations.

PERIOD	OBSERVED	PREDICTED	RMSE	RRMSE (%)	CHI-SQUARE
JAN	3.82	3.89	0.07	1.83	0.0013
FEB	4.54	4.23	0.31	6.83	0.0212
MAR	3.98	3.75	0.23	5.78	0.0133
APR	3.56	3.31	0.25	7.02	0.0176
MAY	3.19	3.07	0.12	3.76	0.0045
JUN	2.79	2.72	0.07	2.51	0.0018
JUL	2.39	2.39	0.00	0.00	0.0000
AUG	2.58	2.13	0.45	17.44	0.0785
SEP	2.06	1.88	0.18	8.74	0.0157
OCT	2.26	2.08	0.18	7.96	0.0143
NOV	3.21	2.53	0.68	21.18	0.1440
DEC	3.01	3.27	0.26	8.64	0.0225
ANNUAL	3.12	2.94	0.29	9.42	0.3346

3. Results and Discussion

This section focuses on the analysis and interpretation of the data to transform raw potential into an energy exploitation strategy.

3.1. Periodic Wind Variation

Wind speed data collected at the NASA POWER site over two decades (2000-2020) are presented in **Table 4** and allowed us to map the wind energy potential of the study area (see **Figures 3-5**).

Table 4. Wind speed data at a height of 10 m for the period 2000-2020.

Month	Jan	Feb	Mar	Ap	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Annual
V_{moy}	3.52	3.89	3.78	4.04	3.61	3.10	2.84	2.53	2.33	2.30	2.46	3.08	3.12
V_{mini}	0.42	0.65	0.25	0.18	0.16	0.19	0.14	0.11	0.10	0.12	0.20	0.49	0.10
V_{max}	7.98	8.87	8.92	8.37	7.68	6.78	6.48	5.80	5.02	5.04	5.62	6.87	8.92

Table 4 shows an actual average annual wind speed of approximately 3.12 m/s,

with peaks in February–March (up to 8.92 m/s) and lows from August through October. This seasonal variability indicates moderate wind potential, suitable for small rural projects. The low minimum wind speeds suggest the need for a hybrid system or energy storage to ensure energy continuity.

3.2. Maps of Wind Potential Based on Wind Speed Variation

The wind potential maps (**Figures 3–5**) were generated using NASA POWER data with a spatial resolution of $0.5^\circ \times 0.5^\circ$. The grid points covering the study area were imported into QGIS and interpolated using the IDW (Inverse Distance Weighting) method to produce continuous surfaces. Given the small number of grid cells available within the study area, the results should be considered an indicative assessment of wind potential at the site scale rather than a detailed representation of local variations.

3.2.1. Map of Wind Potential Based on the Annual Average Wind Speed in Baktchoro

Figure 3 illustrates the spatial distribution of annual average wind speeds in the area between 3.11 m/s and 3.13 m/s.

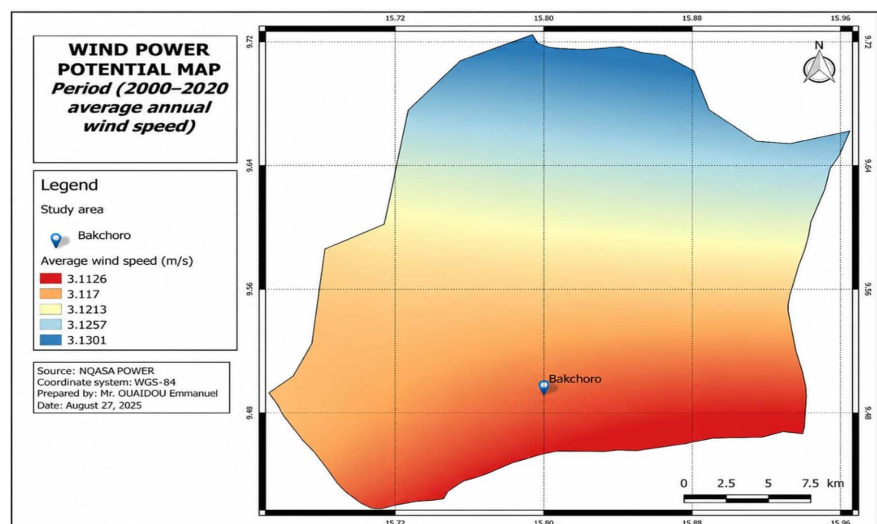


Figure 3. Map of wind energy potential based on the average annual wind speed in Baktchoro.

