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RESEARCH ARTICLE

EFFICIENCY OF SMALL WIND TURBINES IN THE DESERT OF CHAD FOR WATER PUMPING AT KOUBA OLANGA

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ABSTRACT

Access to drinking water and electricity is a major challenge in desert regions like Kouba Olanga in Chad. Renewable energy, in particular wind power, offers a promising solution for pumping water and improving living conditions for local populations. Kouba Olanga, located 740 km from N'Djamena, suffers from a crying lack of water and electricity. The average annual wind speed of 4.64 m/s offers significant wind potential for pumping water. Water is of vital importance for both humans and animals that drink from the same water source. The study uses Weibull and Rayleigh distribution functions to determine wind probability densities. Wind speed analysis shows wide bandwidths and high speeds. Three small pumping turbines were selected for application on site: VESTASV15, VESTASV10 and AEOLOS-H30. The AEOLOS-H30 wind turbine has the best capacity factor with an annual average of 0.39, exceeding international standards. The VESTASV15 and VESTASV10 wind turbines have capacity factors below the standard (0.26). The AEOLOS-H30 wind turbine generates a maximum daily water flow of 3,000 m3/day and an annual average of 1,729.4 m3/day at a head of 50m. The other wind turbines have lower outputs: VESTASV15 with an annual average flow of 1466.7 m3/day and VESTASV10 with a maximum flow of 600 m3/day. The use of the AEOLOS-H30 wind turbine for water pumping in Kouba Olanga is proving to be an effective and sustainable solution for access to drinking water. Wind energy offers great potential for developing rural areas and improving living conditions for populations in desert regions.

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INTRODUCTION

The world is facing growing energy challenges, characterized by the increasing scarcity of fossil fuels and their harmful impacts on the environment, such as air and water pollution, drought, floods, and other extreme climatic events. This situation is plunging the world's population into an apocalyptic energy chaos (1, 2). The need to turn to renewable energy sources has become an urgent necessity. Renewable energies are inexhaustible energy sources derived from natural phenomena (3). They include solar, wind, hydro, geothermal, biomass, and biofuels (4). Unlike fossil fuels, they do not emit greenhouse gases and contribute to ecological transition (5). The development of renewable energies promotes the balance among energy sectors, reduces dependence on polluting energies, and stimulates technological innovation in key areas such as energy storage and distribution (6). Renewable energies, such as wind power, are playing an increasingly important role in the global energy landscape (7, 8). Wind power is of vital importance in desert areas. These regions offer excellent wind potential thanks to their vast, flat expanses and stable winds blowing at high speeds (9, 10). This makes wind power an ideal solution for diversifying the energy mix in these areas, which are often deprived of other traditional resources such as fossil fuels or hydroelectricity (1). Wind power can be used to electrify isolated communities, improving access to electricity for them (11, 12). It can also be used to irrigate crops, which contributes to food security. What's more, as a renewable energy source, wind power plays a crucial role in the adaptation and resilience of these regions to the impacts of climate change (13). Overall, wind power represents a sustainable and appropriate solution to the energy, environmental, and social challenges of desert areas (13)(14). Chad is a country in Central Africa, landlocked between the Sahara in the north and the savannah in the south. Covering an area of 1,284,000 km², it is the fifth largest country in Africa. Despite its vast desert expanses to the north, Chad faces serious energy challenges. The climate is tropical arid, characterized by a prolonged dry season and irregular rainfall (15). Access to drinking water and electricity is particularly problematic (16, 17). Only a small

fraction of the population has access to electricity, mainly concentrated in urban areas. Rural areas, home to the majority of the population, suffer from a dire lack of energy infrastructure (15). This situation is hampering the country's economic and social development. Sustainable solutions, such as solar and wind power, would be essential for meeting these energy and water supply challenges in this vast desert country (11).

The Bodélé Triangle in northeastern Chad is a region of particular interest for wind power (18). This vast desert depression is known to be one of the windiest areas in the world, with gusts reaching very high speeds (18, 19). These constant, powerful winds make it a prime site for the development of wind power (20). The study of wind energy potential in Kouba Olanga is justified by the essential issues at stake, which have a direct impact on the quality of life of the region's inhabitants. First of all, it is crucial to highlight the pressing need for drinking water faced by the local population. Limited access to this vital resource is a major concern, compromising the health and well-being of local residents. In addition, the health risks associated with the quality of the available water in the region are a cause for concern. The presence of contaminants and the spread of waterborne diseases represent serious threats to public health, requiring urgent action. Moreover, the cohabitation of inhabitants and animals for access to water creates situations conducive to cross-contamination and the development of transmissible diseases, jeopardizing the health of the local population. The region's desert climate further aggravates the situation, making access to water even more vital, especially in times of drought when water requirements are heightened. Finally, Kouba Olanga's geographical remoteness from N'Djamena complicates water supply, underlining the importance of a sustainable, self-sufficient solution to meet the population's drinking water needs. By using wind power to pump water, it is possible to provide an effective and sustainable response to these challenges, guaranteeing a reliable supply of drinking water (21, 22), improving the living conditions of the inhabitants, and safeguarding public health. Harnessing wind power to pump water represents a promising solution to the challenges of providing access to drinking water in this small, isolated desert town. The aim of the present study is to analyze the efficiency of small wind turbines in the specific context of this area, where the average wind speed is 4.5 m/s. Considering the information provided above, it is essential to assess the advantages and limitations of this technology, as well as its potential impact on the quality of life of the local population. In a context where access to drinking water is crucial for public health and the well-being of local residents, the use of wind energy for water pumping appears to be a sustainable and autonomous alternative. To complete this article, we have structured it as follows: Section I provides a general introduction, Section II presents the study area, materials, and methods, Section III discusses the results and the different Weibull and Rayleigh distributions, along with their application to small wind turbines for pumping applications, and we conclude with a final section.

MATERIALS AND METHODS

Study equipment: The present work, based on the study of wind energy potential for applications in electricity generation and water pumping, requires the use of equipment for the collection, analysis, and processing of meteorological data. In our case, given the isolation and lack of measuring equipment in the field, the data we use are derived from NASA satellite sources. The wind speed data span from 2000 to 2022. The second type of data included in this study is the hourly wind speed direction for the year 2020. We used Microsoft Excel and Libre Office Calc to process the collected data. Numerical simulations were carried out using MATLAB, and the wind rose diagram was plotted using WRPLOT.

