Research article

Performance evaluation of wind turbines for sites in Chad

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A B S T R A C T

For the production of electricity, the use of wind energy has become more interesting in recent years. In this present study, the authors assessed wind potential using wind speed data measured at 10 m altitude for a period of 18–30 years in Chad. The statistical method of Rayleigh's law was deployed in this study. In addition, the performance of five wind turbines in five different sites were examined based on their capacity factor and annual energy production. The results shows that the average monthly velocities of the five sites range from 2.54 m/s to 3.25 m/s and the power density varies from 20.80 W/m^2 to 44.17 W/m^2. By focusing on the annual energy production of these turbines, the results obtained show that the Enercom E-82 can be adapted for all the five sites.

1. Introduction

In the electricity generation sector, renewable energy sources have received particular attention due to the pollution caused by traditional systems as well as population growth [1]. The energy generated by fossil fuels and the combustion of coal produces dangerous gases (hydrocarbons, carbon monoxide, ionizing radiation, hydrochloric acid, etc.) which can degrade the environment. To overcome the problems of environmental degradation and pollution, renewable energy resources such as solar, wind etc. are very suitable. To make up for the lack of hydropower during the dry season, emphasis is placed on the use of wind turbines [2]. Wind energy has become a cheaper source in recent decades as it avoids environmental degradation and is inexhaustible. Thus, based on the linear regression model of the Weibull distribution, the analysis of wind speed data for four locations in Ireland was performed [3]. The global technique for extracting wind energy that is renewable, inexhaustible, sustainable, non-polluting and profitable is the use of modern wind turbines. An experimental study on new vertical axis wind turbines has been carried out. It traces the evolution of this knowledge and assesses the implications of these discoveries in terms of global warming [4, 5]. The demand for wind energy in Africa over the past decades has increased exponentially due to the economic and population growth of the countries. To ensure security of energy supply and an energy mix less dependent on hydrocarbons, they have favored renewable energies, in particular solar, wind, hydraulic, biomass, etc. [6]. In Chad, only 8% of the population has access to electricity, with a significant gap between rural (1%) and urban (20%) areas. Chad is one of the countries with the lowest electricity access rates

in the world. Paradoxical situation with regard to the natural resources available to the country, in particular oil and renewable energies. Apart from the 1 MW wind power plant (composed of 4 wind turbines) in Amdjarass, a city located in the East of the country, electricity is now only supplied by generators, which regularly break down. Oil, which is used to run the groups, is a non-renewable, an expensive, and very polluting energy source. This situation hinders the socio-economic development of the country and affects the quality of life of the population [7]. As wind energy is increasingly becoming a major area of development in the coming years, it is a good idea to motivate researchers on the benefits of the said field. Given the importance given by electrical systems to the wind potential, efforts are made to study the production of electrical energy as well as the behavior of the wind [8]. To date, in several countries of the world, several works have been carried out on the potential as well as its characteristics. The authors conducted a technical and economic study of wind turbines in Nigeria [9]. In addition to this, they ranked the sites based on their wind energy densities, estimated capacity factor value, and present value cost. The authors did a study on the performance of wind turbines in Nigeria [10]. The annual energy production and the capacity factor of these turbines have been determined. While the authors were interested in energy potential and wind speed in China [11]. For the use of wind energy and optimize the production and transmission of electricity on the network for better performance of the system, the results should help decision makers to identify favorable areas. The authors made a statistical analysis of power density and wind speed of Jumla based on Rayleigh and Weibull models. Thus, the result showed a good approximation for the power density estimation with a maximum error of 3.68%

