Assessment of wind potential for electricity production: case of the rural community of Logone Birni

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Abstract. Many non-electrified rural communities find it challenging to follow a precise scientific protocol to assess the feasibility of installing a wind turbine on their site. The objective of the present work is to define a clear protocol for the assessment of wind potential of a rural site. The case of Logone Birni (LB) is taken as a case study. For this purpose, a protocol, integrating the wind parameters of the site have been used to calculate the wind power density, annual energy yield, and capacity factors at 10, 30, and 50 m height using 15 years data. The wind frequency distribution including seasonal has been investigated to determine accurately the wind power of the site. The coefficient of variation is calculated at three different heights. Also, an economic assessment per kWh of energy has been carried out. The results of this study show that it is possible to install a wind farm in LB site with a minimum of 30m height. In addition, wind turbines with a starting speed of 1.5 m/s and a rated power of 20 kW will produce electricity at a low cost (0.453USD/kWh). **Keywords:** wind energy, renewable energy, wind assessment, rural area, Weibull

1 Introduction

As in many Sub-Saharan Africa countries, electricity consumption in Cameroon is increasing at an annual rate of around 8% [1]. Electricity access rate in rural areas of Cameroon remains low at around 23% with nearly 11,000 localities not electrified to date. [2].

Renewable energy systems remains the appropriate solutions for rural/isolated areas. In view of the country's objectives to increase the proportion of renewable energy in the country's energy mix from 1% to 25% by 2035, wind energy, whose strong potential is not yet exploited, needs to be highlighted (see figure 1).

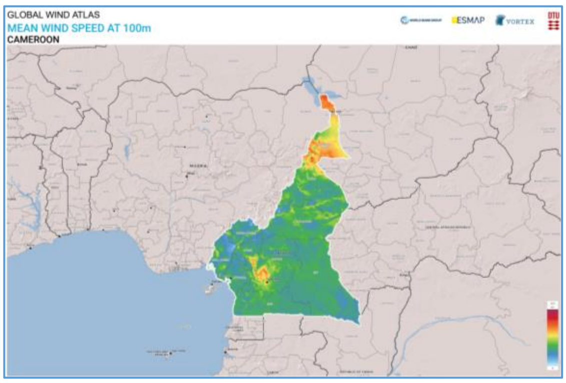

Fig. 1. Overview of Wind energy potential in Cameroon

Several studies have been carried out concerning the development of wind energy in rural areas. Offshore wind energy potential was investigated for the state of Kuwait by [3] using four years hourly data at 10m height. The parameters of Weibull were estimated by MLM and wind power density was estimated at an extrapolated elevation of 30 m. Then, the offshore wind farm was analysed from an economic view (Levelized Electricity Cost) and financial view (Net present value, Rate of return, Payback period). On the other hand, Adnan *et al.* (2021) studied the installation of wind farm by considering the wind power density and cost of land acquisition. The study was conducted by analyzing mean wind speeds, estimated Weibull parameters, power and energy densities calculation for various heights of selected wind turbines. The data used was for only one year at 80m and 67m height. Gormo *et al.* (2021) discussed the electrification of Garoua and Guider by wind energy, taking bihourly data collected at 10 m over a period of fifteen years. These sites are characterized by analyzing the direction, the hourly and monthly variation of wind. They determined Weibull parameters using MLM before evaluating wind power density and wind energy density. In addition, this study give the mapping of 2D and 3D topographical maps of the wind resource to take into account the local effects (surface roughness, topography, wind shear profile and the influence of terrain contour). Ahmad *et al.* (2022) analysed a feasibility of wind energy in coastline of Pakistan, based on four years monthly data (at the measured height of 10 m). They assessed wind speed, wind density, wind directions, economic feasibility, GHG emission reduction, and fuel saving.