Methods for determining wind potential

The Weibull distribution function: The Weibull distribution function is a statistical method commonly used to model the distribution of wind speed in a given area. It is based on two parameters: shape and scale, which are determined from wind speed measurement data. The Weibull distribution function is used to determine the probability of obtaining a certain wind speed in a specific area (8, 23, 24). This information is essential for the design and optimization of wind energy systems, as it enables us to determine the theoretical electrical power produced by wind turbines. It is given by:

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

Where k is the shape parameter (dimensionless), which gives the shape of the distribution; ccc is the scale factor (in m/s), and v is the velocity. The shape parameter, denoted as k, is an important feature of the Weibull distribution. It determines the shape of the distribution's probability curve and influences the probability of wind occurrence. A high shape parameter indicates a narrower distribution, more concentrated around the mean value, while a low shape parameter indicates a more spread-out distribution with a longer tail.The scale parameter, denoted as ccc, is also crucial in the Weibull distribution. It defines the range of possible values for the random variable and influences the dispersion of the data. A higher scale parameter corresponds to higher values of the random variable, while a lower scale parameter indicates lower values. Together, these two parameters provide an accurate characterization of the Weibull distribution and are used in many fields to model phenomena such as wind speeds, component lifetimes, waiting times, and more. Careful selection of these parameters is essential to ensure adequate modeling of the observed data.

The hybrid Weibull distribution function: The Weibull hybrid distribution function is used when the frequency of calm wind recorded at the site is greater than or equal to 15% (25). This proportion of calm wind becomes very important and cannot be neglected; it must be considered when studying a wind power project (26, 27). The mathematical expression of this distribution isgivenby:

$$f(v) = (1 - ff_0)\left(\frac{k}{c}\right)\left(\frac{v}{c}\right)^{k-1} \exp\left(-\left(\frac{v}{c}\right)^{k}\right) \quad \text{for} \quad v > 0 \qquad (2)$$

$f(v) = ff_0$ for $v=0$

Where ff_0 represents the frequency of calm wind.

The Rayleigh distribution function: The Rayleigh speed distribution function is a statistical distribution used to model the distribution of wind speeds. It is often used in conjunction with the Weibull distribution to more accurately characterize wind behavior at a given site (23, 29, 30).The Rayleigh velocity distribution is generally used to represent wind speeds in the absence of specific directional phenomena, such as obstacles or significant topographical effects. It assumes that wind speed follows a Rayleigh distribution, which describes the probability of wind speed reaching a given value.This distribution is characterized by a single parameter, called the scale parameter, which determines the shape of the distribution curve. Using wind speed data collected on-site, engineers can adjust this parameter to obtain an accurate representation of the wind speed distribution according to the Rayleigh distribution. This is a special case of the Weibull distribution.

When the shape parameter k=2, we obtain the Rayleigh distribution function (30, 32) by:

$$f(v) = \left(\frac{2v}{c^2}\right) exp\left(-\left(\frac{v}{c}\right)^2\right) (3)$$

Vertical extrapolation of wind speed: Vertical extrapolation of wind speed involves estimating wind speed at different heights above ground level based on measurements taken at a single height. This extrapolation plays a very important role in the study of wind potential, as wind speed varies with altitude and can be significantly different at different heights. By extrapolating the wind speed to different heights, we can obtain a better estimate of the available wind resource and, therefore, better plan the installation of wind farms to maximize their efficiency and energy production (33).

If V1 is a wind speed extrapolated from an altitude Z1 to another altitude Z2 according to the relationship given by equation (4), thenV2 can be calculated as follows: (34).

$$V_2 = V_1\left(\frac{Z_2}{Z_1}\right)^{\alpha} (4)$$

α is the roughness coefficient, Z1 is the wind speed at a height of 10 m, andZ2 is the wind speed at height Z, where Z is the altitude. The roughness coefficient is defined by:

$$\alpha = 0.37 - 0.088ln(V_{10}) (5)$$

On the other hand, and, respectively the Weibull scaling factor and the shape parameters determined at 10 m height are adjusted to any desired height, as shown (35, 36):

$$C_z = C_{10}\left(\frac{z}{10}\right)^{n} (6)$$

$$k_z = \frac{k_{10}}{1 - 0.00881ln(z/10)} (7)$$

k_z is the form factor at height z and C_z is the scale factor at height z.

The exponent n of the power law is given by:

$$n = [0.37 - 0.0088ln(10)] (8)$$

Method for determining Weibull parameters

The Moroccan method: There are several methods for determining Weibull parameters, depending on the site. In our case, we use the so-called Moroccan method. This method is generally used for areas with high wind speeds (34, 32). The shape parameter k and the scaling factor c are determined by the following relationships:

$$k = 1 + \left(0.483(\overline{v} - 2)\right)^{0.51} (9)$$

The scaling factor is obtained by the following equation (4):

$$c = \frac{\overline{v}}{\Gamma\left(1 + \frac{1}{k}\right)} (10)$$

The EPF energy factor method: This is a more accurate and efficient method for determining Weibull parameters. This specific approach is used to estimate the parameters of the Weibull distribution in the context of wind energy. It is given by equation (6):

$$k = 1 + \frac{3,69}{(EPF)^2} \quad (11)$$

With EPF given by (37, 38, 39):

$$EPF = \frac{\frac{1}{n}\sum_{i=1}^{n} v_i^{\,3}}{\left(\frac{1}{n}\sum_{i=1}^{n} v_i\right)^3} \quad (12)$$

In this way, the scale factor is easily determined from the mean velocity and the shape parameter (40):

$$c = \frac{v_m k^{2.6674}}{0.184 + 0.8116k^{2.73855}} \quad (13)$$

Power of a wind turbine

Average usable power: Given the variability of wind speed and the characteristics of a wind turbine as a function of its starting speed v_1, rated speed v_n and stopping speed v_s, the usable power of a wind turbine is given by the following relationship (12, 42):

$$< P_u >= \frac{1}{2}\rho A < v_u^3 > . \quad (14)$$

With:
ρ: density ρ=1.225kg/m^3
A: area swept by the blades;
α is the roughness coefficient, Z1Z_1Z1 is the wind speed at a height of 10 m, and Z2Z_2Z2 is the wind speed at height ZZZ, where ZZZ is the altitude. The roughness coefficient isdefined by:

$$< P_u >= \begin{cases} 0 & for v < v_i \\ \frac{1}{2}\rho < v^3 > & for v_i \le v \le v_n \\ \frac{1}{2}\rho v_n^2 & for v_n \le v \le v_s \\ 0 & for v > v_s \end{cases} (15)$$

The mean usable cubic velocity is obtained by integrating the cubic velocity weighted by the probability function, taking the integration limits given by the turbine manufacturer as (45, 46):

$$< P_u >= \int_{v_i}^{v_n} f(v)v^3 dv + v_n^3 \int_{v_n}^{v_s} f(v)dv \quad (16)$$

by integration using the normalized gamma distribution:

$$< \overline{v_v^3} >= \left[\Gamma_n\left(\left(\frac{v_n}{c}\right)^k, 1+\frac{3}{k}\right) - \Gamma_n\left(\left(\frac{v_i}{c}\right)^k, 1+\frac{3}{k}\right)\right]\overline{v^3} + v_n^3\left[exp\left(-\left(\frac{v_n}{c}\right)^k\right) - exp\left(-\left(\frac{v_s}{c}\right)^k\right)\right] \quad (17)$$

