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Determination of Feasibility Analysis of Wind Turbines Using Weibull Parameter for Chad

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Abstract

Wind energy is one of the most important renewable energy sources whose technology and use have shown the fastest development and the economy has become competitive with fossil-based energy sources. To assess the potential of wind energy as a source of electricity generation, this paper uses the Weibull probability density function for three sites. Five wind turbines are considered for the study. The standard method is used to determine the values of the Weibull parameters. The average wind speed was measured and collected at the General Directorate of National Meteorology at 10 m altitudes. The results obtained show that the turbine capacity factor for three sites ranges from 0.03% to 6.47% (Enercon-70); 0.09% to 13.50% (Enercon-82); 0.04% to 9.27% (Nordex N90); 0.03% to 9.87% (Nordex S77) and 0.07% to 11.63% (Vestas V90-20). The present cost value (PVC) calculation technique economically evaluates the five wind turbines. The Enercon-82 wind turbine has a capacity factor of up to 13.5% with a cost of USD 23.09, while Enercon-70 has a lower factor of 6.47% with a cost of USD 496,393. Considering its capacity factor and annual energy generation of up to 3,000 TWh, therefore the Enercon-82 wind turbine could be recommended for the three cities in Chad.

Keywords
Wind turbine; Capacity factor; Power generation; Wind energy potential; Weibull and Rayleigh distributions; Feasibility study

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1 Introduction

The world population has grown exponentially in the last few centuries. Due to this rapid increase in population, energy demand is also increasing. In recent years, priority has been given to research on sustainable, renewable, and environmentally friendly energy sources in order to meet the energy demand in the world. Energy is among the essential elements for power generation as well as economic development to meet the global energy demand[1-3]. Conventional fossil fuels have been the main sources for a long time. Thus, it is necessary to reduce their use because of the adverse environmental effects and the exorbitant cost of energy demand. This exponential increase in energy demand leads to a tendency towards alternative energy sources[4-6]. In recent years, the use of wind energy is accepted in the world because of its abundance, inexhaustibility, cleanliness, and environmental friendliness to produce electricity[7]. Some of its advantages considered are no geographical or political impact to its installation and requires less maintenance[8]. Wind energy is known for its rapid growth characteristics among renewable energy sources in developing and developed countries[9]. Some developing countries benefit from such energy due to its abundance in the environment while developed countries such as the United States of America, Spain, Germany, Denmark, and China continue to increase their production capacity from the advancement of renewable energy technologies[10].

There are significant differences in the amount of energy consumed per capita between developed and developing countries. This situation is changing day by day due to the rapid developments in communication technology and the living standards created by the interaction between people. The amount of energy used in the past years has always shown an increasing trend and will continue in the future. For this reason, active use of renewable energy resources which are wasted due to insufficient investments should be started. Wind energy which is one of the most important renewable energy types will continue to produce kinetic energy with wind movements caused by atmospheric conditions as long as the world exists.

Wind energy is an inexhaustible energy source whose use is increasing, and potential is newly discovered. Expectations from wind turbine sites are to recover the investment costs in a minimum time and to convert the produced energy into profit in an optimum way. The turbine efficiency relationship is also important due to the wind parameters and technical potential of the selected site. Besides, in the analysis of the turbine class usage in a particular region, a good calculation should be made of how much of the existing capacity will be converted into electrical energy, which class turbine selection will increase the capacity factor, and that the capacity can be used optimally. Various studies have been carried out by the International Energy Agency (IEA) in order to determine the world's wind energy potential. In these studies, the world technical wind potential has been calculated as 53,000 TWh/year, based on the assumption that 4% of the regions with a wind capacity above 5.1 m s^{-1} will be used due to practical and social constraints. Continents or regions with high wind energy potential are listed respectively; North America (14,000 TWh/year), Eastern Europe and Russia (10,600 TWh/year), Africa (10,600 TWh/year), South America (5,400 TWh/year), Western Europe (4,800 TWh/year), Asia (4,600 TWh/year) and Oceania (3,000 TWh/year). These data show that North America, Eastern Europe, Russia, and Africa have 66% of the world's wind energy potential.

Using different methods to determine the Weibull parameters in two regions of Morocco, the investigation of the wind potential was carried out[11]. The determination of the electrical performance of curved vertical wind turbine blades and the experimental study of a new design was presented by Kalakanda et al.[12]. Onanuga et al.[13], conducted an experimental and even analytical analysis on the bladeless turbine for the incompressible fluid. Recently, Weibull distribution was favoured to find prospective wind locations in wind energy planning software like Wind Atlas. Given that wind power is proportional to the cube of wind speed, the distribution of wind speed is necessary[14]. Mohamadi et al.[15] conducted a study on the assessment of wind resources in eastern Iran in 22 regions. They concluded in their study on the average wind speed, power density, and the estimation of Weibull parameters. Alemzero et al.[16] studied the policy barriers and incentives for wind energy development in Africa. Shields et al.[17] used the techno-economic costs and estimated the total installed capacities and the cost of energy (LCOE) of the nominal turbine power. Dabar et al.[18] through their wind data analyses from three sites in Djibouti presented promising wind potential. Himri et al.[19] used the RETScreen and WAsP tools to estimate the economic reliability in the South-West of Algeria for the establishment of wind farms. Billal et al.[20] were focusing on seasonal and daily analysis of wind data have assessed wind potential as well as energy yield in northwest Africa. Katinas et al.[21] measured the data obtained over a period of 2 years in Lithuania and studied the power density and wind characteristics at different locations. Yilmaz et al.[22] studied the capacity of generating electricity from wind energy to meet the energy demand in Turkey. El Khchine et al.[11] using Weibull probability density function methods evaluated the potential energy in the cities of Dakhla and Taza in Morocco. Saeed and friends[23] have used data from different locations throughout Pakistan and compared the numerous numerical methods of Weibull distribution to evaluate wind energy potential for a proper analysis. Elia et al.[24] showed that over the past 20 years, wind energy costs have fallen. Rogers et al.[25] examined high electricity prices in small states when wind potential is abundant. Electricity production in Chad depends heavily on thermal power plants that run on diesel. Due to a lack of renewal and maintenance, these plants lose efficiency and often break down. Despite huge investments, production capacity throughout the country remains very low in the areas such as N'Djamena (120 MW), Kome (129 MW), Farcha-1 (22 MW), Farcha-2 (63 MW), Djermaya (20 MW), Sarh (10 MW), to name just a few of the major production units. Although the Djermaya refinery supplies the National Electricity Company Société Nationale d'Electricité (SNE) with 10 to 13 tankers a day to run the power stations, the management of this diesel is a source of controversy. This explains the frequent changes in the management of SNE[11]. The total consumption of electrical energy is 208.60 million kWh per year, which represents a consumption of approximately 13 kWh per capita.