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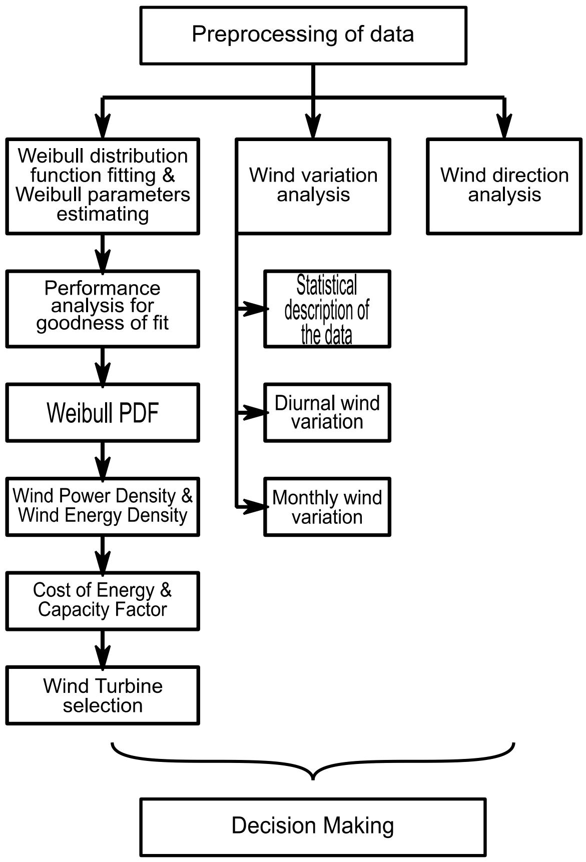
This article aims to bring together the assessment procedures applied by these authors into a protocol that can be easily followed in rural site feasibility studies. This protocol considers the use of Merra data from the wind resource over a 15-year period,

Therefore, this research assess the potential of wind power for electricity production in the rural locality of Logone Birni for applications like residential use, irrigation and livestock, using the protocol presented in the methodology.

2 Methodology and Data

The process of this study is given as follow:



2.1 Characterization of wind data

The wind at a site is described by displaying the daily, monthly, and yearly wind variations. Similarly, the study of wind direction is an important element. This characterization involves the determination of the mean and variance of the wind data. They are determined by equations (1) and (2) [7]:

$$\bar{v} = \frac{1}{n}\sum_{i=1}^{n} v_i \tag{1}$$

$$\sigma = \left[\frac{1}{n-1}\sum_{i=1}^{n}(v_i - \bar{v})^2\right]^{1/2} \tag{2}$$

2.2 Weibull probability distribution function

In the literature, the Weibull probability distribution is the most widely used model for wind speed distribution characterization, wind potential studies, and wind prediction. This distribution has two parameters: scale parameter c (m.s-1) and shape parameter k (unitless) [5, 7, 9, 10]. Its probability density function f (v) is given by:

$$f(v) = \left(\frac{k}{c}\right)\left(\frac{v}{c}\right)^{k-1} \exp\left(-\left(\frac{v}{c}\right)^{k}\right) \tag{3}$$

where v is the wind speed, f (v) is the wind speed probability.

2.2.1 Methods for estimation of Weibull parameters

The scale factor (*c)* determines the quality of the wind while the dimensionless shape factor (k) characterises the shape of the frequency distribution [10,11]. In this regard, several methods have been used to determine these two parameters.

2.2.1.1 Maximum Likelihood Method (MLM)

The determination of the parameters of the Weibull distribution by this method requires the use of numerical methods [12–14]. k and c are expressed as:

$$k = \left[\frac{\sum_{i=1}^{n} v_i^k \ln(v_i)}{\sum_{i=1}^{n} v_i^k} - \frac{\sum_{i=1}^{n} \ln(v_i)}{n}\right]^{-1} \tag{4}$$

$$c = \left[\frac{1}{n}\sum_{i=1}^{n} v_i^k\right]^{1/k} \tag{5}$$

where n is the number of observations and vi is the wind speed measured at interval i.