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[12]. Moreover, authors in were interested in studying the density distribution of wind energy, using the Rayleigh probability density function [13]. The Rayleigh distribution function was derived from available data. Furthermore, authors conducted a study on power generation as well as wind speed characteristics in Lithuania [14]. The study was focused on two regions and wind speed data were collected using an anemometer. To estimate the scale and shape parameters, a new mathematical model was developed. Several wind turbines have been selected to maximize the annual energy production and the selected wind turbines operate at lower wind speeds [15]. In reference [16], the authors selected several wind turbines whose nominal power varies from 1,104W to 16,5104W in their study on the evaluation of wind potential. The optimization by HOMER seems adapted to meet the demand for electrical energy. Authors studied the wind energy potential for sites in Bushehr province in Iran [17]. A comparison of the results for wind turbines indicates that the Proven 15 has the highest capacity factor. While authors compared wind resources by implementing a methodology for two Moroccan sites [18]. The comparison is based on wind data collected from two masts at heights of 30.50 and 60 m. Indeed, in the State of Chuuk, on the island of Weno, a meteorological observation mast is installed to assess the wind potential. Using the Rayleigh distribution, the annual energy production of a 20 kW wind turbine should be approximately 36841.73 kW h/year [19]. Using different methods to determine the Weibull parameters in two regions of Morocco, the investigation of the wind potential was carried. The highest values of wind potential occur during the months of March, July, September and December in Dakhla and during the months of December to March in Taza [20]. The electrical performances of some new wind turbines that have been the subject of an experimental study are presented. The results obtained show that the curved blade wind turbine with a 3-blade configuration performs better than the other two configurations, i.e. 2 blades and 4 blades [21]. In reference [22], the authors conducted an experimental and even analytical analysis on the bladeless turbine for the incompressible fluid. Correlations between performance parameters are examined in experiments. In the present study, the performance evaluation of wind turbines for sites in Chad is conducted. In the first part, the wind speeds at different heights as well as the monthly distribution were discussed and analyzed. To study wind energy and energy production at different heights, the Rayleigh distribution function is deployed. In the second part, five wind turbines were chosen whose power varies from 1, 500 kW to 2,300 kW, the general objective is to determine the most appropriate turbine to install for each of the sites. The choice is based on the energy capacity factor calculation and energy production.

2. Wind data and analysis

In this study, monthly wind speed data for a period of 18–30 years were obtained from the General Directorate of National Meteorology in N'Djamena, Chad. The data obtained were recorded at an altitude of 10 m using an anemometer. Thus the four sites namely, Faya-Largeau in the Saharan zone; Abeche, N'Djamena and Mongo in the Sahelian zone and Moundou in the Sudanian zone. Wind speed at hub height is of interest for wind turbine applications. Thus, it was wise to use the power law given in Eq. (1) [24, 25, 26]:

$$\frac{U}{U_0} = \left(\frac{H}{H_0}\right)^{\alpha} \tag{1}$$

In Eq. (1), U_0 is the wind speed at the original height H_0, U the wind speed at the required height H and α is the assumed coefficient at 0.143 (or 1/7).

2.1. Wind speed parameters of the selected site

To analyze the wind data, the Rayleigh distribution model is used in this study since only monthly speeds are available for the considered sites by Eq. (2) [27, 28]:

$$f(v) = \frac{\pi}{2}\left(\frac{v}{v_m^2}\right) exp\left[-\frac{\pi}{4}\left(\frac{v}{v_m}\right)^2\right] \tag{2}$$

where v_m is mean wind speed and v is wind speed and $f(v)$ Rayleigh probability function. The Rayleigh distribution has the cumulative probability function, F defined by Eq. (3) [29]:

$$F = 1 - exp\left[-\frac{\pi}{4}\left(\frac{v}{v_m}\right)^2\right] \tag{3}$$

The Scale Parameter of the Rayleigh distribution is defined by Eq. (4) [30]:

$$C = \frac{2v_m}{\pi} \tag{4}$$

For a given site, the characteristic wind speeds are the maximum energy carrying wind speed (V_E), the most probable wind speed (V_F) and the average speed (v_m). The first two parameters' Eqs. (5) and (6), can be expressed as [31]:

$$V_F = v_m\sqrt{\frac{2}{\pi}} \tag{5}$$

$$V_E = 2v_m\sqrt{\frac{2}{\pi}} \tag{6}$$

Given the operation of the wind turbine at its design, its maximum efficiency or its nominal speed, it is essential that the wind speed carrying the maximum energy and the nominal wind speed are as close as possible.

Another parameter to be estimated for a given site in addition to the wind speed parameters is the wind power density (P_D). It is defined as the energy per unit area of the rotor. Thus, it can be expressed [32] using Eq. (7):

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

according to the Rayleigh distribution function, the wind power density (wind power per unit area) is calculated according to the equation by Eq. (8) [33]:

$$P_D = P_R = \frac{3}{\pi}\rho C^3\left(\frac{\pi}{4}\right)^{3/2} \tag{8}$$

where ρ is the air density.