The map of wind potential based on average annual wind speed shown in **Figure 3** indicates a relatively modest but consistent wind regime. The northern part shows slightly higher speeds (3.125 to 3.13 m/s), while the southern and central areas record lower values. These results suggest that, although wind resources are not very abundant, they remain viable for small- to medium-scale projects, particularly when combined with solar photovoltaics.

3.2.2. Map of Wind Potential Based on the Annual Minimum Wind Speed in Baktchoro

Figure 4 shows the annual minimum wind speeds in areas with low wind speeds.

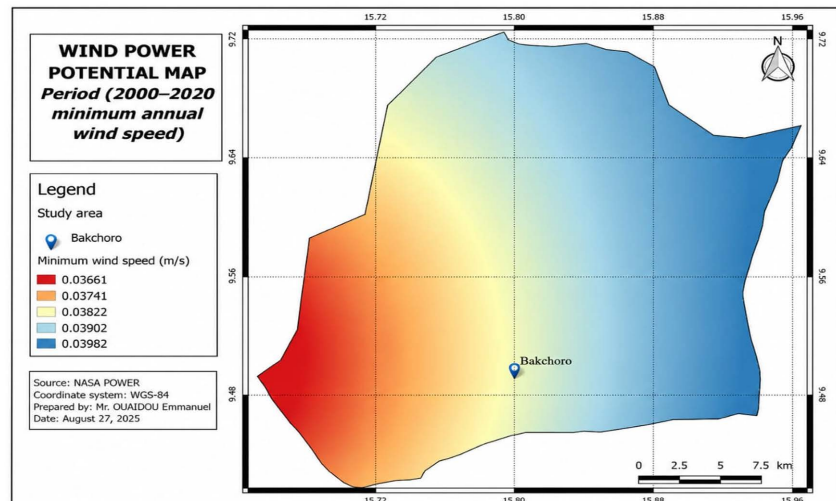


Figure 4. Map of wind energy potential based on the minimum annual wind speed in Bakchoro.

The wind potential map based on the minimum annual wind speed (**Figure 4**) shows relatively low wind speeds, below 2.5 m/s. These relatively low values indicate periods of the year when wind power's contribution to the energy mix would be marginal. It is noted that the western and central areas are most affected by these low speeds, while the far north retains slightly higher potential. This spatial heterogeneity reflects the interannual variability of wind patterns and underscores the need for complementarity with other renewable energy sources.

3.2.3. Map of Wind Energy Potential Based on the Annual Maximum Wind Speed in Bakchoro

Figure 5 shows the annual maximum wind speeds during the periods most favorable for wind energy production.

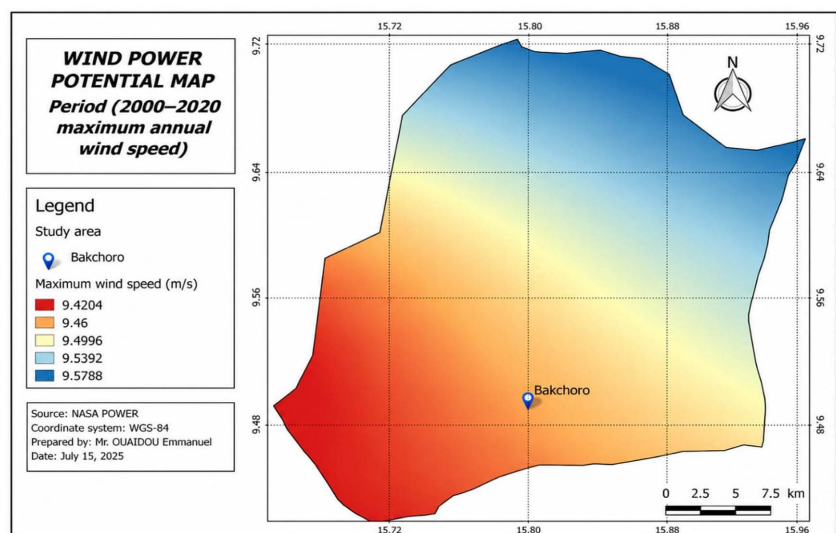


Figure 5. Map of wind energy potential based on the maximum annual wind speed in Bakchoro.

