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ORIGINAL RESEARCH

Evaluation of the cost of producing wind-generated electricity in Chad

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Abstract

This paper presents an economic analysis of the electricity produced by different types of wind turbines selected for Chad. Thus, the data considered for the analysis in this study are the average monthly wind speeds at selected locations, as well as the altitude value. Statistical analysis was performed using the Weibull distribution. The same energy factor allowed determining the Weibull parameters. The results obtained show that the average annual wind speed varies from 1 m/s in Am-Timan to 4.2 m/s in N'Djamena, at a height of 10 m from the ground. Weibull statistical parameters (k and c) were determined at 10, 30, 50, and 70 m. These were obtained by extrapolation using a power law based on Weibull parameters. Three models of wind turbines available on the market were used in this study: Bonus 300 kW/33, Bonus 1 MW/54, and Vestas 2 MW/V80. The performance of these wind turbines was evaluated using the calculation of the capacity factor and the annual energy produced by each type of wind turbine at 12 sites. The PVC (present value) method was used to perform an economic analysis. The lowest cost of wind power generation was obtained with the Vestas 2 MW/V80 model, with a cost per kilowatt-hour (kWh) of approximately $143.08/kWh/year in Moundou and 132343$89/kWh/year in Am-Timan. Therefore, it is recommended the use of a Vestas 2 MW/80 wind turbine in Chad.

Keywords Weibull distribution · Wind turbine · PVC · Wing energy

List of symbols

v	Wind speed
$f(v)$	Probability of observing wind speed (v)
$p(v)$	Wind power
P_{er}	Rated wind turbine power
V_c	Cut-in wind speed
V_r	Rated wind speed
V_f	Cut-off wind speed
C_f	Capacity factor
E_{wt}	Accumulated annual energy out put

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Introduction

The possibility of exploiting renewable energies for electricity generation has been considered by different researchers across the globe because of the negative effects of fossil fuels on the environment. Among the many clean sources of energy is wind energy which has developed very rapidly over the past 2 decades. Great technological progress has been made to reduce the cost of producing wind-generated electricity [1]. The turbine is free of fossil fuel energy and, hence, does not cause an environmental pollution when generating electricity [2]. Similarly, it can produce wind power near load centers, eliminating transmission loss in rural and urban landscape lines [3]. In developing countries, it is important to study and carefully understand the energy model to ensure a good standard of living and to alleviate poverty [4, 5].

Speed, direction, continuity, and availability are the characteristics of the wind that can be developed to determine the wind energy potential of a site [6, 7]. In many countries around the world, studies and assessments of wind characteristics and the potential of wind energy are being conducted. Countries like Hong Kong Islands have its wind analysis discussed by Lu et al. [8]. Youm et al. presented wind energy potential in Senegal and the analysis of wind data using the Weibull probability distribution [9]. Mostafaeipour et al. [10] evaluated wind energy resources for selected sites in Iran. Shaahid et al. [11] studied the economic feasibility of the development of wind power plants in coastal areas of Saudi Arabia. Dursic et al. [12] evaluated the wind energy source in the southern Banat region as a surbie. Statistical analyses focused on the measurement of wind parameters such as mean wind speed, power density, direction, and Weibull distribution parameters. A mathematical method of the sum of the least squares is used to analyze the vertical profile of the wind speed. Alami Els [13] in the Gulf of Tunis in Tunisia during their study on the potential of wind resources considered the hourly data of the wind speed and wind direction every 10 min to assess the wind potential. Worked on the evaluation of wind energy and electricity generation in the Gulf of Tunis, Tunisia. Four different methods were used to determine the Weibull parameters [14]. Worked on the energy balance of the first wind farm of Sidi Daoud in Tunisia. Thus, based on wind speed data measured over a 5-year period. The wind potential of the Sidi Daoud site is analyzed statistically using the Weibull and Rayleigh parameters [15]. Sidi Daoud [15, 16], El-Kefregion [17], and Tunisia [18, 19] in the literature have assessed the potential for wind power and electricity production in 2011 in BorjCedria [20]. For the long-term prediction of electrical energy consumption, they have made a study on the approach based on gene expression. To identify the most important independent variables affecting electricity demand, a sensitivity analysis was performed [21]. Conducted an optimization study based on NSGA-II and MOPSO for sizing a hybrid PV/wind/battery energy storage system. To determine the optimal number of PV panels and wind farm system, the optimized hybrid system was examined in MATLAB [22]. Worked on short-term electricity price forecasting using the hybrid backtracking algorithm and the ANFIS approach. Thus, a hybrid machine learning algorithm and a search algorithm in the learning process of the ANFIS approach have been developed to predict the price of electricity more precisely [23]. Conducted a study on solving the problem of sending non-convex economic load via an artificial algorithm for cooperative research. Thus, they used a method that is to interfere and work with feasible solutions throughout the optimization [24]. As an indication, in 2009, the population of Chad was estimated at 11,039,873 inhabitants, at a growth rate of 6% per year. As a result, current statistics estimate this population at 15,177,557. In Chad, making electricity available everywhere has always been an important socio-economic issue. However, despite the considerable efforts made by the public authorities, the population still encounters many difficulties in accessing electricity. In other words, Chad is one of the poorest-supplied countries in the Economic and Monetary Community of Central Africa (CEMAC) sub-region [25]: less than 5% of the population has access to electricity, mainly in the urban areas (2017), 80% of the country's consumption is in N'Djamena, load shedding is common, because the grid does not provide enough electricity; there is still no national interconnection of the network; domestic wood accounts for 90% of primary energy consumption. Since no study has been conducted to estimate the cost of a wind turbine in Chad, this work is on the determination of Weibull parameters in evaluating wind characteristics in Chad. Also, economic analysis of wind power generation considering three turbines models for the selected locations is carried out using present value cost (PVC) method.

Methodology

Presentation of Chad

A landlocked country in Central Africa, Chad is located between 7° and 24° north latitude and 13° and 24° east longitude (Fig. 1). It is bordered, in the North with Libya, in the East with Sudan, in the South with the Central African Republic, and in the West with Cameroon, Niger and Nigeria (countries with which it shares Lake Chad). The nearest port, Douala, is 1700 km from N'Djamena, the capital. The Chadian population is estimated at 11.5 million inhabitants in 2011 (i.e., 27.2% of the population of the CEMAC zone). It is relatively young, and a large majority live in rural areas. Although on a downtrend, population growth is 2.6% on average each year.

Wind characteristic of the selected locations

The wind data used were obtained from the National Office of Meteorology (ONM). These are monthly wind speed data measured for 12 sites. Geographic coordinates are shown in Table 1.