2.2. Wind turbine performance parameters

The operation of a wind energy conversion system can only be done at its maximum efficiency as its design is made for a given site. Thus, the nominal wind speed (V_R), the cut-off wind speed (V_0), the nominal power (P_R), and the switch-on wind speed (Vc) must take into account the site wind characteristics. However, it is not easy to manufacture a wind turbine for one site and plan for each application. Therefore, it is important to make a choice in such a way as to maximize the amount of wind energy available. The total energy extracted by a wind system according to the Weibull distribution function is given in [33, 34] as:

$$P_T = P_R \left\{ \frac{e^{-\left(\frac{v_c}{c}\right)^k} - e^{-\left(\frac{v_R}{c}\right)^k}}{\left(\frac{v_R}{c}\right)^k - \left(\frac{v_c}{c}\right)^k} - e^{-\left(\frac{v_0}{c}\right)^k} \right\} \tag{9}$$

For Rayleigh distribution function given in equation (9), k is taken to be 2. The capacity factor is an important parameter for evaluating the performance of the wind turbine in addition to the total energy extracted by the system. It is expressed by Eq. (10):

$$C_f = \frac{P_T}{P_R} \tag{10}$$

The capacity factor is usually between 0.25 and 0.40 for a profitable wind energy investment. With $C_f \geq 0.40$ shows a strong interaction between the environment and the wind system [31].

The total energy production and revenue of a system, as well as its economic viability for a given site is determined by the capacity factor (C_f) and the total energy extracted (P_T).

3. Results and discussion

In this section, the data used and results from the proposed method were presented and discussed.

3.1. Wind speed parameters

Tables 1a, 2, 3, 4, and 5 display the data for the five different sites considered in this study. Table 1b presents the different values of the parameters v, c, v_f, v_E and P_D for the Abeche site. This table shows that the minimum and maximum values are respectively v (2 m/s; 3.1 m/s); c (2.26; 3.50); v_F (1.60 m/s; 2.47 m/s); v_E (3.19 m/s; 4.95 m/s) and P_D (9.36 W/m²; 34.87 W/m²). Table 2 also presents the different values of the parameters v, c, v_F, v_E and P_D for the Faya-Largeau site. This table shows that for each of the parameters, the minimum and maximum values are respectively v (2.2 m/s; 4 m/s); c (2.48; 4.51); v_F (1.76 m/s; 3.19 m/s); v_E (3.51 m/s; 6.38 m/s) and P_D (12.46 W/m²; 74.90 W/m²). Table 3 also presents the different values of the parameters v, c, v_F, v_E and P_D for the N'Djamena site. Thus, this table shows that for each of the parameters, the minimum and maximum values are respectively v (2.4 m/s; 4.2 m/s); c (2.71; 4.74); v_F (1.92 m/s; 3.35 m/s); v_E (3.83 m/s; 6.70 m/s) and P_D (16.18 W/m²; 86.71 W/m²). Table 4 presents the different monthly values of the parameters v, c, v_F, v_E and P_D for the Moundou site. This table shows that for each of the parameters, the minimum and maximum values are respectively v (2 m/s; 3.3 m/s); c (2.26; 3.72); v_F (1.60 m/s; 2.63 m/s); v_E (3.19 m/s; 5.27 m/s) and P_D (9.36 W/m²; 42.06 W/m²).

Table 5 presents the different monthly values of the parameters v, c, v_F, v_E and P_D for the Mongo site. This table shows that for each of the parameters, the minimum and maximum values are respectively v (1.8 m/s; 3.1 m/s); c (2.03; 3.50); v_F (1.44 m/s; 2.47 m/s); v_E (2.87 m/s; 4.95 m/s) and P_D (6.83 W/m²; 34.87 W/m²).

Table 6 shows the characteristics of six wind turbines including Enercom E-70, Enercom E-82, Nordex, N90, Nordex S77 and Vestas V90-2.

where P_r, V_{ci}, V_{co} et V_r represent the rated power of the turbine, cut-in wind speed, cut-out wind speed and rated wind speed.

Table 1a. Geographical coordinates of the sites.

Site	Elevation(m)	Latitude (degree)	Longitude (degree)
Abeche	545	13°51	20°51
Faya-Largeau	233	17°55	19°70
N'Djamena	294	12°80	15°20
Moundou	420	08°37	16°40
Mongo	430	12°11	18°41

Table 1b. Different monthly values of the parameters of Abeche.