With :

$$\Gamma_n(x,a) = \Gamma(x,a)/\Gamma(x) \quad (18)$$

Wind turbine power output and capacity factor: Every wind energy conversion system is designed to operate at maximum efficiency within the limits of nominal wind speed and power. Therefore, once the Weibull scaling and shape parameters are estimated, the performance of a wind turbine at a given location can be easily calculated using the average power and capacity factor. In this work, the electrical power of a model wind turbine is simulated using (47, 28, 48):

$$P_e = \begin{cases} 0 & (v < v_D) \\ P_{en}\dfrac{v^k - v_d^k}{v_n^k - v_d^k}(v_d \le v \le v_n) & (19) \\ P_{eR}(v_N \le v \le v_c) & \\ 0 & (v_c < v) \end{cases}$$

With:

P_{en}: nominal electrical power

v_d: wind turbine starting speed;

v_n: rated speed;

v_c: cut-off speed

The power produced by a wind turbine depends on the characteristics specified by the turbine manufacturer. Figure 1 shows the performance curve of an ideal wind turbine as a function of its various speeds.

Figure 1: Performance curve of an ideal wind turbine

The technical parameters of every wind turbine include three essential speed parameters. These are (49):

- Starting speed VD: this is the speed at which the wind turbine begins to produce energy. Below this threshold, the turbine produces no energy.
- -Rated speed VN: this is the speed at which the wind turbine reaches its maximum energy production threshold. This threshold remains constant until the cut-off speed is reached.
- The cut-off speed VC: this is the speed at which the turbine stops producing energy, due to the automatic safety shutdown of the blades. Speeds above VC have no effect on the energy calculation.

The total wind power output is (50, 51):

$$P_u = \int_{v_d}^{v_n} P_i f(V)dV + \int_{v_n}^{v_n} P_n f(V)dV \quad (20)$$

Replacing the instantaneous power and the speed distribution function f(V) by their expressions gives:

$$P_u = \frac{\rho A}{2}\int_{v_d}^{v_n} C_p(V)\, V_{av}^3 \left(\frac{k}{c}\right)\left(\frac{V}{c}\right)^{k-1} exp\left(-\left(\frac{V}{c}\right)^{k-1}\right)dV + \frac{\rho A}{2}\int_{v_n}^{v_a}\left(\frac{k}{c}\right)\left(\frac{V}{c}\right)^{k-1} exp\left(-\left(\frac{V}{c}\right)^{k}\right)dV (21)$$

After integration we have (52, 53, 54):

$$P_u = C_f P_n (22)$$

With :

$$C_f = \left[\frac{e^{-\left(\frac{V_d}{c}\right)^k} - e^{-\left(\frac{V_n}{c}\right)^k}}{\left(\frac{V_n}{c}\right)^k - \left(\frac{V_D}{c}\right)^k} - e^{-\left(\frac{V_a}{c}\right)^k}\right] (23)$$

Thus, the power output of a wind turbine can be written as (55, 45):

$$P_u = \left[\frac{e^{-\left(\frac{V_d}{c}\right)^k} - e^{-\left(\frac{V_n}{c}\right)^k}}{\left(\frac{V_n}{c}\right)^k - \left(\frac{V_D}{c}\right)^k} - e^{-\left(\frac{V_a}{c}\right)^k}\right] P_n (24)$$

C_f is the capacity factor and plays a very important role in the design of a wind farm site. The capacity factor can be estimated from the Weibull parameters and the various operating speeds supplied by the turbine manufacturer. The rated power P_n of a wind turbine is given by the manufacturer. Knowing the power output of a wind turbine, we can calculate the energy produced by a wind turbine over a given period. The energy produced by a wind farm E(KWh) represents the total annual wind energy available at a given site. This energy can be calculated as a function of the number of hours as follows (56):

$$E = P_u T. (25)$$

Where T is the number of hours in a period:

$$E = P_u d24 (26)$$

d being the number of days

Usable wind energy

The average usable (produced) wind energy is (57):

$$P_p = \eta P_u (27)$$

With η the machine efficiency given by (58, 59):

$$\eta = 2\frac{P_n}{\rho A v_n^3} (28)$$

The amount of water pumped by a wind turbine depends on a number of parameters, such as (57)(58) :

$$Q = 3600 * 24 * \left(\frac{\eta Pu}{\rho g H}\right) (29)$$

Geographical coordinates of the study area: Kouba Olanga is a small Chadian town located around 740 km from the capital N'Djamena. Table 1 gives the geographical coordinates of this town.

Table 1. Geographical coordinates of Kouba Olanga.

Town	Latitude	Longitude	Altitude	Data range
Kouba Olanga	15°45'0" N	18°18'0" E	247 m	2000-2022

RESULTS AND DISCUSSION

Determination of Weibull parameters

Energy factor method: We determined the annual and monthly values of the Weibull parameters. With an annual average speed of 4.64 m/s, the shape parameter gives a value of 4.02, and the scale factor, in turn, gives a value of 5.21 m/s. The monthly values are shown in Table 2 below. Compared to annual values, we note a significant variation in the scale factors and a small monthly variation in the shape parameter values.The scale factor reaches its maximum in February at 6.16 m/s and its minimum in September at 3.64 m/s. This shows that, given the random nature of the wind, it is important to consider seasonal variations in these values when planning wind turbines at a wind site. Figure 2 shows the monthly wind speed chart for the site. In this figure, we observe a seasonal variation. The windiest months are from December to April, while the least windy months are from June to September.

Table 2. Weibull parameters by the energy factor method

Month	V	k	c
January	5.44	4.44	6.01
February	5.57	4.43	6.16
March	5.48	4.36	6.05
April	5.03	4.37	5.56
May	4.30	4.51	4.74
June	3.58	4.55	3.95
July	4.30	4.55	4.74
August	3.92	4.62	4.32
September	3.31	4.65	3.64
October	4.26	4.28	4.72
November	4.91	4.56	5.41
December	5.56	4.36	6.15