In this paper, wind speed data are extracted over a 20-30-year period at the Abeche, Mongo, and N'Djamena sites to analyse the wind potential. The standard variation method predicts energy production and wind power as well as selects the most appropriate wind turbines for each site and the unit cost of energy. This study consists of four chapters. In the first part, the wind energy installation model is examined. In the second part, the method used in the study is explained. In the third section, the results obtained from the running of the model are presented and a wind power plant installation has been carried out according to these results. In the last part, the electrical energy that can be produced from different types of wind turbines is examined and the results obtained are discussed.

2 Materials and Methods

2.1 Characteristics of the Selected Locations

The coordinates of the places selected within the scope of the study are given in Table 1.

Table 1. Geographic coordinates of the selected study locations.

Location	Latitude (°N)	Longitude (°E)	Altitude (m)
Abeche	13°51	20°51	545
Mongo	12°11	18°41	430
N'Djamena	12°80	20°17	432

2.2 Probability Density Function

To analyse and describe wind resources, Weibull and Rayleigh distributions are used. The Weibull distribution among the different statistical methods proved to be the most accurate. Thus, the probability of observing wind speed, f(*v*), is given by Equation 1[26-29],

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

and f(*v*), the cumulative distribution function, is given by Equation 2.

$$\mathrm{f}(v) = 1 - \exp\left(-\left(\frac{v}{c}\right)^{k}\right) \tag{2}$$

where, c and k (Equations 3 and 4)[11] are the Weibull scale and shape parameters respectively, *v* is the speed of wind (m s^{-1}), and f(*v*) is the cumulative distribution function.

$$\mathrm{c} = \frac{\bar{v}}{\Gamma\left(1+\frac{1}{k}\right)} \tag{3}$$

$$\mathrm{k} = \left(\frac{\sigma}{\bar{v}}\right)^{-1.086} \tag{4}$$

2.3 Standard Deviation Method

Steps to be followed when calculating the standard deviation are: 1) The arithmetic mean of the data is found. 2) The difference between each data and the arithmetic mean is found. 3) Each of the differences found is squared and the obtained numbers are added up. 4) This sum is divided by 1 minus the number of data and the square root of the quotient is found. The mean wind speed and the standard deviation are given by Equation 5[30-31].

$$\sigma = \sqrt{\frac{1}{N-1}\sum_{i=1}^{N}(v_i - \overline{v})^2} \tag{5}$$

where $\overline{v}$ is the average wind speed and can be expressed as in Equation 6.

$$\overline{v} = \frac{1}{N}\sum_{i=1}^{N} v_i \tag{6}$$

where N, the number of measured daily wind speed data; σ, standard deviation (m s^{-1}); $\overline{v}$, mean wind speed (m s^{-1}).

2.4 Evaluation of Wind Power Density (WPD)

The Weibull cumulative distribution function is one of the most widely used statistical distributions for determining wind energy potential. Wind energy estimation, average WPD, and average wind speed are usually based on the two-parameter Weibull probability density function. The wind energy density is expressed as in Equations 7 and 8[11].

$$\mathrm{p}(v) = \frac{1}{2}\rho A(v)^3 \tag{7}$$

$$\mathrm{P} = \int_0^{\infty} \frac{\mathrm{p}(v)}{A}\mathrm{f}(v) = \frac{1}{2}\rho c^3 \Gamma\left(1 + \frac{3}{k}\right) \tag{8}$$

The average power density for the Weibull distribution is obtained from Equation 9 as follows.

$$\mathrm{E} = \frac{1}{2}\rho c^3 \Gamma\left(1 + \frac{3}{k}\right) T \tag{9}$$

where Γ is the gamma function; E is the energy density, ρ represents the wind power density (the air density value at sea level is 1.225 kg m^3) and T is the desired time.

2.5 Extrapolation of Wind Speed

With the help of the recorded wind speed extrapolation methods, the wind speed at the hub heights of the wind turbine can be estimated. The extrapolation Equations 10, 11, 12, and 13 used in wind speed estimation have been formulated[11]. In general, the wind speed values to be used in extrapolation methods can be used at least 2 m high.

$$\mathrm{v} = v_0 \left(\frac{z}{z_0}\right)^{\alpha} \tag{10}$$

$$\alpha = \frac{[0.37 - 0.088\ln(v_0)]}{\left[1 - 0.088\ln\left(\frac{z_0}{10}\right)\right]} \tag{11}$$

where v, the wind speed, v_0 the wind speed is measured at a height of 10 m[11].

$$k_z = \frac{k_0}{1 - 0.088\ln\left(\frac{z}{10}\right)} \tag{12}$$

$$c_z = c_0 \left(\frac{z}{z_0}\right)^{\alpha} \tag{13}$$

where c_z and k_z are the scale factor and shape parameter at α measured height z_0.