The map in **Figure 5** shows high wind speeds in the southeastern part of Baktchoro, where seasonal peaks can be harnessed. This is particularly true during climatic transition periods (the dry and rainy seasons). The disparity between areas with high wind intensity and those with low wind speeds confirms the spatial and temporal variability of the resource. These observations reinforce the value of integrated energy planning, favoring hybrid systems to compensate for occasional shortfalls in wind power.

3.3. Baktchoro Wind Rose Diagram

The wind rose for the Baktchoro area is an essential diagnostic tool that allows for the visualization of the statistical distribution of wind directions and their associated intensities. This Cartesian or polar representation is crucial for several technical reasons.

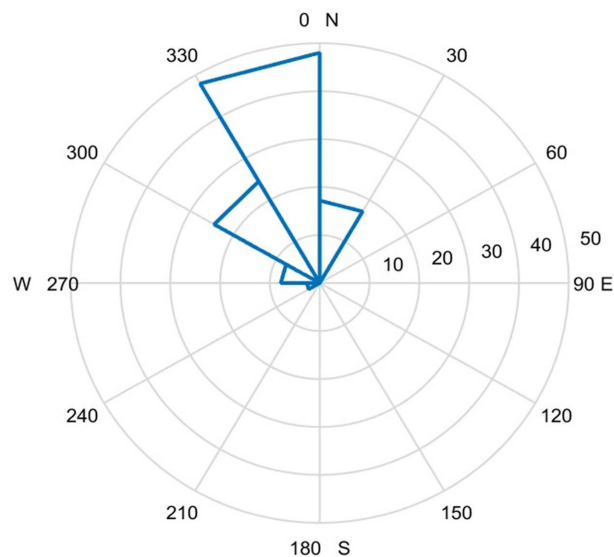


Figure 6. Compass rose of the Baktchoro site.

Figure 6 of the Baktchoro wind rose reveals a highly directional wind pattern dominated by the north-northwest sector, which optimizes aerodynamic efficiency by minimizing repositioning losses. The consistent wind direction observed throughout the 2000-2020 reanalysis period reflects the stability of wind conditions at the site and supports its potential for the deployment of decentralized power generation systems, despite the lack of local anemometric data.

3.4. Extrapolation of Wind Data at Different Altitudes

Weibull Results for Each Height

Wind speed data collected at the NASA POWER site are used to determine the monthly variations in Weibull statistical parameters at a height of 10 meters. These values are then extrapolated to heights of 30 m, 50 m, 80 m, and 100 m. The results are presented in **Tables 5-9**.

Table 5. Weibull results at a height of 10 m.

Month	Height: 10 m			
	V_{moy} (m/s)	$C_{weibull}$ (m/s)	$K_{weibull}$	P (W/m ²)
JAN	3.52	3.95	1.76	58.28
FEB	3.89	4.38	1.85	74.49
MAR	3.78	4.25	1.82	68.98
APR	4.04	4.56	1.88	81.91
MAY	3.61	4.05	1.79	61.42
JUN	3.1	3.46	1.66	43.02
JUL	2.84	3.19	1.39	30.46
AUG	2.53	2.84	1.32	23.35
SEP	2.33	2.6	1.27	19.17
OCT	2.3	2.56	1.26	18.49
NOV	2.46	2.75	1.29	21.6
DEC	3.08	3.44	1.65	42.27

Table 6. Weibull results at a height of 30 m.

Month	Height: 30 m			
	$V_{weibull}$ (m/s)	$C_{weibull}$ (m/s)	$K_{weibull}$	P (W/m ²)
JAN	4.68	5.25	1.75	138.29
FEB	5.17	5.82	1.84	175.88
MAR	5.02	5.65	1.82	163.01
APR	5.38	6.06	1.88	193.53
MAY	4.79	5.38	1.78	145.31
JUN	4.11	4.59	1.64	101.64
JUL	3.78	4.25	1.76	72.37
AUG	3.37	3.77	1.66	55.15
SEP	3.1	3.46	1.59	45.46
OCT	3.06	3.41	1.58	44.11
NOV	3.27	3.66	1.64	51.19
DEC	4.09	4.57	1.64	100.16

Table 7. Weibull results at a height of 50 m.