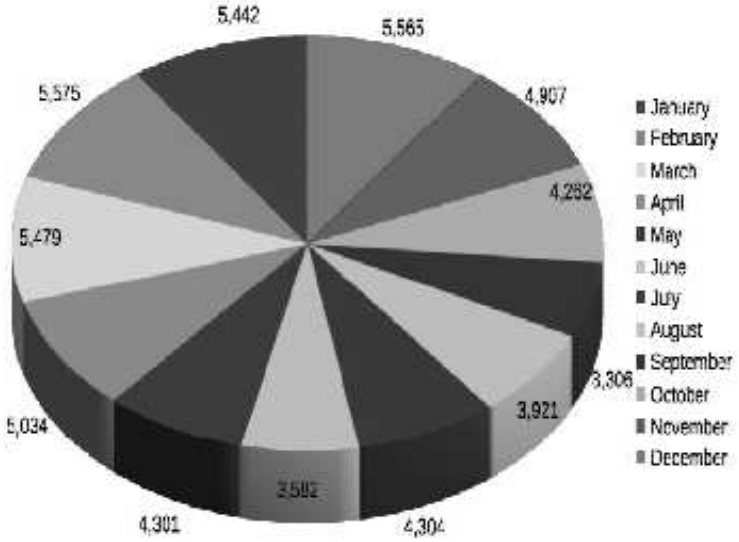


Figure 2. Monthly wind speed change

Moroccan method: Table 3 summarizes the monthly and annual values of the Weibull parameters, ccc and k. A detailed analysis reveals significant monthly variations in both the shape factor, ranging from 2.32 to 1.87, and the scale factor, ranging from 6.28 to 3.72 m/s. The annual mean of k is 2.13, while ccc is 5.26 m/s.A comparison with the values obtained by the Moroccan method reveals a significant difference in the shape factor. In the present study, the latter oscillates around 2, while it is close to 4

according to the energy factor method. These variations, due to methodological differences, underline the importance of the choice of analysis method in assessing the wind potential of a given site.

Table 3. Monthly values of the Weibull parameters by the Moroccan method

Month	v	k	c
January	5.44	2.3	6.14
February	5.57	2.32	6.29
March	5.48	2.3	6.18
April	5.03	2.22	5.68
May	4.3	2.06	4.85
June	3.58	1.87	4.03
July	4.3	2.06	4.86
August	3.92	1.96	4.42
September	3.31	1.79	3.72
October	4.26	2.05	4.81
November	4.91	2.19	5.54
December	5.56	2.32	6.28

Distribution of Weibull from Kouba Olanga according to the Moroccan method: Figure 3 shows the Weibull distribution for the KOUBA OLANGA site, exhibiting a probability density of 0.17. The scale factor is 5.24 m/s, while the shape factor reaches 2.13. This analysis reveals a spread distribution, characterized by a significant bandwidth.Figure 4, in turn, shows the Rayleigh distribution for the KOUBA OLANGA site. In comparison with the Weibull distribution, a similarity is observed; however, subtle differences remain in terms of probability density and distribution of values. The shape factor is set to 2, and the scale factor remains unchanged at 5.24 m/s.The results obtained indicate a significant dispersion of wind speed values, highlighting substantial variability in the data collected. This observation underscores the importance of a thorough analysis of probability distributions for a better understanding of the wind potential of the KOUBA OLANGA site.

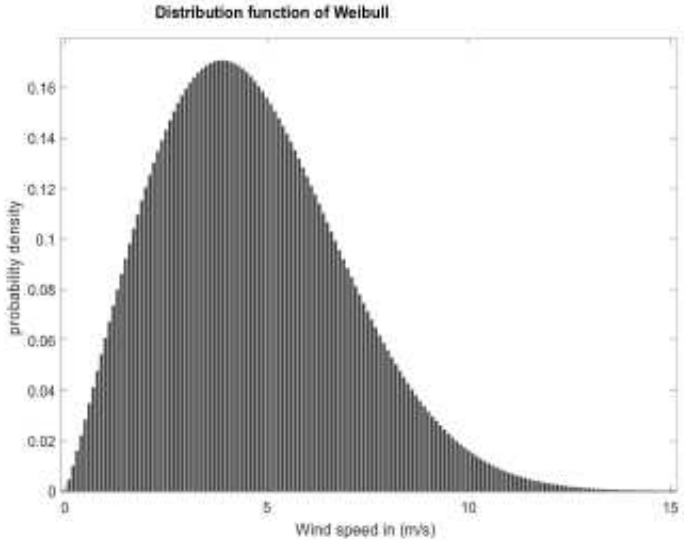


Figure 3. Weibull distribution by the Moroccan method

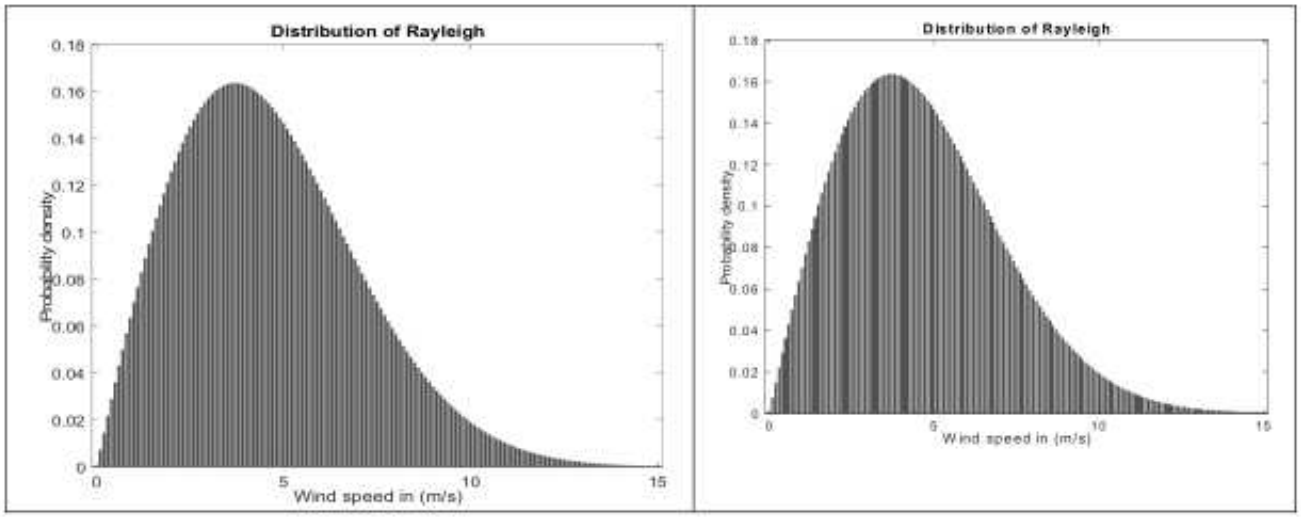


Figure 4. Rayleigh distribution by the Moroccan method

Kouba Olanga Weibull distribution by the energy factor method: Figures 5 and 6 show the Weibull and Rayleigh distributions according to the values of ccc and k obtained by the energy factor method. The results for the Weibull distribution, with a scale factor of 5.22 m/s and a shape factor of 4.02, reveal a probability density of 0.29. This analysis indicates a more pointed distribution with an average bandwidth, suggesting a higher concentration of the observed values around the mean.For the Rayleigh distribution, with a scale factor of 5.22 m/s and k set to 2, the probability density obtained is 0.16. This distribution has characteristics similar to those observed previously by the Moroccan method, with a significantly wide bandwidth.Comparing the results obtained by the energy factor method with those obtained by the Moroccan method, the Weibull distribution is more pointed and has a higher concentration of velocity values around the mean than the Moroccan method. The Rayleigh distribution, on the other hand, shows similar general characteristics to previous results but with slightly different values in terms of probability density. These variations can be attributed to the different methods used for determining the Weibull parameters.