2.6 Output Power of the Capacity Factor and Wind Turbine

Since wind speed is the variable, the wind turbine can never produce as much as its nominal power multiplied by the total hours in a year. The ratio of the average power of the plant to its nominal power is called the capacity factor. The capacity factor is a parameter that shows how efficiently a power plant is used. In the wind energy conversion system, the average power is expressed by Equations 14, 15, 16, 17 and 18[32,33].

$$P_{\mathrm{avr}} = \int_{V_{ci}}^{V_{c0}} \mathrm{P}(v)\mathrm{f}(v)\mathrm{d}v \tag{14}$$

$$\mathrm{P} = \left\{ \begin{array}{ll} P_r = \frac{V_i^2 - V_{\mathrm{ci}}^2}{V_r^2 - V_{\mathrm{ci}}^2} & V_{ci} \le V_i \le V_r \\ \mathrm{P}_r = \frac{1}{2}\rho A C_p V_{\mathrm{i}}^3 & V_r \le V_i \le V_{\mathrm{c0}} \\ 0 & V_r \le V_{ci} \ \& \ V_i \ge V_{\mathrm{c0}} \end{array} \right\} \tag{15}$$

$$P_{\mathrm{avr}} = P_r \left[\int_{V_{ci}}^{V_r} \frac{V_{\mathrm{i}}^2 - V_{\mathrm{ci}}^2}{V_{\mathrm{r}}^2 - V_{\mathrm{ci}}^2} f(v)\mathrm{d}v + \int_{V_{ci}}^{V_{c0}} \mathrm{P}(v)\mathrm{f}(v)\mathrm{d}v\right] \tag{16}$$

$$P_{\mathrm{avr}} = P_r \left\{ \frac{e^{-\left(\frac{v_{ci}}{c}\right)^k} - e^{-\left(\frac{v_r}{c}\right)^k}}{\left(\frac{v_r}{c}\right)^k - \left(\frac{v_{ci}}{c}\right)^k} - e^{-\left(\frac{v_{c0}}{c}\right)^k} \right\} \quad (17)$$

$$C_f = \frac{P_{\mathrm{avr}}}{P_r} = \left\{ \frac{e^{-\left(\frac{v_{ci}}{c}\right)^k} - e^{-\left(\frac{v_r}{c}\right)^k}}{\left(\frac{v_r}{c}\right)^k - \left(\frac{v_{ci}}{c}\right)^k} - e^{-\left(\frac{v_{c0}}{c}\right)^k} \right\} \quad (18)$$

2.7 Econometric of the Wind Energy System

The ability to generate energy at an optimal cost is the economic viability of a wind turbine. For a given site, the cost of a wind turbine takes into account the wind speed and the following costs: the cost of operation and maintenance (C_{opm})[6]:

$$\mathrm{PVC} = I_{\mathrm{inv}} + C_{\mathrm{opm}} \times \left[\frac{1+i}{r-\mathrm{i}}\right] \times \left[1 - \left(\frac{1+i}{1+r}\right)^t\right] - \mathrm{S_v} \times \left(\frac{1+i}{1+r}\right)^{\mathrm{t}} \quad (19)$$

where PVC, the present value of costs; I_{inv}, the investment cost (20%); S_v, the scrap value (10%); i, the inflation rate (3.6%); i_0, the nominal interest (16%); t, the lifetime of turbine in years (20); C_{opm}, the operation, maintenance, and repair cost (7.5%); r, the discount rate given by Equation 20[34].

$$r = \frac{i_0 - i}{1 + i} \quad (20)$$

For electricity production, the availability of the wind resource (A) is taken as 75% and the total energy E_T is estimated by Equation 21[35].

$$E_T = 8760 \cdot A \cdot t \cdot \mathrm{P_r} \cdot \mathrm{C_f} \quad (21)$$

Using the *PVC* method, the cost of electricity (COE) per unit in kWh is calculated as in Equation 22[36,37].

$$\mathrm{COE} = \frac{\mathrm{PVC}}{E_T} \quad (22)$$

As a collective result from conferences, research, and statistics, it has been determined that the most effective way to reduce carbon emissions is wind energy. Important companies around the world prefer the use of wind energy and invest in the sector. With this environmentally concerned awareness from the companies, the competition to use wind energy increases, and the value of companies increases. Companies that choose wind energy effectively reduce the emissions they produce, while investing in cheap and reliable energy. When energy sources other than wind are examined, it is seen that the least cost is in wind energy. With the developments made, the cost of wind energy is decreasing, and the production capacity is increasing.

2.8 Weibull Distribution Equations

Today, the most widely used method for determining wind potential is the Weibull distribution method. With this method, shape and scale parameters are found. These parameters were calculated using Graphic and Moment methods. These two methods were preferred because they are two of the most used methods today[26]. In the graphical method, the available data is used, and the coefficients are found by obtaining a linear equation. In the Moment method, the coefficients are calculated by numerical methods using the gamma function depending on the average wind speed and standard deviation.

Equations 23, 24, and 25 show us the functions with Weibull parameters determined for the three sites in central Chad. Based on these equations, it was noticed that the different parameters vary from one city to another. In the next section, the necessary calculations were made by giving the formulas of the methods used, and the results and graphics were given in detail.