Months	V_m (m/s)	C (m/s)	V_F (m/s)	V_E (m/s)	P_D (W/m²)
January	2.7	3.047	2.155	4.310	23.037
February	2.8	3.160	2.235	4.469	25.692
March	3.1	3.499	2.474	4.948	34.867
April	3	3.386	2.394	4.789	31.600
May	2.7	3.047	2.155	4.310	23.037
June	2.4	2.709	1.915	3.831	16.179
July	2.6	2.935	2.075	4.150	20.571
August	2.1	2.370	1.676	3.352	10.839
September	2	2.257	1.596	3.192	9.363
October	2.6	2.935	2.075	4.150	20.571
November	2.9	3.273	2.314	4.629	28.544
December	2.8	3.160	2.235	4.469	25.692
Average	2.642	2.982	2.108	4.217	22.499

Table 2. Different monthly values of the parameters of Faya-Largeau

Months	V_m (m/s)	C (m/s)	V_F (m/s)	V_E (m/s)	P_D (W/m²)
January	4	4.515	3.192	6.385	74.904
February	3.8	4.289	3.033	6.065	64.221
March	3.7	4.176	2.953	5.906	59.283
April	3.3	3.725	2.634	5.267	42.060
May	2.9	3.273	2.314	4.629	28.544
June	2.7	3.047	2.155	4.310	23.037
July	2.3	2.596	1.836	3.671	14.240
August	2.2	2.483	1.756	3.512	12.462
September	3	3.386	2.394	4.789	31.600
October	3.4	3.837	2.713	5.427	46.001
November	3.9	4.402	3.113	6.225	69.426
December	3.8	4.289	3.033	6.065	64.221
Average	3.25	3.668	2.594	5.188	44.167

Table 3. Different monthly values of the parameters of N'Djamena.

Months	V_m (m/s)	C (m/s)	V_F (m/s)	V_E (m/s)	P_D (W/m²)
January	3.6	4.063	2.873	5.746	54.605
February	4	4.515	3.192	6.385	74.904
March	4.2	4.740	3.352	6.704	86.711
April	3.2	3.612	2.554	5.108	38.351
May	3.2	3.612	2.554	5.108	38.351
June	3.6	4.063	2.873	5.746	54.605
July	3.2	3.612	2.554	5.108	38.351
August	2.5	2.822	1.995	3.990	18.287
September	2.4	2.709	1.915	3.831	16.179
October	2.4	2.709	1.915	3.831	16.179
November	3.3	3.725	2.634	5.267	42.060
December	3.4	3.837	2.713	5.427	46.001
Average	3.250	3.668	2.594	5.188	43.716

Table 4. Different monthly values of the parameters of Moundou.

Months	V_m (m/s)	C (m/s)	V_F(m/s)	V_E (m/s)	P_D (W/m²)
January	3.1	3.499	2.474	4.948	34.867
February	3.3	3.725	2.634	5.267	42.060
March	3.1	3.499	2.474	4.948	34.867
April	3.3	3.725	2.634	5.267	42.060
May	2.9	3.273	2.314	4.629	28.544
June	2.8	3.160	2.235	4.469	25.692
July	2.7	3.047	2.155	4.310	23.037
August	2.3	2.596	1.836	3.671	14.240
September	2.1	2.370	1.676	3.352	10.839
October	2	2.257	1.596	3.192	9.363
November	2.1	2.370	1.676	3.352	10.839
December	2.6	2.935	2.075	4.150	20.571
Average	2.6917	3.038	2.148	4.296	24.748

Table 5. Different monthly values of the parameters of Mongo.

Months	V_m (m/s)	C (m/s)	V_F(m/s)	V_E (m/s)	P_D (W/m²)
January	2.2	2.483	1.756	3.512	12.462
February	2.7	3.047	2.155	4.310	23.037
March	3.1	3.499	2.474	4.948	34.867
April	3.1	3.499	2.474	4.948	34.867
May	3.1	3.499	2.474	4.948	34.867
June	2.9	3.273	2.314	4.629	28.544
July	2.5	2.822	1.995	3.990	18.287
August	2.1	2.370	1.676	3.352	10.839
September	1.8	2.032	1.437	2.873	6.826
October	2.3	2.596	1.836	3.671	14.240
November	2.5	2.822	1.995	3.990	18.287
December	2.2	2.483	1.756	3.512	12.462
Average	2.5417	2.869	2.028	4.057	20.799

Table 6. Selected wind turbine characteristics [35].