2.2.1.2 Energy Pattern Factor method (EPF)

This is a non-numerical method and easier to implement. The energy pattern factor is first determined by the ratio of the mean cubic to the cube of mean wind speed of the data [10, 12–14]. From this result, k and c can be deduced. The following expressions define these parameters.

$$E_{pf} = \frac{\frac{1}{n}\sum_{i=1}^{n} v_i^3}{\left(\frac{1}{n}\sum_{i=1}^{n} v_i\right)^3} \tag{6}$$

$$k = 1 + \frac{3,69}{\left(E_{pf}\right)^2} \tag{7}$$

$$c = \frac{v_m}{\Gamma\left(1+\frac{1}{k}\right)} \tag{8}$$

2.2.1.3 Empirical Method of Justus (EMJ)

EMJ was introduced by Justus in 1977 according to the studies of Chaurasiya et al., (2018), Li et al., (2020) and Ouahabi et al., (2020). According to Justus, the parameters k and c can be estimated from the mean and standard deviation of wind speeds. They are given by:

$$k = \left(\frac{\sigma}{v_m}\right)^{-1{,}086} \tag{9}$$

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

2.2.1.4 Moment Method (MOM)

It is applied on the bases of the mean and standard deviation of the Weibull distribution. The parameter k is obtained by solving equation (11), which is obtained by taking the ratio of the standard deviation and the mean speed, by the numerical method [10, 12–14].

$$\left(\frac{\sigma}{v_m}\right)^2 = \frac{\Gamma\left(1+\frac{2}{k}\right)}{\Gamma^2\left(1+\frac{1}{k}\right)} - 1 \tag{11}$$

"c" is calculated by:

$$c = \frac{v_m}{\Gamma\left(1+\frac{1}{k}\right)} \tag{12}$$

2.2.2 Statistical performance of the models

In the evaluation of the performance of these four Weibull methods, the following statistical tools are used: Root Mean Squared Method (RMSE) and Coefficient of determination (R^2).

2.2.2.1 Root Mean Square Error (RMSE)

The RMSE provides information on the accuracy of the distribution. It ranges from zero to infinity. Its ideal value is close to zero. Thus, the more the value of the RMSE is low, the more the distribution is well adapted to the data. It is given by [10]:

$$RMSE = \sqrt{\frac{1}{n}\sum_{i=1}^{n}\left(x_i - y_i\right)^2} \tag{13}$$

Where: y_i is the actual data (measured, observed), x_i is the predicted data using the Weibull distribution, and n is the number of all observed wind data.

2.2.2.2 Coefficient of determination (R^2)

It determines the linear relationship between the calculated values from the Weibull distribution and the calculated values from measured data. A higher R^2 represents a better fit using the theoretical or empirical function and the highest value it can get is 1. R^2 is expressed by [10]:

$$R2 = 1 - \frac{\sum_{i=1}^{n}\left(y_i - x_i\right)^2}{\sum_{i=1}^{n}\left(y_i - \bar{y}\right)^2} \tag{14}$$

Where: y_i is the actual data (measured, observed), x_i is the predicted data using the Weibull distribution, $\bar{y}$ is the mean value of y_i, n is the number of all observed wind data.

2.3 Wind power density and energy

Wind Power Density (WPD) is used with wind speed as the best indicator of the wind resource at a considered location. Based on the Weibull pdf, the WPD is expressed as follows [8]:

$$WPD = \frac{1}{2}\rho_a c^3 \Gamma\left(1+\frac{3}{k}\right) \tag{15}$$

Where ρ is the air density depending on the elevation (z) and the temperature (T) at the site. It is given by [11]:

$$\rho_a = \frac{353.049}{T}\exp\left(-0.034\frac{z}{T}\right) \tag{16}$$

The wind energy density is deducted by multiplying the WPD with the time (yearly, monthly, and daily). It defines by the expression below [8]:

$$WED = WPD \times time \tag{17}$$

2.4 Power output and Capacity Factor (CF)

The average electrical power output (*Pe,ave*) from the turbine can be evaluated as follows [7, 10]:

$$P_{e,ave} = P_{eR} \times \left[\frac{\exp\left[-\left(\frac{v_c}{c}\right)^k\right] - \exp\left[-\left(\frac{v_R}{c}\right)^k\right]}{\left(\frac{v_R}{c}\right)^k - \left(\frac{v_c}{c}\right)^k} - \exp\left[\left(\frac{v_F}{c}\right)^k\right]\right] \tag{18}$$