For the Abeche city:
$c = 1.65$; $k = 3.65$

$$f(v) = 2.21 \left(\frac{v}{1.65}\right)^{2.65} \cdot \exp\left(-\left(\frac{v}{1.65}\right)^{3.65}\right) \quad (23)$$

For the Mongo city:
$c = 1.59$; $k = 3.74$

$$f(v) = 2.35 \left(\frac{v}{1.59}\right)^{2.65} \cdot \exp\left(-\left(\frac{v}{1.59}\right)^{3.74}\right) \quad (24)$$

For the N'Djamena city:
$c = 1.54$; $k = 8.16$

$$f(v) = 5.30 \left(\frac{v}{1.54}\right)^{7.16} \cdot \exp\left(-\left(\frac{v}{1.54}\right)^{8.16}\right) \quad (25)$$

3 Results and Discussion

Table 2 shows the different values of the Weibull parameters extrapolated at 105 m altitudes for the three locations. Thus, from 10 to 105 m altitude, the highest velocity is recorded at N’Djamena city (3.25 to 6.063 m s^{-1} respectively). The lowest speed is recorded at Mongo (2.54 to 4.99 m s^{-1}). The highest values of the scale parameter are recorded in Abeche city after extrapolation (1.653 to 3.186 m s^{-1}). The lowest is observed in N’Djamena city (1.537 to 2.930 m s^{-1}). The highest values of the shape parameter extrapolated from 10 to 105 m altitudes are recorded in N’Djamena city (8.162 to 8.304) and the lowest are recorded in Abeche city (3.647 to 3.711).

Table 2. The wind parameters.

Location	Wind parameter	Hub-height					
		10 m	65 m	80 m	90 m	100 m	105 m
Abeche	*V*	2.640	4.495	4.768	4.930	5.080	5.151
	k	3.647	3.677	3.683	3.700	3.710	3.711
	C	1.653	2.228	2.364	3.071	3.115	3.186
Mongo	*V*	2.540	4.348	4.616	4.774	4.921	4.990
	k	3.735	3.765	3.772	3.789	3.799	3.800
	C	1.585	2.142	2.274	2.690	2.962	3.005
N’Djamena	*V*	3.250	5.339	5.641	5.820	5.985	6.063
	k	8.162	8.228	8.242	8.279	8.301	8.304
	C	1.537	2.083	2.213	2.621	2.888	2.930

These tables (Table 3 to Table 8) show that for all three cities, the Weibull scale and shape of the parameters increase with altitude. Thus, for the city of Abeche, the average value of the shape parameter k, varies from 3.647 (at 10 m altitude) to 3.711 (at 105 m altitude). The scale factor c is from 1.653 (at 10 m altitude) to 3.186 m s^{-1} (at 105 m altitude). For the city of Mongo, k varies from 3.735 (at 10 m altitude) to 3.800 (at 105 m altitude). The scale parameter for the city is 1.585 (at 10 m altitude) to 3.005 m s^{-1} (at 105 m altitude). For the city of N’Djamena, the form factor is 8.162 (at 10 m altitude) to 8.304 m s^{-1} (at 105 m altitude).

Table 3. Extrapolation of shape parameter for the city of Abeche at 105 m.

Month	k10	k65	k80	k90	k100	k105
January	3.63	3.66	3.67	3.69	3.70	3.70
February	4.02	4.06	4.06	4.08	4.09	4.09
March	3.77	3.80	3.81	3.83	3.84	3.84
April	4.01	4.04	4.05	4.07	4.08	4.08
May	3.29	3.32	3.33	3.34	3.35	3.35
June	3.49	3.52	3.53	3.54	3.55	3.55
July	3.30	3.32	3.33	3.34	3.35	3.35
August	2.86	2.89	2.89	2.91	2.91	2.91
September	3.08	3.10	3.11	3.12	3.13	3.13
October	3.64	3.67	3.67	3.69	3.70	3.70
November	4.58	4.62	4.63	4.65	4.66	4.66
December	4.09	4.13	4.13	4.15	4.16	4.16

Table 4. Extrapolation of scale parameter for the city of Abeche at 105 m.

Month	c10	c 65	c 80	c90	c100	c105
January	1.69	2.27	2.41	3.13	3.17	3.24
February	1.67	2.25	2.38	3.10	3.14	3.21
March	1.90	2.54	2.69	3.45	3.50	3.58
April	1.79	2.40	2.54	3.28	3.33	3.40
May	1.78	2.38	2.52	3.26	3.31	3.38
June	1.53	2.08	2.21	2.88	2.92	2.99
July	1.71	2.30	2.44	3.16	3.20	3.28
August	1.50	2.03	2.16	2.83	2.87	2.94
September	1.37	1.87	1.99	2.62	2.66	2.73
October	1.63	2.19	2.33	3.03	3.07	3.14
November	1.63	2.20	2.34	3.04	3.09	3.16
December	1.66	2.23	2.37	3.08	3.12	3.19

Table 5. Extrapolation of shape parameter for Mongo city at 105 m.

Month	k10	k 65	k 80	k 90	k 100	k 105
January	4.80	4.84	4.85	4.87	4.88	4.88
February	4.45	4.49	4.49	4.51	4.53	4.53
March	4.96	5.00	5.01	5.03	5.04	5.04
April	3.67	3.70	3.71	3.72	3.73	3.74
May	3.31	3.34	3.35	3.36	3.37	3.37
June	3.36	3.38	3.39	3.41	3.41	3.42
July	3.24	3.27	3.27	3.29	3.30	3.30
August	2.90	2.93	2.93	2.95	2.95	2.95
September	2.95	2.97	2.98	2.99	3.00	3.00
October	3.67	3.70	3.70	3.72	3.73	3.73
November	3.95	3.98	3.99	4.01	4.02	4.02
December	3.57	3.60	3.60	3.62	3.63	3.63

Table 6. Extrapolation of scale parameter for the city of Mongo at 105 m.