Month	Height: 50 m			
	$V_{weibull}$ (m/s)	$C_{weibull}$ (m/s)	$K_{weibull}$	P (W/m ²)
JAN	5.34	5.9	1.75	195.74
FEB	5.9	6.44	1.84	238.36
MAR	5.73	6.28	1.81	225.69
APR	6.14	6.67	1.88	257.95
MAY	5.47	6.03	1.77	205.76

Continued

JUN	4.7	5.27	1.64	153.44
JUL	4.31	4.91	1.76	111.94
AUG	3.84	4.44	1.66	90.06
SEP	3.54	4.12	1.59	77.05
OCT	3.49	4.07	1.58	75.07
NOV	3.73	4.32	1.63	85.33
DEC	4.67	5.24	1.63	152.29

Table 8. Weibull results at a height of 80 m.

Month	Height: 80 m			
	V_{weibull} (m/s)	C_{weibull} (m/s)	K_{weibull}	P (W/m ²)
JAN	6.03	6.63	1.74	279.98
FEB	6.66	7.21	1.84	334.49
MAR	6.47	7.04	1.81	317.94
APR	6.93	7.45	1.87	361.76
MAY	6.18	6.77	1.77	291.19
JUN	5.30	5.95	1.64	220.82
JUL	4.87	5.57	1.75	164.70
AUG	4.34	5.06	1.65	134.54
SEP	4.00	4.71	1.59	115.12
OCT	3.94	4.66	1.57	113.89
NOV	4.22	4.93	1.63	126.82
DEC	5.27	5.92	1.63	219.60

Table 9. Weibull results at a height of 100 m.

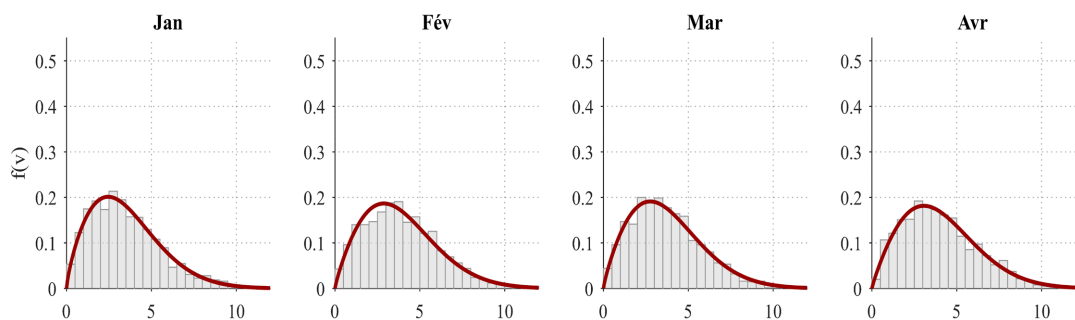
Month	Height: 100 m			
	V_{weibull} (m/s)	C_{weibull} (m/s)	K_{weibull}	P (W/m ²)
JAN	7.06	7.61	1.83	330.93
FEB	6.86	7.43	1.81	396.00
MAR	7.34	7.86	1.87	373.76
APR	6.55	7.16	1.77	424.83
MAY	5.62	6.31	1.63	344.47
JUN	5.16	5.91	1.75	265.92
JUL	4.6	5.38	1.65	196.74
AUG	4.23	5.03	1.58	161.71
SEP	4.17	4.97	1.57	141.70
OCT	4.47	5.25	1.63	138.16
NOV	5.59	6.28	1.63	153.16
DEC	6.39	7.01	1.74	262.15

