*Research Journal of Engineering Sciences* ISSN 2278 – 9472
Vol. **6(11),** 43-53, December **(2017)** *Res. J. Engineering Sci.*

***Case Study***

# Evaluation of wind potential in the sahelian area: case of three sites in Burkina Faso

**Seydou Ouedraogo[1], Ayité Sénah Akoda Ajavon[2]*, Adekunlé Akim Salami[2], Mawugno Koffi Kodjo[2] and Koffi-Sa Bédja[2]**
[1]Equipe de Recherche en Sciences de l'Ingénieur (ERSI), Department of Electrical Engineering, Institut Universitaire de Technologie, University Nazi BONI of Bobo-Dioulasso, 01 BP 1091 Bobo-Dioulasso 01, BURKINA FASO
[2]Equipe de Recherche en Sciences de l'Ingénieur (ERSI), Department of Electrical Engineering, Ecole Nationale Supérieure d'Ingénieurs (ENSI), University of Lomé, 01 BP 1515 Lomé 01, Lomé TOGO
asajavon@yahoo.fr

**Available online at: www.isca.in, www.isca.me**
Received 25th September 2017, revised 6th December 2017, accepted 23rd December 2017

## Abstract

*This article proposes the evaluation of wind potential at different altitudes. A good wind speed data analysis with an accurate wind energy potential evaluation are very important factors for suitable development of wind power use or application at a given zone or region. This paper presents wind speed distribution for three (3) weather stations in Burkina Faso (Dori, Ouagadougou et Ouahigouya), to select the two-parameter Weibull method that provide accurate and efficient evaluation of energy output for wind energy devices. The shape parameter k and the scale parameter c are calculate based on measured three-hourly mean wind speed data in times-series from 2004 to 2013, collected for three (3) weather stations in Burkina Faso. Three numerical methods, namely Graphical Method (GM), Justus Method (JM) and Power Density Method (PDM) are examined to calculate the Weibull parameters. To analyze the efficiency of the methods and to ascertain how closely the measured data follow the Weibull methods, goodness of fit tests were performed using the correlation coefficient ($R^2$) and Root Mean Square Error (RMSE). The obtained results revealed that the power density method is the most accurate and efficient method for calculating the value of the shape parameter k and the scale parameter c. The annual variation in the recoverable wind power density varies between 42.11 W/m$^2$ in Ouahigouya and 12.78 W/m$^2$ in Dori for the maximum and minimum value and 36.41 W/m$^2$ in Ouagadougou. The results show that the energy potential of the Dori site is not suitable for electrical production. However, the average speed of Ouagadougou and Ouahigouya sites shows that electricity can be generated from wind power at these sites, but from a height of 80 meters.*

**Keywords:** Weibull parameters, Graphical method, Justus Method, Power density method, Wind rose.

## Introduction

There has been renewed interest in renewable energy sources (RES) in recent years. The main cause of this boom is the depletion of conventional energy resources and the degradation of the environment. Today, wind energy is the fastest growing source of renewable energy on a global scale. With the rapid development of technologies in recent years, wind power generation has reached a high level of technological maturity and industrial reliability, which in a positive way has considerably decreased the cost of producing wind power[1]. The conversion of wind energy into electrical energy or mechanical energy for pumping could therefore contribute considerably to the reduction of the poverty problems of the African populations[2,3].

In Burkina Faso, electricity is produced by thermal and hydro power plants and by imports from Cote d'Ivoire and Ghana. Production is mainly through the use of fossil fuels[4]. Demand continues to outstrip supply and breakdowns are common in peak periods. The demand for electricity is also constantly increasing. It is therefore urgent that Burkina Faso find a solution to cover the demand with a clean energy source. The sectoral energy policy 2014-2025 of Burkina Faso also recommends research on the evaluation and exploitation of wind potential[5-7], with the aim of increasing the share of renewable energies in the energy mix of Burkina Faso's energy needs to 50% by 2025[4].

Regarding the exploitation of wind resources and its contribution to the country's energy mix, knowledge of wind speed characteristics of sites is important. Wind speed varies in different seasons[8,9]. A modeling of wind speed distribution on a monthly basis can help to control seasonal variations of wind potential at a site[10,11]. For statistical data analysis of wind speed distribution, Weibull Power Density Function (PDF) is often used as the most appropriate function due to its high accuracy[1]. A large numbers of studies have been published in scientific literature that proposes the use of two-parameter Weibull PDF methods to describe wind speed frequency distributions. According to IEC 61400-12 (International Electrotechnical Community), an International Standard, the two-parameter

Weibull Probability Density Function is the most appropriate distribution function for wind speed data as it gives a good fit to the observed wind speed data both at surface and in the upper air[2,12,13].

The main objective of the article is to evaluate the wind resource available at three sites (Dori, Ouagadougou and Ouahigouya), whose climate is Sahelian[12,14], in order to assist in the development of the country's wind resource uses. First, we present the study sites and the method of data collection, and then the presentation of the materials and methods used the results and finally summarizes the work and the perspectives for the future.

## Wind data

The sites concerned are Dori in the North-East, Ouahigouya in the North-West and Ouagadougou in central Burkina Faso. The data used for the study are provided by the National Directorate of Meteorology of Burkina Faso[15]. The geographic coordinates of the sites are given in Table-1.