Month	c 10	c 65	c 80	c 90	c 100	c 105
January	1.22	1.68	1.79	2.15	2.38	2.42
February	1.54	2.09	2.22	2.63	2.90	2.94
March	1.69	2.28	2.42	2.85	3.14	3.18
April	1.93	2.57	2.72	3.19	3.49	3.54
May	2.03	2.69	2.85	3.34	3.65	3.70
June	1.89	2.52	2.67	3.13	3.43	3.48
July	1.66	2.24	2.37	2.80	3.08	3.13
August	1.48	2.02	2.15	2.55	2.81	2.85
September	1.26	1.74	1.85	2.21	2.45	2.49
October	1.43	1.95	2.08	2.47	2.72	2.77
November	1.50	2.04	2.17	2.57	2.84	2.88
December	1.39	1.90	2.02	2.40	2.66	2.70

Table 7. Extrapolation of shape parameter for the city of N'Djamena at 105 m.

Month	k10	k65	k80	k90	k100	k105
January	10.10	10.18	10.20	10.25	10.27	10.28
February	8.53	8.59	8.61	8.65	8.67	8.67
March	10.89	10.98	11.00	11.05	11.07	11.08
April	6.69	6.75	6.76	6.79	6.80	6.81
May	6.89	6.95	6.96	6.99	7.01	7.01
June	10.15	10.24	10.25	10.30	10.33	10.33
July	8.07	8.13	8.15	8.18	8.20	8.21
August	7.80	7.87	7.88	7.92	7.94	7.94
September	5.89	5.94	5.95	5.97	5.99	5.99
October	4.84	4.88	4.89	4.91	4.92	4.92
November	8.48	8.55	8.56	8.60	8.62	8.63
December	9.62	9.69	9.71	9.75	9.78	9.78

Table 8. Extrapolation of scale parameter for the city of N'Djamena at 105 m.

Month	c10	c 65	c 80	c 90	c 100	c105
January	1.62	2.18	2.32	2.74	3.02	3.06
February	1.86	2.49	2.63	3.09	3.39	3.44
March	1.86	2.48	2.63	3.09	3.39	3.44
April	1.59	2.14	2.28	2.69	2.97	3.01
May	1.57	2.13	2.26	2.67	2.95	2.99
June	1.62	2.18	2.32	2.74	3.01	3.06
July	1.51	2.05	2.18	2.58	2.85	2.89
August	1.19	1.65	1.76	2.10	2.33	2.37
September	1.24	1.71	1.82	2.18	2.41	2.45
October	1.32	1.82	1.93	2.31	2.55	2.59
November	1.54	2.09	2.22	2.63	2.89	2.94
December	1.54	2.09	2.22	2.63	2.90	2.94

3.1 Monthly Wind Speeds of Selected Cities

Table 9 shows the different wind speed values extrapolated at 65 m, 80 m, and 90 m altitude for the three sites. At 65 m, the minimum wind speed of 3.27 m s^{-1} was recorded in Mongo in September while the maximum wind speed of 6.63 m s^{-1} was recorded in N'Djamena in March. At 80 m altitude, it shows that the maximum wind speed of 6.97 m s^{-1} was recorded in March in N'Djamena, while the minimum wind speed of 3.49 m s^{-1} was recorded in Mongo in September. At 90 m altitude for the three sites, the minimum wind speed of 3.62 m s^{-1} was recorded at Mongo while the maximum value of 7.17 m s^{-1} was recorded at N'Djamena. This table shows that wind speed varies with altitude and season. In Table 9, monthly wind speeds distributed over 12 months are given. With the help of this table, the months with the highest wind potential can be easily seen.

Table 10 summarizes wind speed values extrapolated at 100 m and 105 m altitude. At 100 m, the maximum wind speed of 7.36 m s^{-1} was recorded in N'Djamena, and the minimum speed of 3.75 m s^{-1} in Mongo. At 105 m altitude, the minimum value is 3.8 m s^{-1} in Mongo, and the maximum value is 7.4 m s^{-1} in N'Djamena.

Table 9. Wind speed varies with altitude and season.

Month	65 m			80 m			90 m		
	Abeche	Mongo	N'Djamena	Abeche	Mongo	N'Djamena	Abeche	Mongo	N'Djamena
Jan.	4.58	3.86	5.83	4.86	4.11	6.15	5.02	4.26	6.34
Feb.	4.72	4.58	6.36	5.01	4.86	6.70	5.17	5.02	6.90
Mar.	5.14	5.14	6.63	5.44	5.44	6.97	5.62	5.62	7.17
Apr.	5.00	5.14	5.28	5.30	5.44	5.58	5.47	5.62	5.76
May	4.58	5.14	5.28	4.86	5.44	5.58	5.02	5.62	5.76
Jun.	4.15	4.86	5.83	4.41	5.15	6.15	4.57	5.32	6.34
Jul.	4.44	4.30	5.28	4.71	4.56	5.58	4.87	4.72	5.76
Aug.	3.71	3.71	4.30	3.96	3.96	4.56	4.10	4.10	4.72
Sept.	3.57	3.27	4.15	3.80	3.49	4.41	3.94	3.62	4.57
Oct.	4.44	4.01	4.15	4.71	4.26	4.41	4.87	4.41	4.57
Nov.	4.86	4.30	5.42	5.15	4.56	5.72	5.32	4.72	5.91
Dec.	4.72	3.86	5.56	5.01	4.11	5.87	5.17	4.26	6.05