Analysis of the wind data collected at the Baktchoro site, presented in **Tables 5-9**, reveals seasonal variability in wind potential, which is strongly influenced by elevation. At a height of 10 m, average wind speeds range from 3.5 to 4.0 m/s during the dry season, particularly between January and April. They then decrease significantly during the wet season, from July to October, with values ranging from 2.3 to 2.8 m/s. The effect of height appears to be a determining factor in assessing the resource. Due to the vertical velocity gradient, winds become significantly more favorable at higher altitudes, reaching, for example, 7.06 m/s at 100 m in January. Furthermore, the relative stability of the coefficients of variation indicates a certain regularity in the structure of the wind resource, despite the observed seasonal fluctuations. The estimate of available wind power confirms this dependence on both season and altitude. The highest performance is achieved in April, with a maximum power estimated at 424.83 W/m² at 100 m, while the minimum is recorded in October, at 138 W/m² at the same height. This difference reflects the strong seasonality of the winds at the site, characterized by greater potential during the dry season and a notable weakening during the rainy season. The effect of hub height is also very clear. For example, in January, the estimated power output increases from 58 W/m² at 10 m to 330.93 W/m² at 100 m. This result confirms the benefits of using tall towers to optimize the utilization of wind energy resources. Overall, these results demonstrate the suitability of a hybrid photovoltaic-wind architecture for the Baktchoro site. Wind power generation, which is more favorable during the dry season, can effectively complement photovoltaic generation, which remains particularly useful when winds weaken during the wet season. This complementarity would ensure more stable and sustainable electricity production, while reducing the intermittency associated with the use of a single energy source.

3.5. Frequency Distribution of Wind Speeds at Baktchoro

Figure 7 and **Figure 8** present the frequency distribution of wind speed. The goal is to reproduce the frequency dynamics observed in the Weibull parameters on a monthly and annual basis.

An analysis of **Figure 8** shows a low-intensity wind resource. The prevailing wind speed is below 3 m/s. Selecting wind turbines suitable for “small-scale wind power” with a very low cut-in speed ideally around 2 m/s will be crucial for harnessing this energy.



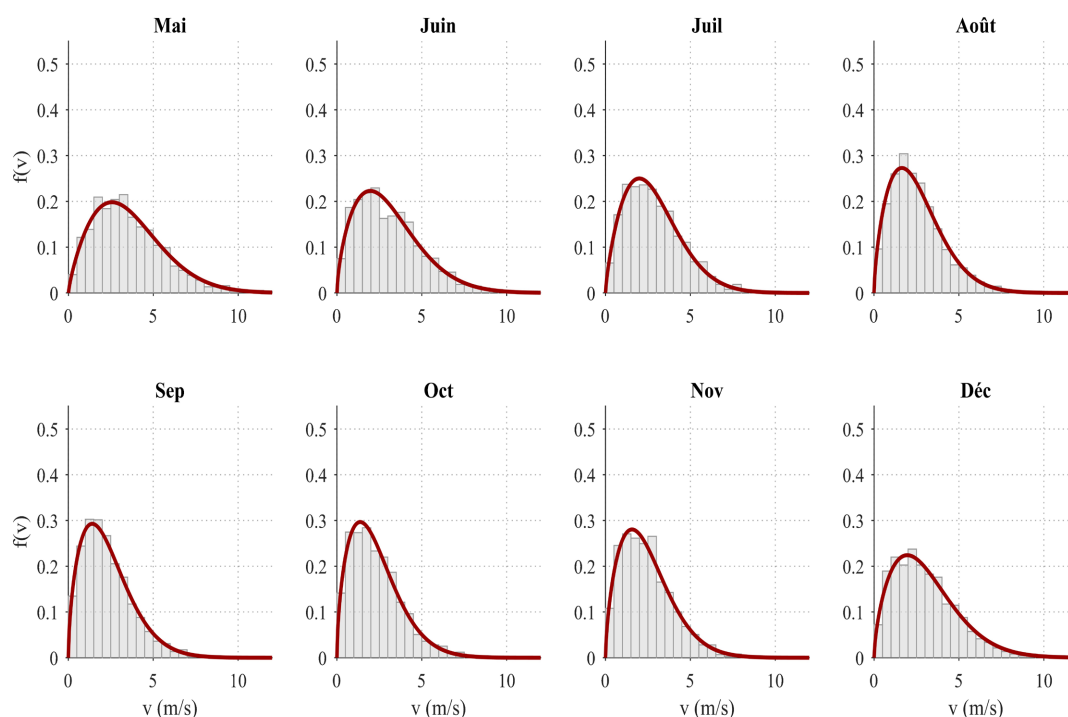


Figure 7. Weibull monthly distribution.