Turbine Model	P_r (kW)	V_{ci}	V_r	V_{co}	Hub height (m)
Enercom E-70	2300	2	16	25	105
Enercom-82	2000	2	13	25	105
Nordex, N90	2300	3	13	25	100
Nordex S77	1500	3	13	25	90
Vestas V90-2	2000	2.5	13	25	105

Tables 7, 8, and 9 present the different monthly values of C_f and E_{WT} of five wind turbines for three sites in Chad respectively N'Djamena, Moundou and Mongo. For the N'Djamena site, the minimum and maximum values are respectively C_f (1.69%; 7.46%); E_{WT} (27962 kW h; 123564 kW h) for Enercom70. Enercom E-82, C_f (2.58%; 11.39%) and E_{WT} (37135; 163997 kW h). Nordex90, C_f (1.35%; 9.40%) and E_{WT} (22282 kW h; 155660 kW h), Nordex S77, C_f (1.35%; 9.40%) and E_{WT} (14532 kW h; 101518 kW h). Finally, Vestas 90, C_f (1.92%; 10.45%) and E_{WT} (27707 kW h; 150410 kW h). The profitable wind turbine in terms of capacity factor is Enercom82. As for the extrapolation of the parameters k and c, the results are supported by authors in [17]. As for the Moundou site, the minimum and maximum values are respectively C_f (0.92%; 4.13%); E_{WT} (15265; 68346) for Enercom70. Enercom E-82, C_f (1.41%; 6.30%) and E_{WT} (20273; 90768 kW h). Nordex90, C_f (0.54%; 4.53%) and E_{WT} (9010 kW h; 75075 kW h), Nordex S77, C_f (0.54%; 4.53%) and E_{WT} (5876 kW h; 48962 kW h). Finally, Vestas 90, C_f (0.92%; 5.43%) and E_{WT} (13215 kW h; 78248 kW h). The profitable wind turbine in terms of capacity factor is Enercom E- 82. Finally, for the Mongo site, the minimum and maximum values are respectively C_f (0.62%; 3.50%); E_{WT} (10299; 58030) for Enercom70. Enercom82, C_f (0.95%; 5.35%) and E_{WT} (13677 kW h; 77068 kW h). Nordex90, C_f (0.29%; 3.67%) and E_{WT} (4832 kW h; 60754 kW h), Nordex S77, C_f (0.29%; 3.67%) and E_{WT} (3152 kW h; 39622 kW h). Finally, Vestas 90, C_f (0.56%; 4.52%) and E_{WT} (8041 kW h; 65016 kW h). The profitable wind turbine in terms of capacity factor is Enercom 82.

Similarly, Tables 10 and 11 present the monthly values of C_f and E_{WT} of five wind turbines for the Faya-Largeau and Abeche sites respectively. For the Faya-Largeau site, the minimum and maximum values are

Table 7. Presents the different monthly values of C_f and E_{WT} of N'Djamena.

Month	Enercom 70		Enercom 82		Nordex 90		Nordex S77		Vestas 90	
	C_f (%)	E_{WT} (kWh/mon)	C_f (%)	E_{WT} (kWh/mon)	C_f (%)	E_{WT} (kWh/mon)	C_f (%)	E_{WT} (kWh/mon)	C_f (%)	E_{WT} (kWh/mon)
January	5.14%	85137.452	7.85%	113062.789	5.98%	99045.244	5.98%	64594.725	6.95%	100019.887
February	6.65%	110092.046	10.15%	146165.182	8.19%	135627.258	8.19%	88452.560	9.21%	132695.610
March	7.46%	123563.836	11.39%	163996.702	9.40%	155660.285	9.40%	101517.577	10.45%	150409.888
April	3.81%	63096.160	5.82%	83795.421	4.09%	67739.347	4.09%	44177.835	4.97%	71496.499
May	3.81%	63096.160	5.82%	83795.421	4.09%	67739.347	4.09%	44177.835	4.97%	71496.499
June	5.14%	85137.452	7.85%	113062.789	5.98%	99045.244	5.98%	64594.725	6.95%	100019.887
July	3.81%	63096.160	5.82%	83795.421	4.09%	67739.347	4.09%	44177.835	4.97%	71496.499
August	1.91%	31669.145	2.92%	42058.627	1.61%	26622.268	1.61%	17362.349	2.23%	32145.169
September	1.69%	27961.632	2.58%	37134.816	1.35%	22281.734	1.35%	14531.565	1.92%	27707.152
October	1.69%	27961.632	2.58%	37134.816	1.35%	22281.734	1.35%	14531.565	1.92%	27707.152
November	4.13%	68346.451	6.30%	90767.788	4.53%	75075.252	4.53%	48962.121	5.43%	78247.635
December	4.45%	73730.837	6.80%	97917.888	4.99%	82685.373	4.99%	53925.243	5.92%	85202.486

Table 8. Presents the different monthly values of C_f and E_{WT} of Moundou.