Application of the standards to small-power wind turbines: Small wind turbines are ideal for pumping applications in desert and remote environments. Their reliability, energy efficiency, and low operating costs make them sustainable and cost-effective solutions to meet water needs efficiently. For pumping applications at our site, we selected three small-power wind turbines: VESTAS V15, VESTAS V10, and AEOLOS-H30, to assess their energy efficiency in on-site water pumping (60). Table 4 shows the characteristics of these wind turbines.The choice of small-scale wind turbines (Vestas V15, V10, and AEOLOS-H30) in Chad's deserts is based on their low installation costs, suitability for local wind conditions, minimal environmental impact, and ability to provide decentralized power to meet the energy needs of isolated communities. Figure 7 illustrates the performance curves of these various wind turbines as a function of their characteristics.

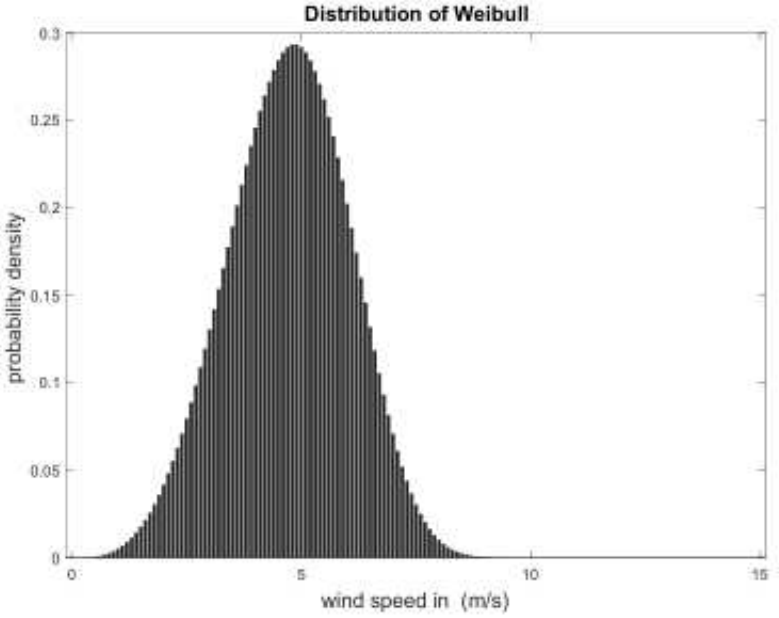


Figure 5. Weibull distribution by EPF method

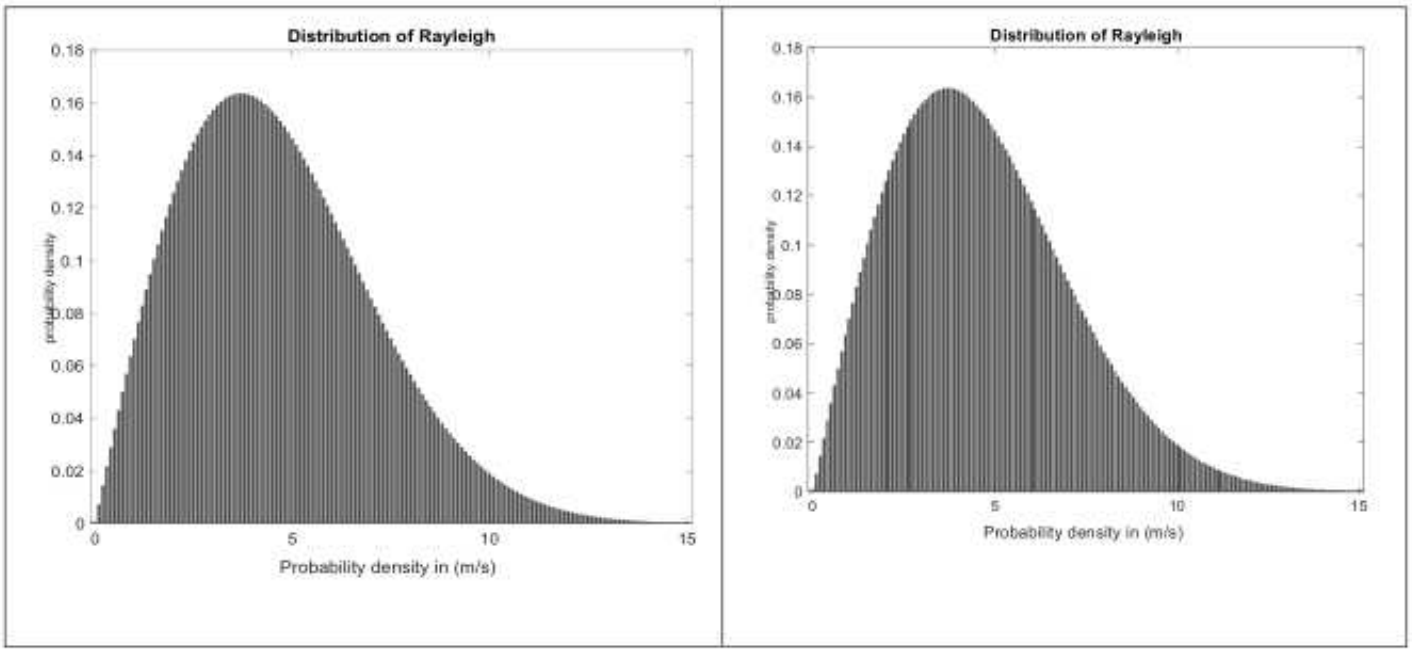


Figure 6. Rayleigh distribution according to the EPF method

Table 4. Characteristics of small-capacity wind turbines

Wind turbine	Start speed	Nominal speed	Cut-off speed	Nominal power	Rotor diameter	Mast height
AEOLOS-H30	2.5 m/s	9 m/s	25 m/s	30 kW	15.5 m	18 m
VESTAS V10	4 m/s	14 m/s	25 m/s	22 kW	10 m	18.5 m
VESTASV15	4 m/s	12.5m/s	25 m/s	55 kW	18 m	22 m

Extrapolation of speeds at the wind turbine height: Because wind speed is subject to variations in altitude, there is a concomitant variation in the Weibull parameters. Table 5 below shows the monthly values of wind speed for different wind turbine heights, while Table 6 presents the various values of the Weibull parameters at these same heights. It is observed that wind speed tends to increase with the increase in the heights considered.