The capacity factor (*CF*) is defined as the ratio of the average power output (*Pe,ave*) to the rated electrical power (*PeR*) of the wind turbine. It is stated as [1, 7]:

$$CF = \frac{\exp\left[-\left(\frac{v_c}{c}\right)^k\right] - \exp\left[-\left(\frac{v_R}{c}\right)^k\right]}{\left(\frac{v_R}{c}\right)^k - \left(\frac{v_c}{c}\right)^k} - \exp\left[-\left(\frac{v_F}{c}\right)^k\right] \tag{19}$$

2.5 Economic assessment of wind turbines

Using different types of wind turbines, the cost of energy generated from wind resources is assessed. The technical specifications of these turbines are given in Table 2. The objective of this section is to quantify the performance-based price of energy from each type of turbine. The cost of energy is given by [5, 15]:

$$CoE = \frac{NPV}{E} \quad (20)$$

The Net Present Value of Costs (NPV) of energy produced per year:

$$NPV = I + C_{om}\left(\frac{1+i}{r-i}\right)*\left(1-\left(\frac{1+i}{1+r}\right)^{n}\right) - s\left(\frac{1+i}{1+r}\right)^{n} \quad (21)$$

The discount rate (r) is determined using the following expression:

$$r = \frac{i_0 - i}{1+i} \quad (22)$$

I is the investment cost, which includes the wind turbine price in addition to 20% for civil works and other connections; n is the useful lifetime of WT in years; i_o is the nominal interest rate; Com is the operation and maintenance costs; S is the scrap value; i is the inflation rate.

2.6 Case study: Logone Birni village

Table 1 presents the study site coordinates. The meteorological data for this site are the hourly average of 2001 – 2015 satellite measurements at 10m height [16].

The energy needs for the development of this locality are classified into three sectors:

- Household demand: lights, cell phone charging, TVs, fans and radios
- Institutional demand (off-grid public sectors): Water supply (pumping systems), health (Health facilities), education (Primary and secondary schools), street lighting.
- Productive energy use: SME applications for village businesses (micro-businesses (stores, hairdressers, tailors, kiosks, crafts), value-added applications (solar irrigation, refrigeration/refrigeration and milling), connectivity/ICT applications (cell phone charging).

Table 1. Coordinates of Logone Birni.

Latitude	11.7781° N
Longitude	15.1038° E
Division	Logone & Chari
Region	Extrême Nord
Country	Cameroun

To conduct the studies, the following parameters have been considerated (table 2 and 3) [7].

Table 2. Economic assessment parameters [7].

Parameters	Values
Investment cost (**I**)	20% of WT price
Operation & maintenance costs (**Com**)	7.5% of investment cost
Scrap value (**S**)	10% of WT price
nominal interest rate (**i_o**)	16%
Inflation rate (**i**)	3.6%
useful lifetime of WT (n)	20 years

Table 3. Technical specifications of five wind turbines [7].

Characteristics	**WT-A**	**WT-B**	**WT-C**	**WT-D**	**WT-E**
Hub height (m)	30	30	30	30	30
Rated power RP (kW)	20	20	20	20	20
Rotor diameter (m)	10	10	10	10	10
Cut-in wind speed Vc	1.5	2.0	2.5	3.0	3.5
Rated wind speed VR	8	9	10	11	12
Cut-off wind speed VF	25	25	25	25	25
Price (USD/kW)	1.775	1.775	1.775	1.775	1.775

3 Results and Analysis

This section highlights the results of the study and their interpretation. The focus is first on the statistical characterisation of the wind variation at the study sites (Logone Birni). Secondly, the statistical analysis of the performance of the different methods of determining the Weibull parameters. Finally, the wind potential assessment as well as the economic feasibility study for a wind power installation on this site.