Month	Enercom 70		Enercom 82		Nordex90		Nordex S77		Vestas 90	
	C_f (%)	E_{WT} (kWh/mon)	C_f (%)	E_{WT} (kWh/mon)	C_f (%)	E_{WT} (kWh/mon)	C_f (%)	E_{WT} (kWh/mon)	C_f (%)	E_{WT} (kWh/mon)
January	3.50%	58030.480	5.35%	77068.039	3.67%	60753.516	3.67%	39621.858	4.52%	65016.436
February	4.13%	68346.451	6.30%	90767.788	4.53%	75075.252	4.53%	48962.121	5.43%	78247.635
March	3.50%	58030.480	5.35%	77068.039	3.67%	60753.516	3.67%	39621.858	4.52%	65016.436
April	4.13%	68346.451	6.30%	90767.788	4.53%	75075.252	4.53%	48962.121	5.43%	78247.635
May	2.93%	48460.580	4.47%	64358.702	2.89%	47859.155	2.89%	31212.493	3.67%	52887.545
June	2.65%	43960.806	4.05%	58382.727	2.53%	41964.860	2.53%	27368.387	3.28%	47248.730
July	2.39%	39654.609	3.66%	52663.827	2.20%	36448.984	2.20%	23771.076	2.91%	41901.098
August	1.48%	24462.320	2.26%	32487.509	1.11%	18346.947	1.11%	11965.400	1.64%	23587.552
September	1.09%	18108.376	1.67%	24049.068	0.71%	11710.187	0.71%	7637.078	1.13%	16334.013
October	0.92%	15265.178	1.41%	20273.121	0.54%	9009.612	0.54%	5875.834	0.92%	13214.758
November	1.09%	18108.376	1.67%	24049.068	0.71%	11710.187	0.71%	7637.078	1.13%	16334.013
December	2.15%	35580.507	3.28%	47253.164	1.89%	31362.658	1.89%	20453.907	2.56%	36894.184

Table 9. Presents the different monthly values of C_f and E_{WT} of Mongo.

	Enercom 70		Enercom 82		Nordex90		Nordex S77		Vestas 90	
Month	C_f(%)	E_{WT} (kWh/mon)	C_f(%)	E_{WT} (kWh/mon)	C_f(%)	E_{WT} (kWh/mon)	C_f(%)	E_{WT} (kWh/mon)	C_f(%)	E_{WT} (kWh/mon)
January	1.28%	21176.089	1.95%	28123.185	0.90%	14822.347	0.90%	9666.748	1.37%	19793.986
February	2.39%	39654.609	3.66%	52663.827	2.20%	36448.984	2.20%	23771.076	2.91%	41901.098
March	3.50%	58030.480	5.35%	77068.039	3.67%	60753.516	3.67%	39621.858	4.52%	65016.436
April	3.50%	58030.480	5.35%	77068.039	3.67%	60753.516	3.67%	39621.858	4.52%	65016.436
May	3.50%	58030.480	5.35%	77068.039	3.67%	60753.516	3.67%	39621.858	4.52%	65016.436
June	2.93%	48460.580	4.47%	64358.702	2.89%	47859.155	2.89%	31212.493	3.67%	52887.545
July	1.91%	31669.145	2.92%	42058.627	1.61%	26622.268	1.61%	17362.349	2.23%	32145.169
August	1.09%	18108.376	1.67%	24049.068	0.71%	11710.187	0.71%	7637.078	1.13%	16334.013
September	0.62%	10298.728	0.95%	13677.362	0.29%	4832.364	0.29%	3151.542	0.56%	8040.966
October	1.48%	24462.320	2.26%	32487.509	1.11%	18346.947	1.11%	11965.400	1.64%	23587.552
November	1.91%	31669.145	2.92%	42058.627	1.61%	26622.268	1.61%	17362.349	2.23%	32145.169
December	1.28%	21176.089	1.95%	28123.185	0.90%	14822.347	0.90%	9666.748	1.37%	19793.986

Table 10. Presents the different monthly values of C_f and E_{WT} of Faya-Largeau