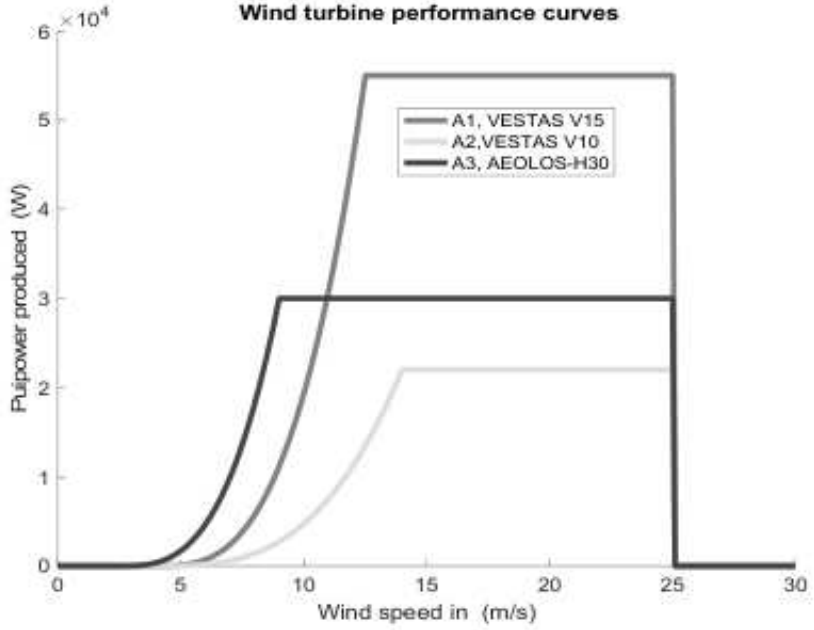


Figure 7. Small wind turbine performance curve

Table 5. Monthly values of speeds at different heights

Month	V10	V18	V18.5	V22
January	5.442	6.771	6.7055	7.2007
February	5.575	6.9347	6.8676	7.3745
March	5.479	6.8167	6.7507	7.2492
April	5.034	6.2655	6.2047	6.6639
May	4.301	5.3576	5.3054	5.6996
June	3.582	4.467	4.4233	4.7535
July	4.304	5.3614	5.3092	5.7037
August	3.921	4.8867	4.839	5.1994
September	3.306	4.1244	4.084	4.3895
October	4.262	5.3099	5.2582	5.649
November	4.907	6.1083	6.049	6.497
December	5.565	6.9223	6.8554	7.3614

Table 6. Vertical extrapolation of Weibull parameters

	10 m		18 m		18.5		22 m	
Month	k	c	k	c	k	c	k	c
January	2.3	6.14	2.31	7.57	2.31	7.64	2.31	8.13
February	2.32	6.29	2.33	7.75	2.33	7.83	2.34	8.32
March	2.3	6.18	2.32	7.62	2.32	7.69	2.32	8.18
April	2.22	5.68	2.23	7.01	2.23	7.07	2.23	7.52
May	2.06	4.85	2.07	5.99	2.07	6.05	2.07	6.43
June	1.87	4.03	1.88	4.98	1.88	5.03	1.89	5.35
July	2.06	4.86	2.07	5.99	2.07	6.05	2.07	6.44
August	1.96	4.42	1.97	5.46	1.97	5.51	1.98	5.86
September	1.79	3.72	1.8	4.59	1.8	4.64	1.8	4.93
October	2.05	4.81	2.06	5.94	2.06	5.99	2.06	6.38
November	2.19	5.54	2.2	6.83	2.2	6.9	2.2	7.34
December	2.32	6.28	2.33	7.74	2.33	7.81	2.34	8.31

Capacity factor and daily water flow for each wind turbine

Capacity factor and daily water flow of VESTASV15 wind turbine: Figure 8 shows the monthly capacity factor diagram of the VESTAS V15 wind generator. This monthly variation in the performance of the VESTAS V15 wind turbine at the KOUBA OLANGA site reveals significant fluctuations, with some months demonstrating remarkable performance. Specifically, the months of December, January, February, March, and April stand out with high and harmonious capacity factor values of 0.3146, 0.3014, 0.3157, 0.3053, and 0.2583, respectively. Their contribution to energy production is truly encouraging. Conversely, the other months show a decline, with capacity factor values below 0.26, relegating them to the category of unfavorable months in terms of wind turbine productivity. This monthly variation highlights fluctuations in the energy performance of the turbine over the seasons, with an annual average capacity factor of 0.2187.Additionally, the flow of water pumped by the wind turbine offers another dimension of energy fluctuation, with months from December to March achieving flows exceeding 2000 m³/day, making December particularly favorable. The annual average of daily flow is 1466.7 m³/day.

Considering all the above, it is clear that the VESTAS V15 wind turbine, according to its characteristics, experiences both favorable and unfavorable months for energy production at the KOUBA OLANGA site. The calculations are based on a total manometric height of 50 m.

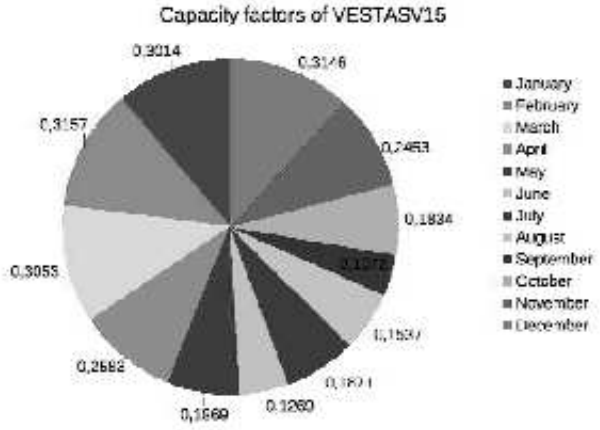


Figure 8. Capacity factor of the VESTASV15 wind turbine

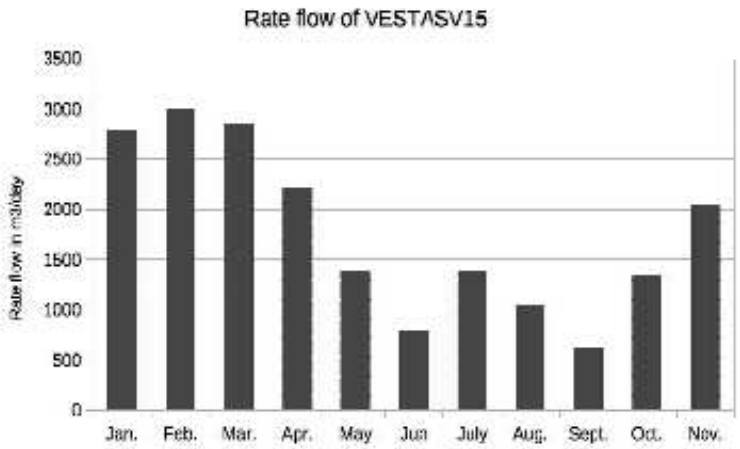


Figure 9. Daily flow rate of the VESTASV15 wind turbine

Capacity factor and daily water flow for the VESTASV10 wind turbine: Figure 10 shows the monthly variation in capacity factor for the VESTAS V10 wind turbine. This figure indicates that capacity factor values remain very low on an annual basis for this turbine. The annual value is notably below the threshold of 0.26 recommended for the operation of a wind farm. The maximum capacity factor is 0.2152 in February, while the minimum is observed in June, with a capacity factor of 0.0839. Additionally, all months are unfavorable due to their low capacity factor values.The daily flow rate, shown in Figure 11, exhibits a similar trend to that of the capacity factor, with a peak of 600 m³/day in January and a minimum of 100 m³/day in September. Compared to the VESTAS V15 wind turbine, the VESTAS V10 wind generator has lower capacity factor and flow rate values, making it unsuitable for wind power generation at the KOUBA OLANGA site.