3.1 Analysis of wind data characteristics

The characteristics of the wind data are described in terms of the daily wind variation, the monthly wind variation and the wind roses at the site.

3.1.1 Mean wind speed & standard deviation

The wind at Logone Birni varies between a minimum of 0.94 m/s and a maximum of 8.87 m/s, with an average of 3.82 m/s. The wind turbulence index is 2.76 and the standard deviation is 1.38 m/s (table 4).

Table 4. Main characteristics of the wind data.

Data (m/s)	**min**	**max**	**mean**	**std**	**Turbulence**
Logone Birni	0.94	8.47	3.82	1.38	2.76

3.1.2 Wind Rose Graph

Figure 2 shows the distribution of wind speeds by sector at the Logone Birni site. The Logone Birni site is characterised by winds whose most dominant directions are 45°NE and 60°NNE with frequencies of 10.5% and 26.3% respectively. The least representative directions are 0°E, 90°N, 180°W with frequencies of 4%, 6%, 3% and speeds of 5.2 m/s, 5.8 m/s and 4.1 m/s respectively.

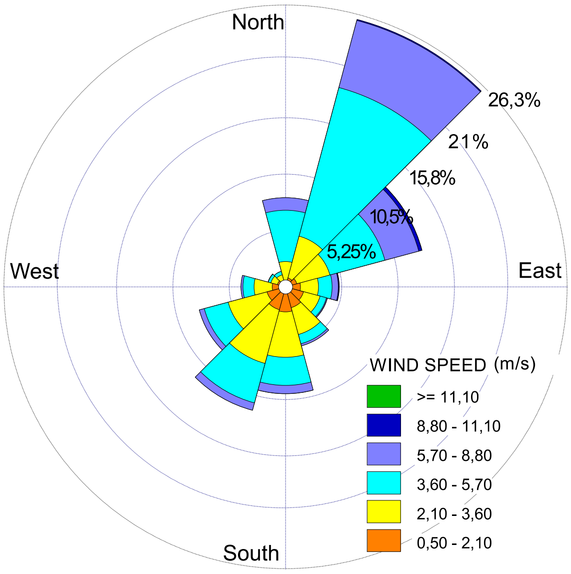


Fig. 2. Wind rose of Logone Birni.

3.2 Performance analysis of the two-parameter Weibull PDF methods

Table 5 presents the results of the performance evaluation of the different methods as well as the values of the parameters k and c. For each method of determining the k and c parameters, the results of analysis by statistical tests (RSME, R^2) are presented. The shape and scale parameters of the Logone Birni site are in the range of 2.85–3.01 and 4.28–4.29 m/s, respectively.

The results show that the best-fit model is the one where k = 2.85272, c = 4.29345 m/s for the Logone Birni site, using the EPF method. In addition, the performance analysis carried out permitted the classification of the four different models. Thus, the R2 value for the EPF method is the closest to unity. Similarly, the EPF method has the smallest value according to the RMSE. The calculated RMSE and R2 demonstrated that the EPF model is appropriate to approximate the real data from the Logone Birni site.

However, the EMJ method is the least suitable for this site, as it has the worst results in the statistical tests performed (Table 5). This can be explained by the fixed constants that are included.

Table 5. Performance analysis of four methods for determining Weibull parameters.

Method	Weibull parameters		Statistical tests		
	k(-)	c(m/s)	RMSE	R2	rank
MLM	3.01660	4.29236	0.18667	0.19641	3
EPF	2.85272	4.29345	0.18611	0.19364	1
EMJ	3.00442	4.28335	0.18663	0.17437	4
MOM	3.01534	4.28343	0.18169	0.19623	2

3.3 Wind speed variation analysis

The wind at a site is described by displaying the daily wind variation, the monthly wind variation and the wind roses at the site.