Statistical analysis of wind data

To estimate the variations of the wind speed, we used the Weibull probability function which is represented by the following equation [26, 27]:

$$f(v) = \left(\frac{k}{c}\right) \cdot \left(\frac{v}{c}\right)^{(k-1)} \cdot \exp\left(-\left(\frac{v}{c}\right)^{k}\right), (k > 0, v > 0, c > 1), \tag{1}$$

where v is the wind speed (m/s), c is the scale parameter (m/s), and k is the shape parameter (dimensionless).

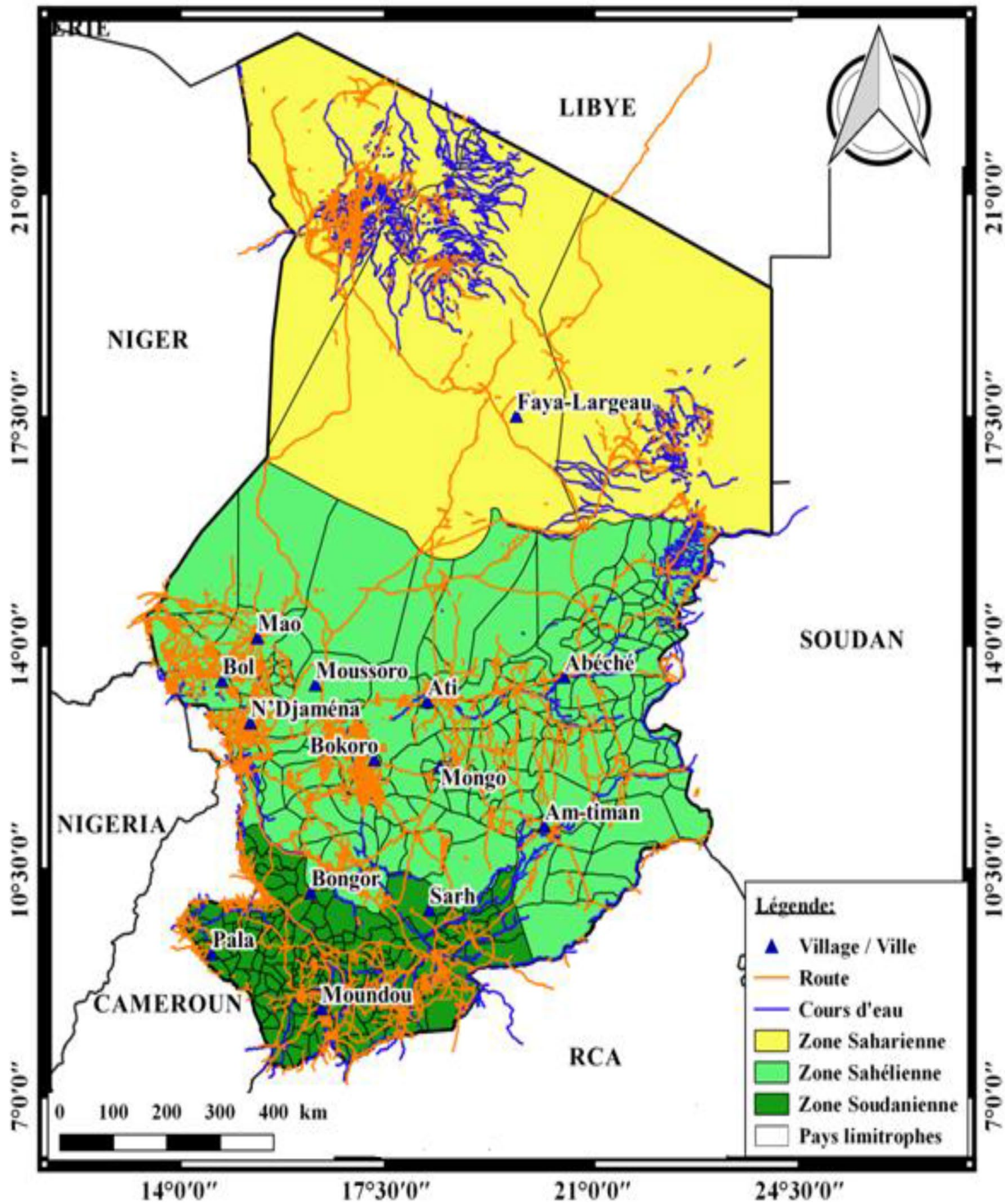

Fig. 1 Map of Chad

Extrapolation of wind speed at different heights

Wind speed is generally measured at 10 m height, while the installation height of wind turbines is always higher than this height. Moreover, the wind speed increases with the altitude because of the existence of the atmospheric boundary layer, it is necessary to extrapolate the measured wind speed up to the hub height of the wind turbine. The most commonly used method for this purpose is the power law [28]. It is expressed by the following relation [29]:

$$v(z_2) = v(z_{10})\left(\frac{z_2}{z_{10}}\right)^m \quad (2)$$

Table 1 Geographical coordinates of stations used in the study

Zones	Station	Longitude (°E)	Latitude (°N)	Elevation (m)	Period of measurement (year)	Height of the mast (m)
Saharan zone	Faya-Largeau	19.7	17.55	233	18	10
	Abeche	20.51	13.51	545	26	10
	Bokoro	17.3	12.23	300	18	10
	N'Djamena	15.2	12.8	294	20	10
Sahelian zone	Mongo	18.41	12.11	430	30	10
	Ati	18.19	13.13	334	19	10
	Mao	15.32	14.12	356	9	10
	Bol	14.72	13.45	291	9	10
	Am-Timan	20.17	11.2	432	28	10
	Moundou	16.4	8.37	420	20	10
Sudanese zone	Pala	14.55	9.22	420	30	10
	Sarh	18.23	9.9	364	20	10

$$m = \frac{\left[0.37 - 0.088\ln\left(v_{10}\right)\right]}{\left[1 - 0.088\ln\left(\frac{z_{10}}{10}\right)\right]}. \tag{3}$$

The Weibull parameters at the measured height are related to the parameters at the height of the wind turbine by the following expressions:

$$c(h) = c_0\left(\frac{h}{h_0}\right)^n \tag{4}$$

$$k(h) = k_0\left[1 - 0.088\ln\left(\frac{h_0}{10}\right)\right] / \left[1 - 0.088\ln\left(\frac{h}{10}\right)\right], \tag{5}$$

where c_0 and k_0 are the scale factor and the shape parameter, respectively, at the measured height h_0, and h is the height of the concentrator.