Table 10. Wind speed values extrapolated to 100 m and 105 m altitude

Month	100 m			105 m		
	Abeche	Mongo	N'Dja.	Abeche	Mongo	N'Dja.
Jan.	5.18	4.40	6.51	5.25	4.46	6.59
Feb.	5.33	5.18	7.08	5.40	5.25	7.17
Mar.	5.78	5.78	7.36	5.86	5.86	7.45
Apr.	5.63	5.78	5.93	5.70	5.86	6.00
May	5.18	5.78	5.93	5.25	5.86	6.00
Jun.	4.71	5.48	6.51	4.78	5.55	6.59
Jul.	5.02	4.87	5.93	5.09	4.94	6.00
Aug.	4.24	4.24	4.87	4.30	4.30	4.94
Sept.	4.07	3.75	4.71	4.14	3.80	4.78
Oct.	5.02	4.55	4.71	5.09	4.62	4.78
Nov.	5.48	4.87	6.07	5.55	4.94	6.15
Dec.	5.33	4.40	6.22	5.40	4.46	6.30

3.2 Wind Turbine Characteristics

When a wind turbine is to be installed in a region, the appropriate blade profile should be selected by considering the specific characteristics of the region. The angle of attachment of this blade to the rotor is as important as the blade selected. In large-scale turbines, the blades can be adjusted as desired, so that the efficiency is optimum, but in small turbines, the blade clamping angle should be selected appropriately. After obtaining the average wind measurement results for at least six months for the annual or preliminary report, it can be determined which turbines will be installed at the measurement point and its immediate surroundings. The capacity factor is the most crucial in choosing the turbine size and tower height. The capacity factor value is calculated as the ratio of the electrical energy that can be produced in a year with the current wind values from the turbine to be installed to the energy to be produced at full power of the turbine and expresses the energy performance of the wind turbine. The cost and characteristics of wind turbines are given in Table 11 and Table 12, respectively.

Table 12 shows the characteristics of five wind turbines including Enercon-70, Enercon-82, Nordex N90, Nordex S77, and Vestas V90-2 where *Pr, Vci, Vco*, and *Vr* represent the rated power of the turbine, cut-in wind speed, cut-out wind speed, and rated wind speed respectively.

Table 11. The cost of the wind turbine.

Wind turbine rated Power, Pr (kW)	Specific cost ($/kW)	Average specific cost (Casp) ($/kW)
<20	2,200 – 3,000	2,600
20-200	1,250 – 2,300	1,775
>200	700 – 1,600	1,150

Table 12. The characteristics of wind turbines.

Turbine Model	*Pr* (kW)	*Vci*	*Vr*	*Vco*	Hub height (m)
Enercon-70	2,300	2	16	25	105
Enercon-82	2,000	2	13	25	105
Nordex, N90	2,300	3	13	25	100
Nordex S77	1,500	3	13	25	90
Vestas V90-2	2,000	2.5	13	25	105

3.3 Estimation Values Output Energy, Capacity Factor, and Seasonal Variation

Table 13 presents the different annual values of capacity factor, Pout, Eout, EWT, USD, and UXAF costs of the wind turbines used in the study. For the Abeche site, the maximum and minimum values of the capacity factor are respectively 13.5% (Enercon-82) and 6.47% (Enercon-70). Power output ranges from 148,763 kW to 269,942 kW. The cost is USD 23.09 to USD 48.55 and XAF 12,548.31 to XAF 26,386.34. The annual energy produced varies from 1,628,954 MWh to 2,955,867 MWh. In view of these different results, it is the Enercon-82 wind turbine that produces more energy and at an acceptable cost.

As for the Mongo site, the minimum and maximum values of the capacity factor are respectively 4.68% (Enercon-70) and 9.55% (Enercon-82). Power output ranges from 74kW (Nordex S77) to 191 kW (Enercon-82). The cost is USD 84.97 to USD 384.06 and XAF 46,178 to XAF 208,728. The annual energy produced varies from 810625 MWh (Nordex S77) to 2091611 (Enercon-82). These results show that Enercon-82 produces more energy and has an acceptable cost.

For the N'Djamena site, the minimum and maximum values of the capacity factor are respectively 0.03% (Enercon-70, Nordex S77) and 0.09% (Enercon-82). Output power varies from 0.385 kW (Nordex S77) to 1.885 (Enercon-82). The cost is USD 60,574 to USD 139,124. The annual energy produced varies from 4,211.70 MWh (Nordex S77) to 20,638 MWh (Enercon-82). The results show that Enercon-82 generates more energy and has an acceptable cost.

Table 13. Annual output energy and capacity factor for five wind turbines.

Location	Unit	Enercon-70	Enercon-82	Nordex N90	Nordex S77	Vestas V90-20
Abeche	Cf (%)	6.47%	13.50%	9.27%	9.87%	11.63%
	P (out)	148.763	269.942	213.293	148.081	232.653
	Eout (Gwh)	107,109.307	194,358.38	153,571.25	106,618.251	167,509.977
	ET (Gwh)	1,628,954.04	2,955,867.03	2,335,562.75	1,621,485.89	2,547,547.57
	USD	48.55	23.09	33.81	31.38	27.03
	XAF	26,386.34	12,548.31	18,372.82	17,055.61	14,690.03
Mongo	Cf (%)	4.68%	9.55%	5.91%	4.94%	8.17%
	P (out)	107.657	191.015	135.880	74.030	163.413
	Eout (Gwh)	77,512.682	137,530.561	97,833.799	53,301.385	117,657.565
	ET (Gwh)	1,178,838.70	2,091,610.62	1,487,889.03	810,625.23	178,9375.47
	USD	219.95	84.97	253.83	384.06	112.79
	XAF	119,539.68	46,177.79	137,953.75	208,727.53	61,298.84
N’Djamena	Cf (%)	0.03%	0.09%	0.04%	0.03%	0.07%
	P (out)	0.683	1.885	0.869	0.385	1.497
	Eout (Gwh)	491.755	1,357.021	625.909	276.934	1,078.183
	ET (Gwh)	7,478.78	20,638.02	9,519.03	4,211.70	16,397.37
	USD	496,393.0	60,574.1	139,123.7	297,671.0	64,801.6
	XAF	269,779,671.0	32,920,804.3	75,610,964.6	161,778,280.0	35,218,365.2