3.3.1 Diurnal Wind variation of Site

As figure 3 shows, the wind blows with an average speed of 3.70 m/s in the intervals of [1h-8h], [11-14h], and [16h-24h]. Thus, the site is windy for 20 hours per day. It is highest at 4 m/s at 01 pm. However, between 8 am and 11 am, the wind is moderately weak on this site with a speed of 3.58 m/s. Therefore, this wind is stable in that it varies little on this site with a rate of 11.73%.

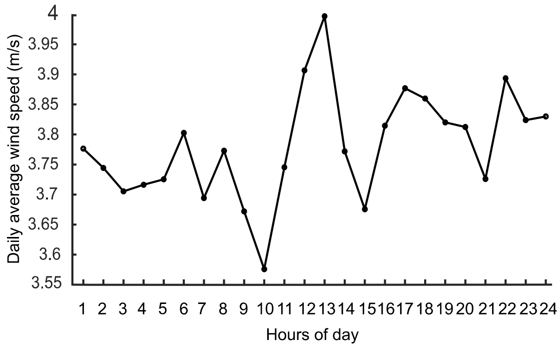


Fig. 3. Daily wind profile.

3.3.2 Monthly Wind variation of Site

The Logone Birni site is characterized by wind availability for the whole year (figure 4). The peak is noted in February and it is weaker in September. January, February, March, and December are the windiest months with an average wind speed of 4.6 m/s (figure 4).

Moreover, figure 4 shows the variations of the monthly average speed at heights of 10, 30, 50, and 100 m respectively, as a function of the month. The graphs show the same trend with the only difference that the more the altitude is increased, the more the wind is better. Similarly, the months from January to July and November to December show the highest wind speeds, with an average of greater than 3.5 m/s. On the other hand, the wind is poor for the months from August to September, as it is less than 3 m/s.

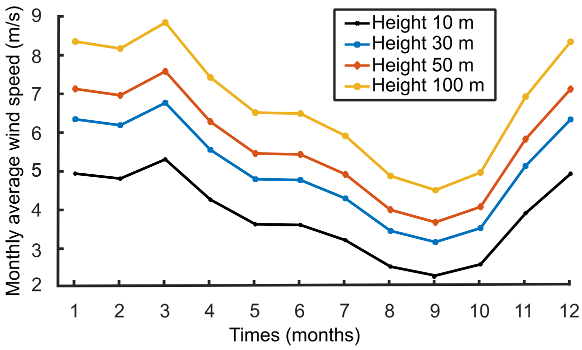


Fig. 4. Monthly wind variation.

3.3.3 Wind Speed Frequency Distribution

The monthly variation of Weibull wind speed frequencies for Logone Birni is illustrated in figure 5. The figure shows that, at a height of 10 m, 25% of the velocity data is in the range of 3 m/s to 8 m/s. Similarly, the average speed is between 3 and 5 m/s, which allows for electricity generation. These results conform with those of Kidmo et al. (2016); Nsouandélé et al. (2016) and Tchinda & Kaptouom (2003).

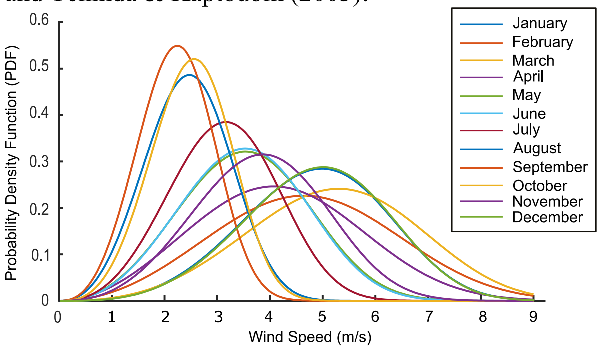


Fig. 5. Monthly wind speed frequency distribution curves at 10 m altitude.

3.4 Calculations of wind power density and energy

The monthly wind power densities and energy densities at different heights are shown in Figure 6 and 7. For the Logone Birni site, the minimum and maximum wind power was observed in December and July with values of 08.7 and 111.649 W/m2, respectively (figure 6). In addition, this site has a higher wind power density during the beginning and end of the year; but has a lower wind power density in the middle of the year.