Estimation of electrical energy supplied by wind turbines

The performance of the wind turbines is estimated with the capacity factor (C_f) which represents the fraction of the average power supplied by the wind turbine ($P_{e,\ moy}$) compared to the nominal power of the wind turbine (P_{eR}). The average power ($P_{e,\ Avg}$) and the capacity factor of wind turbines are calculated using the following equations [30, 31]:

$$P_e = \begin{cases} 0 & (v < v_c) \\ P_{eR}\frac{v^k - v_c^k}{v_R^k - v_c^k} & (v_c \le v \le v_R) \\ P_{eR} & (v_R \le v \le v_F) \\ 0 & (v_F < v) \end{cases} \tag{6}$$

$$P_{e,ave} = P_{eR}\left\{\frac{e^{-\left(\frac{v_c}{c}\right)^k} - e^{-\left(\frac{v_r}{c}\right)^k}}{\left(\frac{v_r}{c}\right)^k - \left(\frac{v_c}{c}\right)^k} - e^{-\left(\frac{v_f}{c}\right)^k}\right\}, \tag{7}$$

and the capacity factor C_f of a wind turbine is given by:

$$C_f = \frac{P_{e,ave}}{P_{eR}}, \tag{8}$$

where V_c, V_r, and V_f, are the zero flow wind speed, the nominal wind speed, and the shutdown speed of the wind turbine, respectively.

Annual cumulative energy production (AEP) is then estimated using equation [30]:

$$E_{out} = P\left(_{e,avg}\right) \times 8760. \tag{9}$$

The availability of the wind power resource for generating electricity is taken as $A = 75\%$ and the total energy output over the WT lifetime is computed as:

$$E_{WT} = 8760 \times A \times n \times P_r \times C_f. \tag{10}$$

Economic analysis of wind energy

According to [32, 33], the main parameters governing the cost of producing wind energy are as follows:

- Investment costs (including ancillary fees for foundations, network connection, etc.);
- Operating and maintenance costs;
- Electricity generation/average wind speed;
- The life of the turbine;
- The discount rate.

These factors may vary from country to country and region to region. However, of all the parameters listed, the price of the wind turbine and other capital costs are the most important. According to [32, 33], the specific cost of a wind turbine varies considerably from one manufacturer to another as shown in Table 2. The choice of the ideal wind turbine is, therefore, essential to ensure economic viability, while the production of electricity is highly dependent on wind conditions. Several methods discussed in [34] have been used in the literature for calculating the cost of wind energy. The PVC method is adopted in this study, because (1) it considers the dynamic development of relevant economic factors and (2) the different cost and income variables, which are taken into account regardless of whether the money has been or will be paid or received in the past or in the future, by deducting the accumulated cost of interest (discounting) of all payment flows at a common reference time [34]. The present value of costs (PVC) is determined using relationship [35]:

$$\mathrm{PVC} = 1 + C_{\mathrm{om}} \times \left[\frac{1+i}{r-i}\right] \times \left[1 - \left(\frac{1+i}{1+r}\right)^{n}\right] - S \times \left(\frac{1+i}{1+r}\right)^{n}, \quad (11)$$

where r represents the interest rate, i the rate of inflation, t the life of the wind turbine, and S the additional costs and includes the costs of operation, maintenance, and repair.

Table 2 Variation in the cost of wind turbines with rated power [34]

WT size (kW)	Specific cost per kW	Average specific per kW
< 20	2200–3000	2600
20–200	1250–2300	1775
> 200	700–1600	1150

To estimate PVC, the following quantities and assumptions are retained [35, 36]:

$$r = \frac{i_0 - i}{1 + i}. \quad (12)$$

In Table 2, it is found that the cost per kW decreases with the increase in the size of the wind turbine. For the machine size above 200 kW, the average cost of a wind turbine is in the order of $ 1150/kW.

The cost of energy (COE) in kW produced is determined by the following expression [37]:

$$\mathrm{COE}(\$/\mathrm{kWh}) = \mathrm{PVC}/\mathrm{E}_{\mathrm{WT}}. \quad (13)$$

Results and discussion

Estimation of wind resources

Average wind speed

The monthly wind speed for 12 selected sites at 10 m altitude is presented in Table 3. It is noted that the least wind speed of 1 m/s is observed in Am-Timan in August, September, and October, while the highest of 4.2 m/s is recorded in N'Djamena in March.

Weibull *k* parameters at 10 m altitude

Table 4 presents the Weibull k parameter at 10 m altitude. From Table 4, it can be seen that the least value of the form parameter (k) of the Weibull distribution of 1.062 is recorded at Am-Timan, while the highest value of 4.907 is observed at Mao in September.

Table 3 Values of the wind speed at 10 m altitude

v (m/s)	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Aver
Abeche	2.7	2.8	3.1	3	2.7	2.4	2.6	2.1	2	2.6	2.9	2.8	2.642
Am-Timan	1.5	1.6	1.4	1.5	1.7	1.5	1.3	1	1	1	1.2	1.4	1.342
Bokoro	1.7	1.9	1.9	1.7	1.7	1.7	1.6	1.3	1.2	1.2	1.5	1.6	1.583
Mongo	2.2	2.7	3.1	3.1	3.1	2.9	2.5	2.1	1.8	2.3	2.5	2.2	2.542
N'Djamena	3.6	4	4.2	3.2	3.2	3.6	3.2	2.5	2.4	2.4	3.3	3.4	3.25
Faya	4	3.8	3.7	3.3	2.9	2.7	2.3	2.2	3	3.4	3.9	3.8	3.25
Moundou	3.1	3.3	3.1	3.3	2.9	2.8	2.7	2.3	2.1	2	2.1	2.6	2.692
Pala	2.6	2.9	2.9	2.8	2.7	2.4	2.1	1.7	1.7	1.9	2	2.3	2.333
Sarh	1.9	2.2	2.4	3.2	2.3	2	1.7	1.4	1.4	1.4	1.4	1.6	1.908
Bol	2.2	2.2	2.2	2	1.9	2	2.2	1.8	1.5	1.8	2.2	2.2	2.017
Mao	2.4	2.5	2.6	2.2	2.1	2.1	2.1	1.8	1.8	2.1	2.4	2.5	2.217
Ati	1.7	1.9	2	1.8	1.8	1.8	1.8	1.4	1.4	1.5	1.7	1.8	1.717