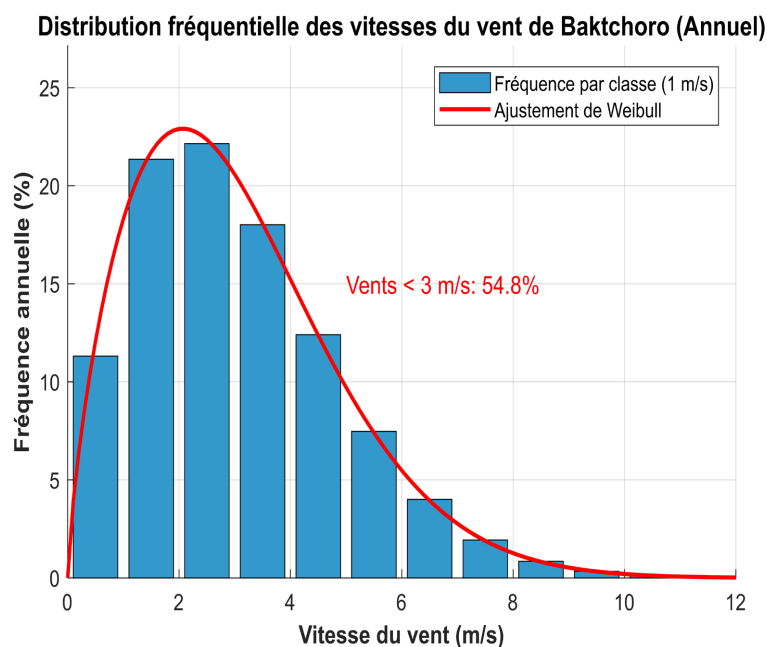


Figure 8. Weibull frequency distribution.

Figure 8 shows the annual frequency distribution of wind speeds at a height of 10 m. The good agreement between the histogram of observed frequencies and the theoretical Weibull distribution confirms that the shape parameter k and scale parameter c are representative of the local wind regime. The results highlight low wind potential, characterized by dominant speeds close to 2 m/s and an unavaila-

bility rate of 54.8%. Under these conditions, the use of wind energy alone remains limited, requiring the integration of a hybrid system combining photovoltaics and energy storage. The use of wind turbines with a low start-up speed, on the order of 2 m/s, as well as increasing the height of the towers, would improve the site's energy performance.

3.6. Technical Specifications of Wind Turbines in the Study Area

3.6.1. Selection of Wind Turbines

Table 10 presents the technical specifications of four models of low-power wind turbines suitable for harnessing the wind energy potential in the Baktchoro area. Under real-world operating conditions, each turbine was evaluated at its manufacturer-specified hub height. The calculated performance figures thus take into account two key factors: the impact of height on wind speed (since available power increases with the cube of wind speed) and the effect of rotor diameter on the energy capture area. First, the start-up speeds of these wind turbines are relatively low, ranging from 2.5 m/s to 2.8 m/s. This facilitates rapid activation under moderate wind conditions, enabling energy production as soon as the wind begins to blow. Second, the rated speeds, which range from 10 m/s to 11 m/s, represent the optimal conditions for achieving maximum power output. This is crucial for the profitability of the installations, as efficient energy production depends on these speeds. Wind turbines also have a cut-off speed of 25 m/s, demonstrating their resilience in extreme wind conditions. This feature ensures the safety and durability of the installations, preventing potential damage during storms. In terms of dimensions, rotor diameters and tower heights vary from model to model. For example, the Bergey Excel 10, with a rotor diameter of 10.2 m, has a larger capture area, allowing it to generate more energy. Finally, the rated power of the wind turbines ranges from 1 kW (for the Wind Spire) to 10 kW (for the Bergey Excel 10), offering flexibility to meet various energy needs, from residential applications to larger installations. **Figure 9** shows the performance curves for these wind turbines. The reason for this selection is the low wind speeds in the Baktchoro area, located in the Sudanese region of Chad.

Table 10. Technical specifications of the wind turbines; selected wind turbine types.

Wind turbine	Starting speed	Rated speed	Stopping speed	Rotor diameter or	Mast height	Rated power
Bergey Excel 10	2.5 m/s	10 m/s	25 m/s	10.2 m	30 m	10 Kw
Skystream 3.7	2.5 m/s	11 m/s	25 m/s	3.7 m	30 m	2.4 kW
Aermotor 602	2.8 m/s	10 m/s	25m/s	6 m	27 m	2.5 kW
Wind spire	2.5 m/s	11 m/s	25 m/s	2.1m	25 m	1 kW

Figure 9 shows the power curves of four wind turbines A1 (Bergey Excel 10), A2 (Skystream 3.7), A3 (Aermotor 602), and A4 (Windspire) as a function of wind speed.