Table 14 presents the different parameters by season for three cities in central Chad. Thus, the highest WPD of 87.786 W m^{-2} in winter is observed in N'Djamena for all seasons. On the other hand, the lowest WPD of 12.041 is observed for all seasons in Mongo in summer. Furthermore, the value of 9.838 of the shape parameter k is recorded in N'Djamena in winter, and the lowest value of 3.031 in Mongo. Finally, the highest value of the scale factor c of 3.58 m s^{-1} is recorded at Abeche and the lowest of 1.228 m s^{-1} at N'Djamena.

Table 14. Seasonal variation.

Location	Parameter	Winter	Spring	Summer	Autumn
Abeche	WPD	28.341	23.885	13.506	25.679
	k	3.810	3.598	3.078	4.103
	c	2.874	2.985	3.200	2.505
Mongo	WPD	24.981	33.328	12.041	15.418
	k	4.735	3.447	3.031	3.728
	c	1.949	3.580	3.134	2.414
N’Djamena	WPD	87.786	51.590	28.252	41.159
	k	9.838	7.912	7.253	7.644
	c	1.371	1.425	1.228	1.393

3.4 *Total Generated Energy and Capacity Factor*

Figure 1 presents the monthly energy produced by the five different wind turbines. Thus, the minimum and maximum values for Abeche are respectively (4,146 kWh; 20,293 kWh) for Enercon-70; (7,588 kWh; 37,135 kWh) Enercon-82; (5,990 kWh; 29,193 kWh) Nordex90; (4,227 kWh; 19,669 kWh) Nordex S77 and (6,843 kWh; 32,348 kWh) Vestas90.

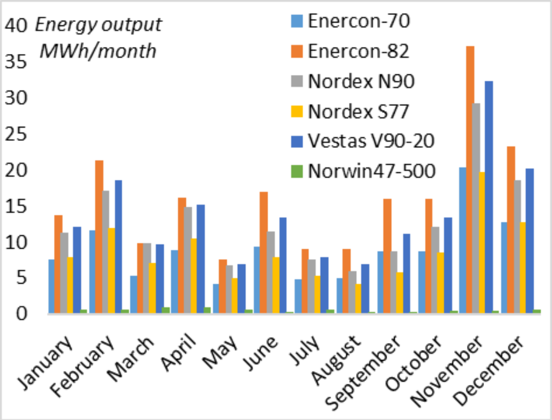

Figure 1. Energy output of Abeche city.

Figure 2 shows the monthly energy produced by the five wind turbines. Thus, the minimum and maximum values for Mongo are respectively (261 kWh; 16,422 kWh) for Enercon-70; (466 kWh; 29,396 kWh) Enercon-82; (171 kWh; 24,531 kWh) Nordex N90; (95 kWh; 13,553 kWh) Nordex S77 and (425 kWh; 26,356 kWh) Vestas V90-20.

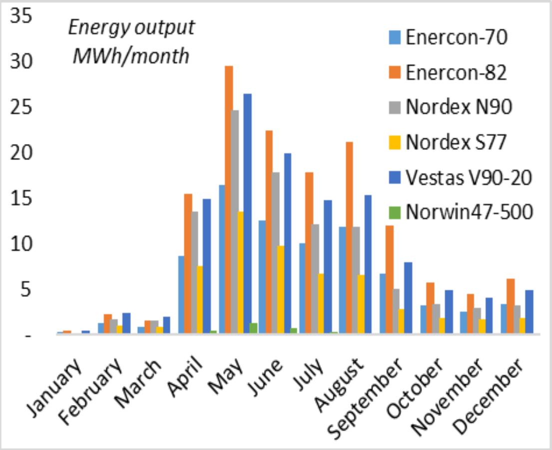

Figure 2. Energy output of Mongo city.

Figure 3 shows the monthly energy produced by the five wind turbines. Thus, the minimum and maximum values for N’Djamena are respectively (0 kWh; 358 kWh) for Enercon-70; (2 kWh; 867 kWh) Enercon-82; (1 kWh; 400 kWh) Nordex N90; (0 kWh; 176 kWh) Nordex S77 and (2 kWh; 656 kWh) Vestas V90-20.

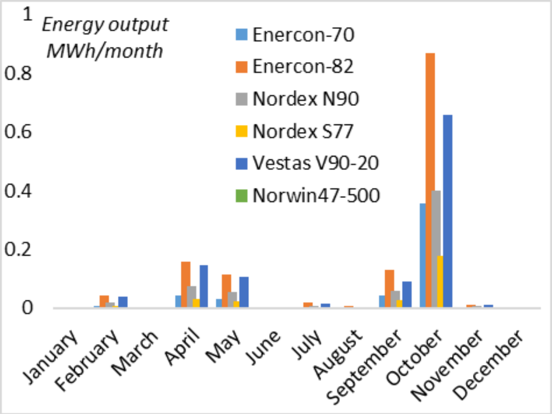

Figure 3. Energy output of N'Djamena city.