Table 4 Form parameter values *k* at 10 m altitude

k (m/s)	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Abeche	3.051	3.513	3.187	3.547	3.051	3.083	3.118	2.789	2.786	3.292	3.76	3.59
Am-Ti	1.094	1.062	4.544	4.431	1.527	2.13	2.454	3.563	3.183	2.441	1.201	1.175
Bokoro	3.84	3.403	4.086	4.294	3.84	3.944	3.476	3.272	3.755	3.498	3.911	3.803
Mongo	3.811	3.482	3.833	3.541	3.078	3.091	2.931	2.873	2.658	3.364	3.632	3.262
N'Djamena	4.621	4.202	4.47	3.926	4.31	4.683	4.368	4.081	4.093	3.528	4.407	4.097
Faya-Larg	3.783	3.679	3.012	3.92	3.628	3.774	3.634	3.554	3.563	4.04	4.19	4.181
Moundou	3.613	3.242	3.256	2.876	3.028	3.144	3.306	2.705	3.058	2.397	3.235	3.355
Pala	3.193	3.539	3.143	3.205	3.482	3.277	3.983	3.559	3.108	3.646	2.64	2.263
Sarh	1.194	1.232	1.307	1.621	3.396	3.73	3.741	3.144	3.144	2.924	1.678	1.294
Bol	4.868	4.521	4.654	4.12	4.258	4.428	4.587	4.162	3.911	4.605	4.458	4.163
Mao	4.308	4.433	4.765	4.587	4.907	4.364	4.507	4.863	5.149	4.739	4.093	4.75
Ati	2.871	2.808	2.883	2.621	2.697	2.697	2.867	3.144	3.144	2.616	2.177	2.779

Weibull *c* parameters at 10 m altitude

Table 5 presents the monthly values of the scale parameter of the Weibull distribution. Thus, the least value of 1.11 m/s is recorded at Am-Timan and the highest value of 4.604 m/s is observed in N'Djamena.

Extrapolation of data at different altitudes

Wind data from the ONM were used to determine monthly variations of statistical parameters at 10 m in height. These quantities are then extrapolated to 30, 50 and 70 m in height.

Extrapolation of wind speed to 30.50, and 67 m altitude

The average wind speed at 30 m altitude is presented in Table 6. From Table 6, it can be seen that the minimum speed of 1.502 m/s is recorded at Am-Timan in the months of August, September, and October, while the maximum speed of 5.490 m/s is recorded in the month of March in N'Djamena.

Extrapolation of the wind speed to 50 m altitude

Table 7 presents the average wind speed at altitude of 50 m. From Table 7, it can be seen that the minimum average wind speed of 1.814 m/s is recorded in Am-Timan in August, September, and October, while the maximum speed of 6.217 m/s is recorded in N'Djamena in March.

Table 8 shows the extrapolation of the wind speed to 67 m altitude. Minimum speed of 2.021 m/s is recorded in the months of August, September, and October in Am-Timan. The maximum speed of 6.677 m/s is recorded in the month of March in N'Djamena. It can be deduced that the wind speed increases with altitude.

Extrapolation of the Weibull *k* and *c* parameters

Table 9 presents the extrapolation of the shape parameter at 30 m altitude. From Table 9, it can be seen that the least l

Table 5 Parameter values *c* at 10 m altitude

c (m/s)	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sept	Oct	Nov	Dec
Abeche	3.021	3.111	3.461	3.332	3.021	2.684	2.906	2.358	2.246	2.898	3.21	3.107
Am-Timan	1.551	1.638	1.533	1.645	1.887	1.693	1.466	1.11	1.117	1.128	1.276	1.48
Bokoro	1.88	2.115	2.093	1.868	1.88	1.877	1.779	1.45	1.328	1.334	1.657	1.77
Faya-Larg	4.426	4.212	4.142	3.645	3.217	2.988	2.551	2.443	3.331	3.749	4.291	4.181
Mongo	2.434	3.001	3.428	3.443	3.467	3.243	2.802	2.356	2.025	2.561	2.773	2.454
N'Djamena	3.938	4.4	4.604	3.534	3.515	3.935	3.512	2.755	2.644	2.666	3.62	3.746
Moundou	3.439	3.682	3.458	3.702	3.246	3.128	3.009	2.586	2.349	2.256	2.343	2.896
Pala	2.903	3.221	3.24	3.126	3.001	2.676	2.317	1.888	1.9	2.107	2.25	2.596
Sarh	2.017	2.353	2.601	3.573	2.56	2.215	1.882	1.564	1.564	1.569	1.567	1.731
Bol	2.4	2.41	2.406	2.203	2.089	2.193	2.408	1.981	1.657	1.97	2.412	2.421
Mao	2.636	2.742	2.839	2.408	2.289	2.305	2.301	1.963	1.957	2.294	2.644	2.731
Ati	1.907	2.133	2.243	2.026	2.024	2.024	2.019	1.564	1.564	1.688	1.919	2.022

Table 6 Mean wind speed at 30 m altitude

Month	Abec	Am-T	Bok	Fay	Mon	Mou	N'Dja	Pala	Sarh	Bol	Mao	Ati
Jan	3.683	2.166	2.425	5.253	3.061	4.173	4.776	3.56	2.681	3.061	3.311	2.425
Feb	3.806	2.296	2.681	5.015	3.683	4.415	5.253	3.929	3.061	3.061	3.436	2.681
Mar	4.173	2.035	2.681	4.896	4.173	4.173	5.49	3.929	3.311	3.061	3.56	2.808
Apr	4.051	2.166	2.425	4.415	4.173	4.415	4.294	3.806	4.294	2.808	3.061	2.554
May	3.683	2.425	2.425	3.929	4.173	3.929	4.294	3.683	3.186	2.681	2.935	2.554
Jun	3.311	2.166	2.425	3.683	3.929	3.806	4.776	3.311	2.808	2.808	2.935	2.554
Jul	3.56	1.903	2.296	3.186	3.436	3.683	4.294	2.935	2.425	3.061	2.935	2.554
Aug	2.935	1.502	1.903	3.061	2.935	3.186	3.436	2.425	2.035	2.554	2.554	2.035
Sept	2.808	1.502	1.77	4.051	2.554	2.935	3.311	2.425	2.035	2.166	2.554	2.035
Oct	3.56	1.502	1.77	4.536	3.186	2.808	3.311	2.681	2.035	2.554	2.935	2.166
Nov	3.929	1.77	2.166	5.134	3.436	2.935	4.415	2.808	2.035	3.061	3.311	2.425
Dec	3.806	2.035	2.296	5.015	3.061	3.56	4.536	3.186	2.296	3.061	3.436	2.554
Aver	3.609	1.955	2.272	4.348	3.483	3.668	4.349	3.223	2.6835	2.828	3.08	2.445