	Enercom 70		Enercom 82		Nordex90		Nordex S77		Vestas 90	
Month	C_f(%)	E_{WT} (kWh/mon)	C_f(%)	E_{WT} (kWh/mon)	C_f(%)	E_{WT} (kWh/mon)	C_f(%)	E_{WT} (kWh/mon)	C_f(%)	E_{WT} (kWh/mon)
January	6.65%	110092.046	10.15%	146165.182	8.19%	135627.258	8.19%	88452.560	9.21%	132695.610
February	5.87%	97260.515	8.97%	129151.827	7.05%	116708.250	7.05%	76114.076	8.05%	115860.852
March	5.50%	91109.962	8.40%	120990.444	6.50%	107716.767	6.50%	70250.065	7.49%	107814.236
April	4.13%	68346.451	6.30%	90767.788	4.53%	75075.252	4.53%	48962.121	5.43%	78247.635
May	2.93%	48460.580	4.47%	64358.702	2.89%	47859.155	2.89%	31212.493	3.67%	52887.545
June	2.39%	39654.609	3.66%	52663.827	2.20%	36448.984	2.20%	23771.076	2.91%	41901.098
July	1.48%	24462.320	2.26%	32487.509	1.11%	18346.947	1.11%	11965.400	1.64%	23587.552
August	1.28%	21176.089	1.95%	28123.185	0.90%	14822.347	0.90%	9666.748	1.37%	19793.986
September	3.21%	53151.258	4.90%	70588.192	3.27%	54124.455	3.27%	35298.558	4.08%	58811.854
October	4.45%	73730.837	6.80%	97917.888	4.99%	82685.373	4.99%	53925.243	5.92%	85202.486
November	6.26%	103588.166	9.55%	137544.370	7.61%	126013.784	7.61%	82182.903	8.62%	124155.975
December	5.87%	97260.515	8.97%	129151.827	7.05%	116708.250	7.05%	76114.076	8.05%	115860.852

respectively C_f (1.28%; 6.65%); E_{WT} (21176; 110092) for Enercom70. Enercom E-82, C_f (1.95%; 10.15%) and E_{WT} (28123 kW h; 146165 kW h). Nordex 90, Cf (0.90%; 8.19%) and E_{WT} (14822 kW h; 135627 kW h), Nordex S77, C_f (0.90%; 8.19%) and E_{WT} (9667 kW h; 88453 kW h). Finally, Vestas 90, C_f (1.37%; 9.21%) and E_{WT} (19794 kW h; 132696 kW h). The profitable wind turbine in terms of capacity factor is Enercom E-82. As for the Abeche site, the minimum and maximum values are respectively C_f (0.05%; 0.42%); E_{WT} (827 kW h; 6965 kW h) for Enercom70. Enercom E-82, Cf (0.10%; 0.67%) and E_{WT} (1487 kW h; 9719 kW h). Nordex 90, C_f (0.07%; 0.26%) and E_{WT} (1137 kW h; 4250 kW h), Nordex S77, C_f (0.07%; 0.26%) and E_{WT} (742 kW h; 2772 kW h). Finally,

Vestas 90, C_f (0.09%; 0.44%) and E_{WT} (1238 kW h; 6290 kW h). The profitable wind turbine in terms of capacity factor is Enercom E-82.

3.2. Wind turbine performance assessment

The wind turbine performance assessment was carried out yearly as given below.

3.2.1. Annual energy output

Table 12 presents the annual values of C_f, Pout and E_{WT} of five wind turbines chosen for the five selected sites in Chad namely Faya-Largeau,

Table 11. Presents the different monthly values of C_f and E_{WT} of Abeche.

	Enercom 70		Enercom 82		Nordex90		Nordex S77		Vestas 90	
Month	C_f (%)	EWT (kWh/mon)	C_f (%)	EWT (kWh/mon)	C_f (%)	EWT (kWh/mon)	C_f (%)	EWT (kWh/mon)	C_f (%)	EWT (kWh/mon)
January	0.12%	1907.944	0.22%	3125.567	0.13%	2101.453	0.13%	1370.513	0.17%	2454.881
February	0.09%	1554.431	0.18%	2606.500	0.11%	1819.211	0.11%	1186.442	0.14%	2081.925
March	0.05%	826.714	0.10%	1486.927	0.07%	1137.304	0.07%	741.720	0.09%	1237.627
April	0.06%	1022.846	0.12%	1797.155	0.08%	1337.267	0.08%	872.131	0.10%	1477.427
May	0.12%	1907.944	0.22%	3125.567	0.13%	2101.453	0.13%	1370.513	0.17%	2454.881
June	0.21%	3441.295	0.37%	5259.610	0.19%	3073.444	0.19%	2004.420	0.27%	3878.295
July	0.14%	2329.584	0.26%	3729.306	0.15%	2405.946	0.15%	1569.095	0.20%	2875.145
August	0.36%	5911.596	0.59%	8436.428	0.24%	4026.258	0.24%	2625.820	0.39%	5679.012
September	0.42%	6964.645	0.67%	9718.833	0.26%	4250.020	0.26%	2771.752	0.44%	6289.820
October	0.14%	2329.584	0.26%	3729.306	0.15%	2405.946	0.15%	1569.095	0.20%	2875.145
November	0.08%	1262.592	0.15%	2167.146	0.09%	1564.319	0.09%	1020.208	0.12%	1757.401
December	0.09%	1554.431	0.18%	2606.500	0.11%	1819.211	0.11%	1186.442	0.14%	2081.925