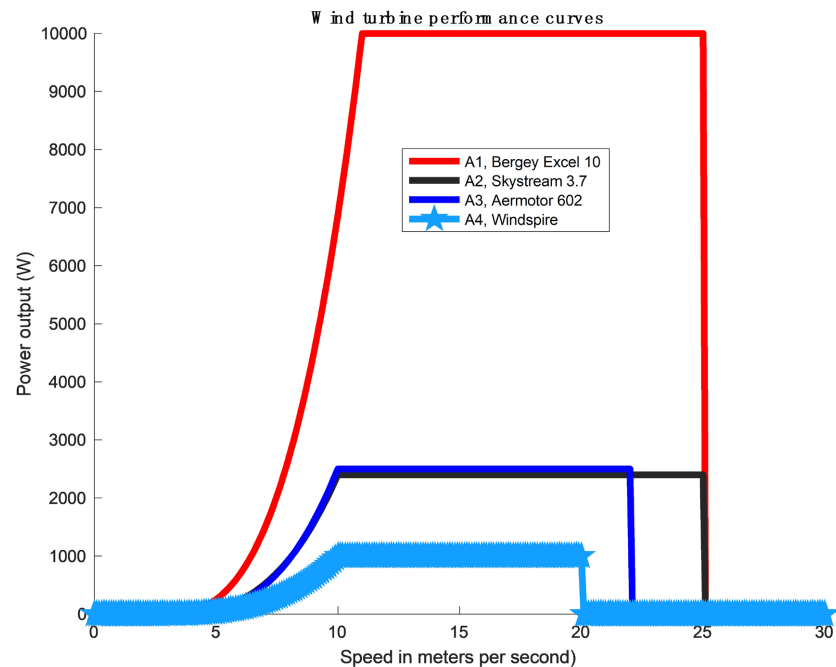


Figure 9. Wind turbine performance curve.

Figure 9 shows the power curves of four wind turbines as a function of wind speed. All turbines exhibit a classic three-phase behavior: no power output below the start-up speed (3 - 4 m/s), a rapid increase in power up to the rated speed (≈ 10 - 11 m/s), and then stabilization at a constant power level before the safety cut-off. The Bergey Excel 10 achieves the highest rated power (≈ 10 kW), while the other three models generate power ranging from 1 to 2.5 kW. However, in a context of moderate wind conditions characterized by low average speeds, actual operation depends primarily on low-speed performance rather than rated power. Thus, the technological choice should prioritize turbines suited to low wind speeds and optimized for frequent operation in the sub-rated power range, particularly in a hybrid configuration with solar photovoltaics.

3.6.2. Wind Power Generated by Wind Turbines

Table 11 shows the power generated by various wind turbines at their respective mast heights, as well as the capacity factors for each turbine. The results obtained which include the power generated by the different wind turbines and their capacity factors serve as relevant indicators for evaluating the energy performance of these systems. The capacity factor reflects the ratio of the energy actually generated to the maximum theoretical energy that can be generated over a given period. The results show that the Bergey Excel 10 performs best among the wind turbines studied, with a generated power of 3.56 kW and a capacity factor of 36%. These values indicate an efficient utilization of available wind potential as well as a greater ability to convert wind energy into electrical energy. The Skystream 3.7 model generates a lower power output, estimated at 0.75 kW, but nevertheless exhibits a relatively high-capacity factor of 31%. This performance reflects good

energy efficiency, particularly given its size and rated power. The Aermotor 602 produces approximately 0.82 kW with a capacity factor of 32%. These results show intermediate energy performance, reflecting a relatively satisfactory conversion of available wind energy. Finally, the Windspire has the lowest power output, at 0.32 kW, with a capacity factor of 32%. Despite its low energy production, this system maintains a level of efficiency comparable to that of some higher-capacity wind turbines, which can be an advantage for low-power applications or sites with moderate wind resources.

Table 11. Generated power and capacity factors at the Baktchoro site.