Table 7 Mean wind speed at 50 m altitude

Mois	Abec	Am-T	Bok	Fay	Mon	Mou	N'Dja	Pala	Sarh	Bol	Mao	Ati
Jan	4.255	2.569	2.86	5.962	3.569	4.791	5.447	4.119	3.147	3.569	3.846	2.86
Feb	4.39	2.715	3.147	5.705	4.255	5.055	5.962	4.524	3.569	3.569	3.983	3.147
Mar	4.791	2.421	3.147	5.576	4.791	4.791	6.217	4.524	3.846	3.569	4.119	3.289
Apr	4.658	2.569	2.86	5.055	4.791	5.055	4.923	4.39	4.923	3.289	3.569	3.004
May	4.255	2.86	2.86	4.524	4.791	4.524	4.923	4.255	3.708	3.147	3.429	3.004
Jun	3.846	2.569	2.86	4.255	4.524	4.39	5.447	3.846	3.289	3.289	3.429	3.004
Jul	4.119	2.272	2.715	3.708	3.983	4.255	4.923	3.429	2.86	3.569	3.429	3.004
Aug	3.429	1.814	2.272	3.569	3.429	3.708	3.983	2.86	2.421	3.004	3.004	2.421
Sept	3.289	1.814	2.121	4.658	3.004	3.429	3.846	2.86	2.421	2.569	3.004	2.421
Oct	4.119	1.814	2.121	5.186	3.708	3.289	3.846	3.147	2.421	3.004	3.429	2.569
Nov	4.524	2.121	2.569	5.834	3.983	3.429	5.055	3.289	2.421	3.569	3.846	2.86
Dec	4.39	2.421	2.715	5.705	3.569	4.119	5.186	3.708	2.715	3.569	3.983	3.004
Aver	4.172	2.33	2.687	4.978	4.033	4.236	4.98	3.746	3.145	3.31	3.589	2.882

Table 8 Mean wind speed at 67 m altitude

Mois	Abec	Am-T	Bok	Fay	Mon	Mou	N'Dja	Pala	Sarh	Bol	Mao	Ati
Jan	4.622	2.833	3.144	6.411	3.897	5.185	5.873	4.479	3.449	3.897	4.19	3.144
Feb	4.764	2.99	3.449	6.143	4.622	5.462	6.411	4.905	3.897	3.897	4.335	3.449
Mar	5.185	2.675	3.449	6.008	5.185	5.185	6.677	4.905	4.19	3.897	4.479	3.6
Apr	5.046	2.833	3.144	5.462	5.185	5.462	5.324	4.764	5.324	3.6	3.897	3.298
May	4.622	3.144	3.144	4.905	5.185	4.905	5.324	4.622	4.044	3.449	3.749	3.298
Jun	4.19	2.833	3.144	4.622	4.905	4.764	5.873	4.19	3.6	3.6	3.749	3.298
Jul	4.479	2.515	2.99	4.044	4.335	4.622	5.324	3.749	3.144	3.897	3.749	3.298
Aug	3.749	2.021	2.515	3.897	3.749	4.044	4.335	3.144	2.675	3.298	3.298	2.675
Sept	3.6	2.021	2.353	5.046	3.298	3.749	4.19	3.144	2.675	2.833	3.298	2.675
Oct	4.479	2.021	2.353	5.6	4.044	3.6	4.19	3.449	2.675	3.298	3.749	2.833
Nov	4.905	2.353	2.833	6.277	4.335	3.749	5.462	3.6	2.675	3.897	4.19	3.144
Dec	4.764	2.675	2.99	6.143	3.897	4.479	5.6	4.044	2.99	3.897	4.335	3.298
Aver	4.534	2.576	2.959	5.38	4.386	4.601	5.382	4.083	3.445	3.622	3.918	3.167

Table 9 Extrapolation of the parameter *k* to 30 m

Mois	Abec	Am-T	Bok	Fay	Mon	Mou	N'Dja	Pala	Sarh	Bol	Mao	Ati
Jan	3.081	1.105	3.878	3.82	3.848	3.648	4.666	3.224	1.206	4.916	4.35	2.899
Feb	3.547	1.072	3.436	3.715	3.516	3.274	4.243	3.574	1.244	4.565	4.476	2.835
Mar	3.218	4.588	4.126	3.041	3.871	3.288	4.514	3.174	1.32	4.7	4.812	2.911
Apr	3.582	4.474	4.336	3.958	3.576	2.904	3.964	3.236	1.637	4.16	4.632	2.647
May	3.081	1.542	3.878	3.664	3.108	3.058	4.352	3.516	3.429	4.3	4.955	2.723
Jun	3.113	2.151	3.983	3.811	3.121	3.175	4.729	3.309	3.767	4.471	4.407	2.723
Jul	3.149	2.478	3.51	3.67	2.96	3.338	4.411	4.022	3.778	4.632	4.551	2.895
Aug	2.816	3.598	3.304	3.589	2.901	2.731	4.121	3.594	3.175	4.203	4.911	3.175
Sept	2.813	3.214	3.792	3.598	2.684	3.088	4.133	3.138	3.175	3.949	5.199	3.175
Oct	3.324	2.465	3.532	4.08	3.397	2.42	3.563	3.682	2.953	4.65	4.785	2.642
Nov	3.797	1.213	3.949	4.231	3.668	3.267	4.45	2.666	1.694	4.502	4.133	2.198
Dec	3.625	1.187	3.84	4.222	3.294	3.388	4.137	2.285	1.307	4.204	4.796	2.806
Aver	3.262	2.424	3.797	3.783	3.329	3.132	4.274	3.285	2.39	4.438	4.667	2.802

value of 1.072 is recorded in February in Am-Timan, while the highest value of 5.199 is recorded in Mao in the month of September.

Table 10 presents values of *k* at altitude of 50 m. From Table 10, it can be seen that at 50 m altitude the minimum *k* value of 1.077 is recorded at Am-Timan in February and the maximum value of 5.223 at Mao is recorded in September.

Table 11 presents extrapolated values of parameter *k* at 67 m altitude. The least value of 1.08 is observed in Am-Timan in February, while the highest value of 5.237 is recorded in Mao in September.

Table 12 presents extrapolated values of the scale parameter *c* at 30 m altitude. From Table 12, it can be seen that the minimum value of 1.65 m/s is recorded in the month of August in Am-Timan, while the maximum value of 5.964 m/s is recorded in N'Djamena in the month of March.

Table 13 presents extrapolated values of parameter *c* at 50 m altitude. From Table 13, it can be seen that the minimum value of parameter *c* is 1.984 m/s in the month of August in Am-Timan, while the maximum value of 6.727 m/s is recorded in N'Djamena in the month of March.

The extrapolated values of parameter *c* extrapolated at 67 m altitude are presented in Table 14. From Table 14, the minimum value of 2.205 m/s is recorded in Am-Timan in August, while the maximum value of 7.208 m/s is recorded in N'Djamena in March. It is found that the value of *c* increases with altitude, and hence, it can be concluded that the site assessed is windy.