The results in Tables 7, 8, 9, 10, and 11 for the calculations of C_f and E_{WT} are supported by the works of authors in [19, 20].

Table 12. Annual output energy and capacity factor for five wind turbines.

Locations		Turbines				
		Enercom E-70	Enorcom E-82	Nordex N90	Nordex S77	Vestas V90-20
Faya-Larg.	C_f (%)	50.02%	76.38%	56.29%	56.29%	66.45%
	P (out)	1150.407	1527.65381	1294.634	844.327	1328.916
	E_{WT} (Gwh)	828293.347	1099910.74	932136.823	607915.319	956819.679
Moundou	C_f (%)	29.97%	45.78%	28.99%	28.99%	37.15%
	P (out)	689.381407	915.540	666.7640	434.846	742.958
	E_{WT} (Gwh)	496354.613	659188.841	480070.125	313089.212	534930.035
N'Djamena	C_f (%)	49.69%	75.88%	55.65%	55.65%	65.88%
	P (out)	1142.901	1517.622	1279.920	834.730	1317.562
	E_{WT} (Gwh)	822888.963	1092687.660	921542.434	601005.935	948644.363
Mongo	C_f (%)	25.41%	38.81%	23.21%	23.21%	30.67%
	P (out)	584.398	776.117	533.816	348.141	613.443
	E_{WT} (Gwh)	420766.520	558804.21	384347.413	250661.356	441678.791
Abeche	C_f (%)	1.87%	3.32%	1.69%	1.69%	2.44%
	P (out)	43.074	66.373	38.947	25.400	48.810
	E_{WT} (Gwh)	31013.6058	47788.8457	28041.8335	18288.1523	35143.4838

Moundou, N'Djamena, Mongo and Abeche. It can be seen that the minimum and maximum values of each wind turbine are respectively: Enercom E-70 (1.87%; 50.02%); Enercom E-82 (3.32%; 76.38%); Nordex N90 and Nordex S77 (1.69%; 56.29%) and Vestas V90-20 (2.44%; 66.45%) whose sites are respectively Abeche and Faya-Largeau.

4. Conclusion

This article examined the performance of five wind turbines as well as the assessment of wind energy potential for five sites in Chad. It appears that the power density varies from 20.80 W/m^2 to 44.17 W/m^2 respectively, minimum value for Mongo and maximum for Faya-Largeau. Focusing on the annual energy production, the Enercom E-82 wind turbine with a power of 200 kW and a nominal speed of 2 m/s could be adapted for the five sites considered in this study. The annual production of the said turbine is approximately 1,099,911 MW h, 659,189 MW h, 109.269 MW h, 558,804 MW h and 47,789 MW h respectively for the Faya-Largeau, Moundou, N'Djamena, Mongo and Abeche sites. In addition, for all the sites, the Nordex S77 wind turbine whose nominal power is 1,500 kW generates the lowest energy production produced 607.915 MW h, 313,089 MW h, 601,006 MW h, 250,661 MW h and 18,288 MW h respectively for the Faya-Largeau, Moundou sites, N'Djamena, Mongo and Abeche. Moreover, if we focus on the capacity factor for the decision to be made, which gives the respective factors of 76.38% (Enercom E-82), 66.45% (Vestas V90-20), 56.29 (Nordex N90 and Nordex S77) and 50.02% (Enercom E-70).

Declarations

Author contribution statement

Marcel Hamda Soulouknga and Tobiloba Emmanuel Somefun: Conceived and designed the experiments; Performed the experiments; Analyzed and interpreted the data; Wrote the paper.

Serge Yamigno Doka: Contributed reagents, materials, analysis tools or data; Wrote the paper.

Data availability statement

Data included in article/supp. material/referenced in article.

Declaration of interest's statement

The authors declare no conflict of interest.

Additional information

No additional information is available for this paper.

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