3.5 *Capacity Factor*

Figure 4 presents the monthly values of the capacity factor for the five wind turbines selected for three sites in central Chad. Thus, the minimum and maximum values for Abeche are respectively (0.25%; 1.23%) for Enercon-70; (0.55%; 2.55%) Enercon-82; (0.36%; 1.76%) Nordex N90; (0.39%; 1.82%) Nordex S77 and (0.48%; 2.25%) Vestas V90-20.

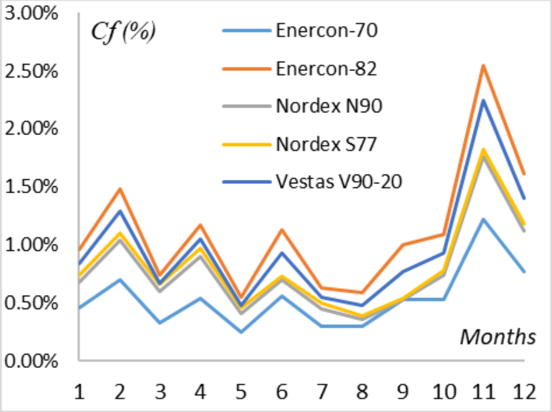

Figure 4. Capacity factor of Abeche city.

Figure 5 shows the monthly values of the capacity factor for the five wind turbines selected for three sites in central Chad. Thus, the minimum and maximum values for Mongo are respectively (0.02%; 0.99%) for Enercon-70; (0.04%; 2.00%) Enercon-82; (0.01%; 1.48%) Nordex N90; (0.01%; 1.28%) Nordex S77 and (0.03%; 1.83%) Vestas V90-20.

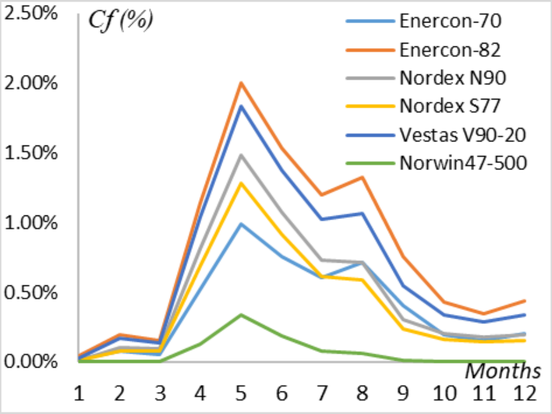

Figure 5. Capacity factor of Mongo city.

Figure 6 shows the monthly values of the capacity factor for the five wind turbines selected for three sites in central Chad. Thus, the minimum and maximum values for N'Djamena are respectively (0.00%; 0.02%) for Enercon-70; (0.00%; 0.06%) Enercon-82; (0.00%; 0.02%) Nordex N90; (0.00%; 0.01%) Nordex S77 and (0.00%; 0.05%) Vestas V90-20.

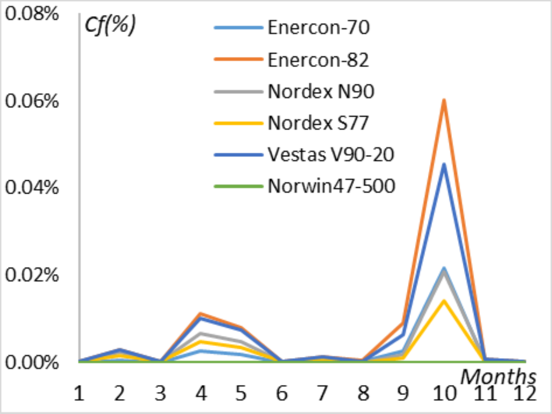

Figure 6. Capacity factor of N'Djamena city.

4 Conclusions

Wind energy is a clean, renewable, and environmentally friendly energy source, and its use is increasing every year due to these features. In this study, the situation of wind energy in Chad was evaluated and the following conclusions were reached:

This paper examined the evaluation of wind energy potential and the techno-economic analysis of five wind turbines for three selected sites in central Chad. Weibull distribution function was used as a statistical approach in the evaluation of wind data.

The highest wind speed is recorded in N'Djamena from 3.25 to 6.063 m s^{-1} respectively from 10 to 105 m altitude; Abeche from 2.64 to 5.151 m s^{-1} and Mongo from 2.54 to 4.99 m s^{-1}.

The capacity factor of the wind turbine for three sites varies from 0.03% to 6.47% (Enercon-70); 0.09% to 13.50% (Enercon-82); 0.04% to 9.27% (Nordex N90); 0.03% to 9.87% (Nordex S77); and 0.07% to 11.63% (Vestas V90-20).

The maximum annual energy produced by the wind turbines is about 1,628,954 GWh (Enercon-70), 2,955,867 GWh (Enercon-82), 2,335,563 GWh (Nordex N90), 1621486 GWh (Nordex S77), and 2,547,548 GWh (Vestas V90-20).

Based on the results, the Enercon-82 wind turbine is applicable for both sites (Abeche and Mongo). In addition, future work consists in seeing other adaptable wind turbines for the N'Djamena site.

As the world strives to minimize the effects of the climate crisis, the African continent is facing different challenges. The ways to overcome these challenges are through reducing carbon emissions and identifying more advanced methods of producing clean energy. Even in megacities like N'Djamena and Moundou people have to deal with constant blackouts, while half of the continent's population suffers from a lack of access to energy sources. Despite being a continent with extensive energy resources, it is a fact that local people have serious problems in accessing energy. In recent years, although countries have made progress in solving the problem of access to energy resources, a sufficient level has not been reached yet. Chad has a high renewable energy potential which can play a major role in resolving this paradox if it receives the necessary investments in line with the right policies and legal frameworks.

Conflict of Interest

The authors declare that there is no conflict of interest.

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