Comparison of the wind energy potential at the three climatic zones assessed

From the comparison of wind characteristics in the three selected climatic zones at 10 m altitude, it can be deduced that:

The minimum wind speed of 1.342 m/s is recorded at Am-Timan, while the maximum speed of 3.25 m/s is recorded at N'Djamena and Faya-Largeau.

Table 10 Extrapolation of the parameter *k* to 50 m

Mois	Abec	Am-T	Bok	Fay	Mon	Mou	N'Dja	Pala	Sarh	Bol	Mao	Ati
Jan	3.095	1.11	3.895	3.837	3.866	3.665	4.688	3.239	1.211	4.938	4.37	2.912
Feb	3.564	1.077	3.452	3.732	3.532	3.289	4.262	3.59	1.25	4.586	4.497	2.848
Mar	3.233	4.609	4.145	3.055	3.888	3.303	4.534	3.188	1.326	4.721	4.834	2.925
Apr	3.598	4.495	4.356	3.976	3.592	2.917	3.983	3.251	1.644	4.179	4.653	2.659
May	3.095	1.549	3.895	3.68	3.122	3.072	4.372	3.532	3.445	4.319	4.978	2.736
Jun	3.127	2.161	4.001	3.828	3.136	3.189	4.75	3.324	3.784	4.492	4.427	2.736
Jul	3.163	2.489	3.526	3.686	2.973	3.354	4.431	4.04	3.795	4.653	4.572	2.908
Aug	2.829	3.614	3.319	3.605	2.914	2.744	4.14	3.61	3.189	4.222	4.933	3.189
Sept	2.826	3.229	3.809	3.614	2.696	3.102	4.152	3.153	3.189	3.967	5.223	3.189
Oct	3.339	2.476	3.548	4.098	3.412	2.432	3.579	3.698	2.966	4.671	4.807	2.654
Nov	3.814	1.218	3.967	4.25	3.684	3.282	4.47	2.678	1.702	4.522	4.152	2.208
Dec	3.642	1.192	3.858	4.241	3.309	3.403	4.156	2.296	1.313	4.223	4.818	2.819
Aver	3.277	2.435	3.814	3.8	3.344	3.146	4.293	3.3	2.401	4.458	4.689	2.815

Table 11 Extrapolation of the parameter k to 67 m

Months	Abec	Am-T	Bok	Fay	Mon	Mou	N'Dja	Pala	Sarh	Bol	Mao	Ati
Jan	3.103	1.113	3.905	3.848	3.876	3.675	4.7	3.247	1.214	4.951	4.381	2.92
Fév	3.573	1.08	3.461	3.742	3.541	3.297	4.274	3.599	1.253	4.598	4.509	2.856
Mar	3.241	4.621	4.156	3.063	3.898	3.312	4.546	3.197	1.329	4.733	4.846	2.932
Apr	3.608	4.507	4.367	3.987	3.601	2.925	3.993	3.26	1.649	4.19	4.665	2.666
May	3.103	1.553	3.905	3.69	3.131	3.08	4.384	3.541	3.454	4.331	4.991	2.743
Jun	3.136	2.166	4.011	3.838	3.144	3.198	4.763	3.333	3.794	4.504	4.438	2.743
Jul	3.171	2.496	3.535	3.696	2.981	3.362	4.442	4.051	3.805	4.665	4.584	2.916
Aug	2.837	3.624	3.328	3.615	2.922	2.751	4.151	3.62	3.198	4.233	4.946	3.198
Sept	2.834	3.237	3.819	3.624	2.703	3.11	4.163	3.161	3.198	3.978	5.237	3.198
Oct	3.348	2.483	3.558	4.109	3.421	2.438	3.588	3.708	2.974	4.684	4.82	2.661
Nov	3.824	1.222	3.978	4.261	3.694	3.29	4.482	2.685	1.707	4.534	4.163	2.214
Dec	3.651	1.195	3.868	4.252	3.318	3.412	4.167	2.302	1.316	4.234	4.831	2.826
Aver	3.286	2.441	3.824	3.81	3.353	3.154	4.304	3.309	2.407	4.47	4.701	2.823

Table 12 Extrapolation of parameter c at 30 m altitude

Months	Abec	Am-T	Bok	Fay	Mon	Mou	N'Dja	Pala	Sarh	Bol	Mao	Ati
Jan	4.076	2.232	2.656	5.756	3.354	4.583	5.179	3.932	2.83	3.311	3.604	2.69
Feb	4.186	2.345	2.954	5.504	4.052	4.874	5.725	4.319	3.253	3.324	3.735	2.977
Mar	4.609	2.209	2.926	5.421	4.569	4.605	5.964	4.342	3.561	3.319	3.854	3.115
Apr	4.454	2.354	2.64	4.83	4.587	4.898	4.697	4.204	4.744	3.065	3.321	2.841
May	4.076	2.665	2.656	4.315	4.616	4.35	4.674	4.052	3.51	2.921	3.173	2.839
Jun	3.663	2.416	2.652	4.036	4.346	4.207	5.176	3.653	3.08	3.052	3.193	2.839
Jul	3.936	2.121	2.527	3.499	3.808	4.062	4.67	3.208	2.658	3.321	3.188	2.833
Aug	3.259	1.65	2.1	3.365	3.256	3.542	3.751	2.666	2.249	2.784	2.761	2.249
Sept	3.119	1.659	1.94	4.452	2.84	3.248	3.614	2.681	2.249	2.37	2.754	2.249
Oct	3.926	1.674	1.948	4.954	3.511	3.131	3.641	2.944	2.256	2.77	3.179	2.41
Nov	4.306	1.871	2.37	5.597	3.773	3.24	4.8	3.124	2.253	3.326	3.614	2.706
Dec	4.181	2.14	2.515	5.467	3.378	3.924	4.951	3.555	2.465	3.337	3.721	2.836
Aver	3.983	2.111	2.49	4.766	3.841	4.055	4.737	3.557	2.926	3.075	3.341	2.715