Wind turbine	Power output (P_u)	Capacity factor (C_f)
Bergey Excel 10	3.56 kW	0.36
Skystream 3.7	0.75 kW	0.31
Aermotor 602	0.81 kW	0.32
Wind spire	0.32 kW	0.32

3.7. Comparison of Results with Previous Work in the Field

The results obtained in this study show an interesting consistency with previous work conducted by researchers in the field of wind energy. In particular, the values of the scale factor (c) and shape factor (k) are nearly identical to those reported by Kidmo Kaoga in Cameroon in 2016 [22], as well as those established by Mahamat Kher Nediguina in 2022 [23]. This similarity suggests that our results are part of a solid scientific tradition and validates the methods used in our research. Furthermore, the wind power generated by the various small-scale wind turbines is consistent with the results of Fia Oung-zetna in 2025 [24]. This reinforces the idea that the measured performance is representative of the actual capabilities of these wind technologies, thereby confirming their potential within the context of local renewable energy solutions. In summary, the similarities observed between our results and those of previous studies underscore the robustness of our analyses and contribute to the establishment of a reliable reference framework for future evaluations in the field of wind energy. These consistencies also point to a general trend that can be leveraged to optimize the implementation of wind turbines in various contexts.

Limitations of the Study and Future Directions

Despite the relevance of the results obtained, certain limitations should be noted. The analysis is based on NASA POWER data, whose spatial resolution may not accurately reflect local microclimatic conditions. Furthermore, validation was performed using data from a single weather station, which may limit the spatial representativeness of the assessment. Other simplifying assumptions, notably the assumption of constant air density and the extrapolation of wind speeds from 10 m to 100 m in height, also constitute potential sources of uncertainty. Thus, the results presented should be considered as an initial assessment of the site's wind

energy potential. Future work would benefit from incorporating *in situ* anemometric measurement campaigns over several years at different heights, as well as more detailed modeling of local atmospheric conditions, in order to improve the reliability of estimates and support investment decisions in wind energy projects.

4. Conclusions

The study of the wind potential of the Baktchoro site, based on the Weibull distribution at different heights, highlights a seasonal wind resource, moderate near the ground but more favorable at altitude. At 10 m, the average monthly speeds range from 2.30 to 4.04 m/s, indicating a light to moderate wind regime. Vertical extrapolation, however, shows a significant improvement in the reservoir, with speeds reaching 7.34 m/s at 100 m height and a maximum power density of 424.83 W/m² in April. The values of the Weibull form factor, between 1.26 and 1.88, reflect a significant variability in the wind, characteristic of the Sahelian zones. The frequency analysis reveals that 54.8% of the winds are less than 3 m/s, which requires the choice of wind turbines with low start-up speeds. Among the turbines studied, the Bergey Excel 10 has the best performance, with an estimated output of 3.56 kW and a capacity factor of 0.36. These results show that the site has exploitable potential for small and medium power applications, particularly in the dry season and at great heights. The main contribution of this paper lies in the detailed characterization of the Baktchoro wind field at several heights, the identification of the most favorable periods for production and the comparison of small wind turbines adapted to low-speed regimes. At the end of this work, we make the following recommendations:

- To the political authorities (Ministry of Petroleum and Energy, ARCET):
 - ✓ Decentralize the electro-energy system;
 - ✓ Promote renewable energies.
- To the electricity operator TCHADLEC:
 - ✓ Integrate wind power into its action plan.

Despite the uncertainties inherent in satellite data and the extrapolations discussed earlier, this study demonstrates the technical feasibility of a wind-solar hybrid system for the village of Baktchoro. The aim of this study is to provide a useful scientific basis for the design of a hybrid photovoltaic-wind energy system capable of improving the stability of power generation and supporting the sustainable electrification of remote areas.

Conflicts of Interest

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

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Abbreviations and Acronyms

$f(V)$: Weibull's Distribution Function	$\langle v_u^3 \rangle$: Mean cubic wind speed, m/s
c : Scale factor	P_{en} : nominal electrical power
k : Form Factor	P_u : Useful Power,
Γ : GAMMA function	P_r : Rated power, W
C_p : Power Coefficient	P_d : Average available wind potential, W/m ²
v_m : average wind speed m/s	v_d : Starting speed, m/s
A : The surface swept by a propeller, m ²	v_r : Rated speed, m/s
	ARSAT: Regulatory Authority for the Downstream Petroleum Sector of Chad
	TCHADLEC: Chadian Electricity Company.