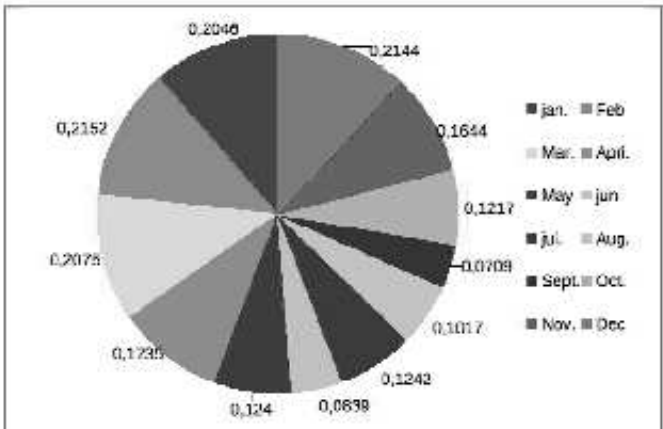


Figure 10. VESTASV10 monthly capacity factor diagram

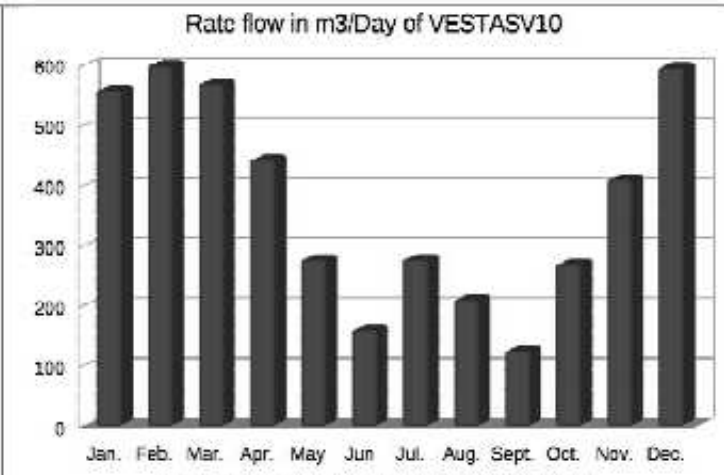


Figure 11. Daily flow rate of VESTASV10

Capacity factor and daily water flow for the AEOLOS-H30 wind turbine: Figure 12 shows the capacity factor diagram for the AEOLOS-H30 wind turbine at the KOUBA OLANGA site. An overall analysis of this figure indicates good capacity factor values

for most months of the year, with an average value of 0.39. This value is well above the normal threshold of 0.26 for the operation and production of wind power at a site.The monthly analysis reveals variation, with a peak capacity factor of 0.5118 in December and a minimum of 0.2251 in September, which is the only unfavorable month for wind turbine operation. Similarly, the monthly daily flow corresponding to this evolution of the capacity factor shows very promising values. The average annual daily flow is 1729.4 m^3/day, with the peak daily flow observed in February at 3000 m^3/day, while the minimum is recorded in September at 623.897 m^3/day. Compared to the capacity factors and daily flow rates of the two previous wind turbines, the AEOLOS-H30 is well suited for wind power generation, particularly for pumping water at KOUBA OLANGA.

Analysis of the wind rose diagram: The observation of Figure 14, which presents the wind rose diagram, shows a directional predominance of the wind in the east-northeast sector. The maximum frequency reaches 45%, with a low calm wind frequency of 0.13%. This low calm wind frequency on the site indicates that the cumulative distribution of Weibull is not suitable for wind characterization at this location. Given the frequency of wind direction and speed on this site, the wind rose diagram allows for informed decision-making regarding a wind project. However, a comprehensive technical and economic study will provide further insights into the feasibility of such a project.