Table 13 Extrapolation of parameter c to 50 m

Months	Abec	Am-T	Bok	Fay	Mon	Mou	N'Dja	Pala	Sarh	Bol	Mao	Ati
Jan	4.686	2.644	3.119	6.503	3.892	5.237	5.883	4.528	3.313	3.846	4.168	3.157
Feb	4.805	2.771	3.45	6.233	4.659	5.553	6.471	4.951	3.781	3.86	4.312	3.476
Mar	5.266	2.618	3.42	6.144	5.223	5.262	6.727	4.976	4.121	3.854	4.442	3.629
Apr	5.097	2.781	3.101	5.505	5.242	5.579	5.361	4.825	5.412	3.573	3.857	3.325
May	4.686	3.129	3.119	4.945	5.273	4.984	5.336	4.659	4.065	3.414	3.693	3.323
Jun	4.233	2.85	3.114	4.642	4.98	4.828	5.879	4.222	3.59	3.559	3.715	3.323
Jul	4.532	2.519	2.974	4.053	4.393	4.67	5.332	3.731	3.121	3.857	3.709	3.315
Aug	3.788	1.984	2.495	3.905	3.785	4.1	4.329	3.13	2.663	3.262	3.236	2.663
Sept	3.633	1.995	2.314	5.095	3.324	3.776	4.179	3.147	2.663	2.798	3.228	2.663
Oct	4.521	2.012	2.323	5.64	4.066	3.647	4.209	3.439	2.67	3.246	3.7	2.843
Nov	4.936	2.236	2.798	6.333	4.353	3.767	5.473	3.639	2.667	3.862	4.179	3.174
Dec	4.8	2.54	2.961	6.193	3.92	4.519	5.636	4.114	2.905	3.875	4.297	3.32
Aver	4.582	2.506	2.932	5.432	4.426	4.66	5.401	4.113	3.414	3.584	3.878	3.184

Table 14 Extrapolation of parameter c to 67 m

Months	Abec	Am-T	Bok	Fay	Mon	Mou	N'Dja	Pala	Sarh	Bol	Mao	Ati
Jan	5.075	2.913	3.419	6.975	4.239	5.653	6.328	4.909	3.625	4.19	4.53	3.46
Feb	5.201	3.049	3.771	6.693	5.047	5.984	6.941	5.353	4.122	4.205	4.682	3.798
Mar	5.683	2.885	3.739	6.6	5.638	5.679	7.208	5.379	4.48	4.199	4.819	3.961
Apr	5.506	3.059	3.401	5.934	5.659	6.011	5.783	5.221	5.836	3.902	4.202	3.639
May	5.075	3.43	3.419	5.348	5.691	5.388	5.757	5.047	4.421	3.733	4.028	3.636
Jun	4.599	3.134	3.415	5.029	5.384	5.224	6.324	4.588	3.919	3.887	4.052	3.636
Jul	4.914	2.78	3.266	4.408	4.767	5.058	5.753	4.069	3.422	4.202	4.046	3.628
Aug	4.129	2.205	2.754	4.252	4.126	4.459	4.7	3.431	2.933	3.571	3.544	2.933
Sept	3.965	2.216	2.56	5.505	3.637	4.116	4.542	3.449	2.933	3.078	3.535	2.933
Oct	4.902	2.235	2.57	6.074	4.423	3.98	4.573	3.76	2.941	3.555	4.035	3.126
Nov	5.338	2.476	3.078	6.797	4.726	4.107	5.9	3.971	2.938	4.208	4.542	3.478
Dec	5.195	2.802	3.252	6.652	4.268	4.9	6.07	4.473	3.192	4.221	4.666	3.633
Aver	4.965	2.765	3.22	5.856	4.8	5.047	5.823	4.471	3.73	3.912	4.223	3.488

Table 15 Characteristics of selected wind turbines

Characteristics	Bonus 300 kW/33	AN Bonus 1 MW/54	Vestas 2 MW/80
Rated power P_r (kW)	300	1000	2000
Hub height h (m)	30	50	67
Rotor diameter (m)	33.4	54.2	80
Rated wind speed V_r (m/s)	14	15	16
Cut-in wind speed V_c (m/s)	3	3	4
Cut-off wind speed V_f (m/s)	25	25	25

As for the power density, the highest power density of 28,609 W/m^2 is recorded at Faya-Largeau and the least power density of 3163 W/m^2 is recorded at Bokoro.

Estimation of electric power generation by wind turbines

Three wind turbines were selected for the estimation of wind power generation: Bonus 300 kW/33, Bonus 1 MW/54, and Vestas 2 MW/V80. Their rated power (Pr) is 300, 1000, and 2000 kW, respectively.

Table 15 shows the characteristic properties of selected wind turbines (Bonus 300 kW/33, Bonus 1 MW/54 and Vestas 2 MW/80).

For the three wind turbines, the one whose power is high is Vestas 2 MW/V80 including Faya-Largeau (327.18 kW) and Bokoro (9.49 kW). The wind turbine with the lowest power is Bonus 300 kW/33, Faya-Largeau (61.53 kW), and Bokoro (1.19 kW).

Table 16 Calculated annual energy estimate for selected wind turbines for selected sites

Sites	BONUS 300 kW/33			BONUS 1 MW/54			VESTAS 2 MW/V80		
	$P_{e,m}$	C_f (%)	E_{out}	$P_{e,m}$	C_f (%)	E_{out}	$P_{e,m}$	C_f (%)	E_{out}
Abeche	7.52	2.51	5418	197.43	19.74	142,148	327.18	16.36	235,569
Am-Timan	50.18	16.73	36,132	240.28	24.03	173,003	382.92	19.15	275,703
Bokoro	1.19	0.4	855	10.49	1.05	7554	9.49	0.47	6830
Mongo	36.02	12.01	25,935	172.26	17.23	124,026	283.76	14.19	204,304
N'Djamena	34.18	11.39	24,609	152.89	15.29	110,080	283.31	14.17	203,984
Faya-Larg	61.53	20.51	44,301	266.06	26.61	191,564	488.34	24.42	351,603
Moundou	56.07	18.69	40,373	257.30	25.73	185,257	435.46	21.77	313,533
Pala	31.78	10.59	22,879	154.81	15.48	111,464	247.86	12.39	178,457
Sarh	115.50	38.5	83,159	493.72	49.37	355,477	840.42	42.02	605,101
Bol	1.99	0.66	1435	13.79	1.38	9925	16.84	0.84	12,124
Mao	3.42	1.14	2461	20.03	2.00	14,423	29.39	1.47	21,162
Ati	12.45	4.15	8964	77.93	7.79	56,109	96.59	4.83	69,548

Annual energy generated by the three turbines for the 12 selected locations in Chad

Table 16 shows the annual energy generated by wind turbines selected for this study. It can be seen from Table 16 that:

- Bonus 300 kW/33 has the lowest capacity factor of 0.4% recorded in Bokoro and the highest capacity factor of 38.5% in Sarh.
- Bonus 1 MW/54 has the least capacity factor of 1.05% in Bokoro and the highest capacity factor of 49.37% in Sarh.
- 2 MW/V80 Bonus has the least capacity factor of 0.47% in Bokoro and highest capacity factor of 42.02% in Sarh.