Furthermore, the energy density of the site is presented in figure 7. Thus, this graph shows a variation between 6.264 kWh/m²/day, in September, and 83.067 kWh/m²/day, in February. Thus, the average extractable wind energy in one day at this site is 2 kWh/m²/day.

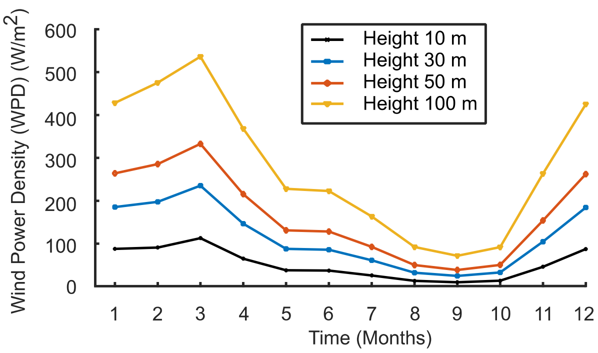


Fig. 6. Wind Power Density (WPD) (W/m^2).

Nevertheless, to classify the wind characteristics, Teimourian et al., (2019) quoting Fazelpour et al., (2015, 2017), proposed the use of the average wind power density as an indicator. Therefore, based on the criteria and results presented, this site is suitable for the installation of a wind pumping system.
Similarly, it appears that Logone Birni's site is identified as an appropriate location for the installation of large-scale wind turbines, when considering a minimum elevation of 30 m (113.563 W/m2 of mean WPD).

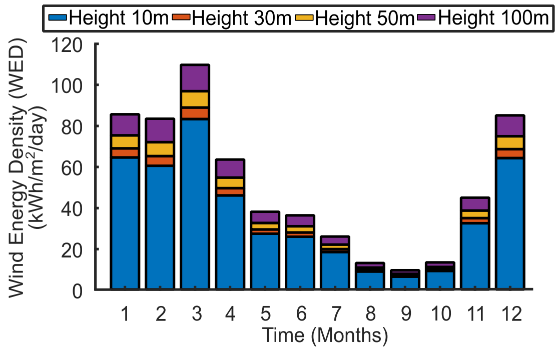


Fig. 7. Wind Energy Density (kWh/m2/day).

3.5 Analysis of the electricity cost and choice of the wind turbine model

As per the cost estimation of selected wind turbines, the wind turbine WT-A has a capacity factor (33.068 %) up to 25%, therefore the preferred for electricity production (table 6). According to Nsouandélé et al. (2016), with a wind turbine whose capacity factor is greater than this value (25%), wind power can be generated.

In terms of price per kilowatt-hour, the results show that the wind turbine WT-D has the lowest cost of energy (0.299 USD/kWh) over the other wind turbines. However, its capacity factor indicates that it will not produce electricity. Further, the details are given in Table 6.

Table 6. Comparative analysis of CF and Cost of Energy for different Wind turbine.

Wind Turbine	WT-A	WT-B	WT-C	WT-D	WT-E
CF (%)	33.068	24.021	17.287	12.397	8.849
Cost Energy (USD/kWh)	0.453	0.713	0.373	0.299	0.308

4 Conclusions

The aim of this study was to assess/evaluate the wind energy available in rural area following a clear protocol for electricity production. Logone Birni site has been taken as case study. The results of this research revealed the potential of wind energy, the adapted method for estimating Weibull parameters, performance assessment of wind turbine and the cost of energy produced in a site should be accurate. For Logone Birni case, this study shows that:

- Logone Birni's site is can be identified as an appropriate location for the installation of large-scale wind turbines, when considering a minimum elevation of 30 m (113.563 W/m^2 of mean WPD).
- The adapted method for estimating Weibull parameters is the Energy Pattern Factor Method
- The average extractable wind energy in one day at this site is 2 kWh/m²/day.

- The wind turbine with a CF of 33.068 % and cost of energy of 3.453 USD/kWh is desired for electricity production in this area.

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