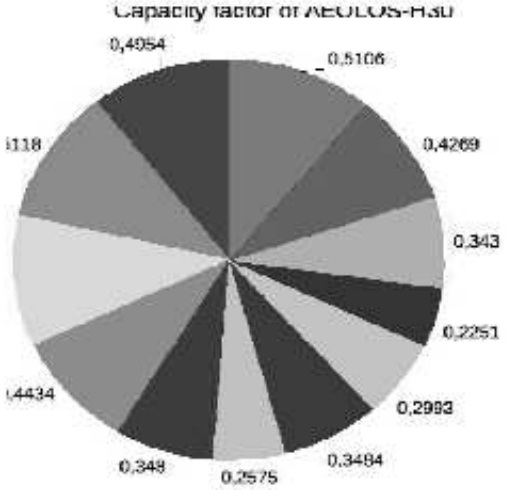


Figure 12. AEOLOS-30 capacity factor

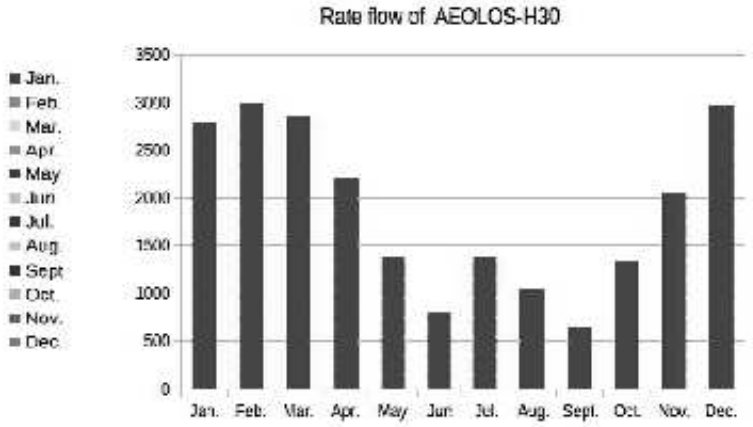


Figure 13. Daily flow diagram for the AEOLOS-H30 wind turbine

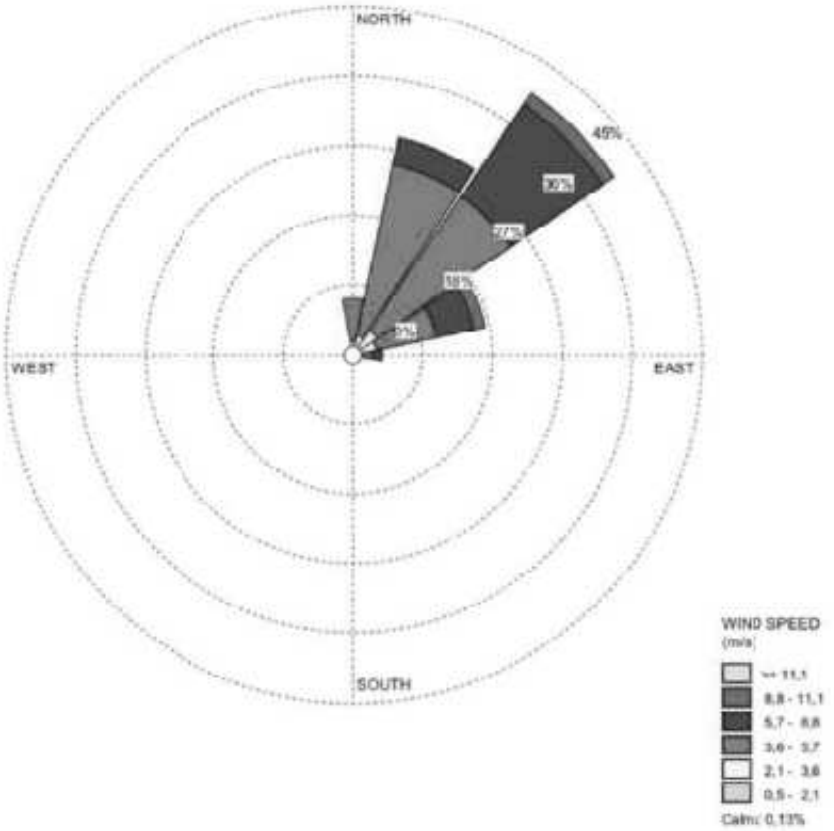


Figure 14. Wind rose diagram

DISCUSSION

The analysis of the efficiency of small wind turbines for water pumping at KOUBA OLANGA, in the Bodélé depression, reveals significant variability in wind parameters, measured by the Energy Factor method and the Moroccan method. The Weibull parameters, with an annual average wind speed of 4.64 m/s and values for the shape (k) and scale (c) parameters of 4.02 and 5.21 m/s, respectively, indicate good suitability for wind operation, although seasonal variations must be considered. The results show that small wind turbines, such as the VESTAS V15, VESTAS V10, and AEOLOS-H30, offer varying performances. The VESTAS V15 has a better capacity factor with favorable months, while the VESTAS V10 demonstrates insufficient performance. The AEOLOS-H30 appears to be the optimal choice for this region, with an average capacity factor of 0.39 and impressive daily flows of up to 3000 m³/day.The study of small wind turbines at KOUBA OLANGA highlights their potential for pumping water, particularly through the use of efficient models like the AEOLOS-H30. The results are consistent with trends in the literature, underscoring the importance of accurate local assessments to optimize the use of wind energy for pumping applications.

CONCLUSION

This study on the analysis of small wind turbines for the exploitation of wind potential at Kouba Olanga in the Chad desert highlights the importance of wind speed in this region for the efficient harnessing of wind energy. We utilized the Weibull and Rayleigh distribution functions to study wind frequencies, determining the Weibull parameters using both the Moroccan method and the energy factor method. Tests conducted on three small-capacity wind turbines (VESTAS V15, VESTAS V10, and AEOLOS-H30) indicated that the AEOLOS-H30 had the best performance, with an average annual capacity factor of 0.39, generating a maximum daily water flow of 3000 m³/day and an annual average of 1729.4 m³/day at a total manometric height of 50 m.

In comparison, the VESTAS V15 turbine had an average capacity factor of 0.2187 with an average annual flow rate of 1466.7 m³/day, while the VESTAS V10 turbine showed maximum efficiency with a capacity factor of 0.2157 and a maximum flow rate of 600 m³/day.By effectively exploiting the wind potential at Kouba Olanga, small wind turbines can contribute to water availability by pumping water independently and ecologically, reducing the dependence of local populations on often expensive and unreliable external water sources.

This sustainable approach also promotes community resilience to challenges posed by water scarcity and climate change, while providing opportunities for economic and social development.These results highlight the effectiveness of small wind turbines for harnessing the wind potential at Kouba Olanga, offering promising prospects for water pumping applications in this desert region of Chad.

Declaration of competing interest: The authors declare that this study has in no way been funded by any company or institution. It is the personal contribution of the paper authors.

Author contribution

A. Fia Oung-zetna (Lead author): Managed the study design, supervised data collection, and performed data analysis.
B. Boukar Michel: Actively participated in data processing in collaboration with the lead author, Fia Oung-zetna.
C. Amir Moungache: Provided overall supervision of the study in collaboration with Djongyang Noel.
D. Foulla Dieudonné Platou: Provided overall supervision of the study in collaboration
E.Djongyang Noel: Provided overall supervision of the study in collaboration with Amir Moungache.
F. Ouaïdou Emmanuel: Contributed to the proofreading and correction of the manuscript, as well as the validation of the methodology in collaboration with Beuteubé Rianbé François.
F. Beuteubé RianbéFrançois: Contributed to proofreading and editing the manuscript, as well as validating the methodology in collaboration with Ouaïdou Emmanuel.
All authors have read and approved the final version of the manuscript and agree to its publication.

Clinical Trial Declaration

Clinical Trial: NOT APPLICABLE

Consent to Publication Declaration

Consent to Publication Statement: not applicable

Ethics and Participation Consent Declarations

Ethics and Participation Consent Statements: not applicable

Data Availability: The data from this study can be obtained from the corresponding author upon request.

Declarations

Ethical Approval: The study was approved by the ethics committee of the University of Maroua. All participants were informed of the study's objectives and provided their informed consent.

Consent to Participate: All researchers involved in the writing of this article, namely Fia Oung-Zetna, Boukar Michel, Foulla Dieudonné Platou, Amir Moungache, Ouaïdou Emmanuel, Noel Djongyang and Beuteubé Rianbé François, collaborated under the supervision of the University of Maroua and the University of N'Djamena. They provided written consent to participate in the study.

Consent to Publish: The authors Fia Oung-Zetna, Boukar Michel, Foulla Dieudonné Platou, Amir Moungache, Ouaïdou Emmanuel, Noel Djongyang, and Beuteubé Rianbé François declare that they have obtained written consent from all co-authors to publish the results of this research. No personally identifiable information is included in the article.

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