In addition, Vestas 2 MW/V80 wind turbine produces highest energy output of 601.10 MWh/year and capacity factor of 42.02% in Sarh. According to [1], the value of this factor is generally affected by the intermittent nature of the wind, the availability of the machine and the efficiency of the turbine. Capacity factor usually varies from 20 to 70% in practice.

Where $P_{e,\,m}$ (kW/year) is the annual power produced by the turbine, C_f (%) is the capacity factor of the wind turbine, and E_{out} (MWh/year) is the annual production of accumulated energy.

Cost of electrical energy generated by the wind energy

Costs per kilowatt-hour (kWh) of electrical energy generated by the three wind turbines at 12 selected sites. This calculation was performed for the maximum and minimum values of thes specific cost of wind turbines (Tables 17, 18, 19).

The results obtained are shown in Table 17 which shows that the lowest value of the cost of wind power varies from \$143.08/kWh/year to \$132,343.89/kWh/year. This value was obtained for the Vestas 2 MW/V80 wind turbine.

Table 17 Cost of electrical energy generated by Bonus 300 kW/33 wind turbine

Locations	P_{out}	P_{er}	C_f (%)	E_{WT}	C_{USS}	C_{XAF}
Abeche	7.52	300	2.51	82,391.09	960.59	5801.97
Am-Timan	50.18	300	16.73	549,504.95	215,527.37	1,301,785.29
Bokoro	1.19	300	0.4	13,002.03	73,249.9	442,429.41
Faya	61.53	300	20.51	673,753.5	193.91	1171.2
Mongo	36.02	300	12.01	394,426.67	281.27	1698.88
Moundou	56.07	300	18.69	614,002.64	168.23	1016.13
N'Djamena	34.18	300	11.39	374,250.2	281.79	1702.02
Pala	31.78	300	10.59	347,950.49	742.03	4481.88
Sarh	115.5	300	38.5	1,264,705.29	2083.28	12,583.03
Bol	1.99	300	0.66	21,818.97	6044.97	36,511.62
Mao	3.42	300	1.14	37,432.58	7313.61	44,174.2
Ati	12.45	300	4.15	136,324.22	1635.68	9879.49

Table 18 Cost of electrical energy generated by BONUS 1 MW/54 wind turbine

Locations	P_{out}	P_{er}	C_f (%)	E_{WT}	C_{USS}	C_{XAF}
Abeche	197.43	1000	19.74	2,161,858.5	118.22	714.05
Am-Timan	240.28	1000	24.03	2,631,109.8	27,527.15	166,264
Bokoro	10.49	1000	1.05	114,876.45	6226.88	37,610.3
Faya	266.06	1000	26.61	2,913,378.9	130.13	785.98
Mongo	172.26	1000	17.23	1,886,247	174.7	1055.2
Moundou	257.3	1000	25.73	2,817,435	110.45	667.15
N'Djamena	152.89	1000	15.29	1,674,101.7	191.6	1157.24
Pala	154.81	1000	15.48	1,695,191.4	349.21	2109.21
Sarh	493.72	1000	49.37	5,406,234	649.77	3924.59
Bol	13.78	1000	1.38	150,934.8	2081.97	12,575.1
Mao	20.03	1000	2.00	219,361.35	2510.57	15,163.8
Ati	77.93	1000	7.79	853,333.5	539.67	3259.62

Table 19 Cost of electrical energy generated by VESTAS 2 MW/V80 wind turbine

Locations	P_{out}	P_{er}	C_f (%)	E_{WT}	C_{USS}	C_{XAF}
Abeche	327.18	2000	16.36	3,582,621	147.39	890.25
Am-Timan	382.92	2000	19.15	4,192,996	132,343.89	799,357.1
Bokoro	9.49	2000	0.47	103,916	56,876.63	343,534.87
Faya	488.34	2000	24.42	5,347,279	159.67	964.4
Mongo	283.75	2000	14.19	3,107,150	234.9	1418.8
Moundou	435.46	2000	21.77	4,768,309	143.08	864.21
N'Djaména	283.31	2000	14.17	3,102,266	224.59	1356.5
Pala	247.86	2000	12.39	2,714,045	619.44	3741.39
Sarh	840.42	2000	42.02	9,202,555	1733.31	10,469.17
Bol	16.84	2000	0.84	1,84,420	4935.24	29,808.88
Mao	29.39	2000	1.47	3,21,821	5896.99	35,617.82
Ati	96.59	2000	4.83	1,057,661	1369.09	8269.3

Conclusion

In this study, comprehensive estimation of the electrical energy generated and cost per kilowatt-hour of electrical energy generated by three different types of wind turbines at selected locations in Chad are carried out. The results obtained showed that:

- The average annual speed varies from 1 m/s in Am-Timan to 4.2 m/s in N'Djamena at 10 m high. The maximum wind speed occurs in the month of March, while the least speed occurs in the months of August, September, and October.
- The wind speed is extrapolated to 30.50 and 67 m altitude. Similarly, Weibull parameters k and c are also extrapolated to 30.50 and 67 m altitude.
- The capacity factor values vary from one wind turbine to another: for the 300 kW/33 Bonus wind turbine, it varies from 0.4 to 38.5%. For Bonus 1 MW/54, the value varies between 1.05 and 49.37% and Vestas 2 MW/V80, it is from 0.47 to 42.02%.
- Comparative assessment of electricity generated by the three types of wind turbines was carried out. Result of this study shows that Vestas 2 MW/V80 wind turbine with a hub height of 80 m produced the highest energy.
- For the Sarh site, the highest capacity factor, annual power, and energy output are 42.02%, 840.42 kW/year, and 605.10 MWh/year, respectively, recorded. The least capacity factor, annual power, and energy output of 0.47%, 9.49 kW/year, and 6830 MWh, respectively are recorded in Bokoro.
- The average least cost per kWh of electricity generated was obtained at Moundou of 143.08$/kWh/year the model Vestas 2 MW/V80, while the highest average cost of $132,343.89/kWh/year recorded in Am-Timan. Based on these values, it can be concluded that for the Am-Timan site, wind power generation, with wind turbines, is not economical.
- For the three wind turbines, the one whose power is high is Vestas 2 MW/V80 including Faya-Largeau (327.18 kW) and Bokoro (9.49 kW). The wind turbine with the lowest power is Bonus 300 kW/33, Faya-Largeau (61.53 kW), and Bokoro (1.19 kW).
- Electrical and mechanical applications not connected to the network (water pumping, recharging of batteries) would be more suitable. On the other hand, the construction of a wind farm in the Moundou region can be considered.

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Compliance with ethical standards

Conflict of interest The authors declare that there is no conflict of interests regarding the publication of this paper.

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