**Table-1:** Geographical coordinates of study sites.

| Country | Sites | Longitude | Latitude | Altitude |
|---|---|---|---|---|
| Burkina Faso | Dori | 0°03 West | 14°03 North | 282 m |
| | Ouagadougou | 1°32 West | 12°21 North | 299 m |
| | Ouahigouya | 2°25 West | 13°35 North | 339 m |

The data for our study are three-hour observations of the force (FF_XX) and direction (DD_XX) of the wind, from 0 hours to 24 hours and 10 meters above the ground, at the three meteorological stations. They correspond to a collection period of 10 years, from 2004 to 2013. Recordings are made daily, at 3-hour intervals, i.e. a total of 29,224 measurements collected over the ten (10) year (2004 - 2013) period for each site[15]. Figure-1 illustrates the wind speed histogram of the three sites.

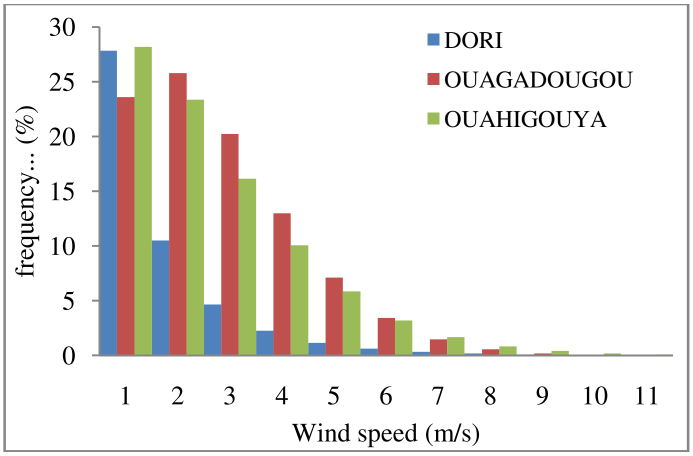

**Figure-1:** The wind speed histogram of the three sites.

## Methodology

To evaluate wind potential at a site, the frequency distribution of wind speed must be expressed[16,17]. Weibull distribution is the most widely used and recommended in the literature to express the frequency distribution of wind speed[2,18].

The distribution of Weibull is a special case of Pearson distribution[19]. In this distribution, the variations of the wind speed are defined by two functions, namely: the Probability Density Function (PDF) and the Cumulative Distribution Function (CDF). The PDF, $f(v)$, shows the fraction of time (or probability) for which the wind gave the speed. It is expressed by equation (1).

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

Where: c is the Weibull scale parameter (m/s); k is a dimensionless morphological parameter, which characterizes frequency distribution at a site; *v* is wind speed.

The CDF, $F(v)$, of the wind speed v gives the fraction of time (or probability) for which the wind speed is less than or equal to v. The corresponding cumulative frequency is given by equation (2).

$$F(v)=\int_0^v f(v)\,dv=1-\exp\left[-\left(\frac{v}{c}\right)^{k}\right] \quad (2)$$

The mean wind speed $\overline{V}$ is defined by equation (3).

$$\overline{V}=\int_0^{+\infty} v f(v)\,dv \quad [\mathrm{m/s}] \quad (3)$$

Where: $v_i$ is the classed wind velocity, $f(v_i)$ is the frequency of occurrence, n is the number of observations.

Several methods are used for calculating Weibull parameters from wind data at a site. However, we will evaluate the shape parameter k and scale parameter c on the three study sites, with Graphical Method (GM), Justus Method (JM) and Power Density Method (PDM)[12,13,20,21]. It is the most precise of these methods that will be adopted to determine the recoverable power of the wind on the studied sites.

The description of the three methods, the vertical extrapolation of Weibull parameters and mean wind speed, the average Wind Power Density and the wind rose are presented as follows:

**Graphical Method (GM):** The Graphical Method is based on Weibull's cumulative function. For the determination of the shape and scale parameters (k and c), equation (2) is transformed in the form given by equation (4).

$$\ln\left[-\ln\left(1-F(v)\right)\right]=k\ln(v)-k\ln(c) \qquad (4)$$

Since wind speed is known, we can find k and c by linear regression, using the least squares method, which consists in adjusting the experimental points. The interpolation is linear and take the form $y = ax + b$ ; The expressions for x and y are given by expression (5).

$$\begin{cases} y=\ln\left[-\ln\left(1-F(v)\right)\right] \\ x=\ln(v) \end{cases} \qquad (5)$$

Expression (6) gives the values of the shape and scale parameters (k and c).

$$\begin{cases} k=a \\ c=\exp(-b/a) \end{cases} \qquad (6)$$

**Justus Method (JM):** This method is based on mean wind velocity $\overline{V}$ and Standard Deviation $\sigma$ . The estimation of shape parameter k and scale parameter c is done by equations (7)-(9).

$$\sigma=\left[\frac{1}{N-1}\sum_{i=1}^{N}\left(v_i-\overline{V}\right)^2\right]^{1/2} \qquad (7)$$

$$k=\left(\frac{\sigma}{\overline{V}}\right)^{-1.086} \qquad (8)$$

$$c=\frac{\overline{V}}{\Gamma(1+\frac{1}{K})} \qquad (9)$$

Where: N is the total number of intervals, $\Gamma$ is Gamma function defined by equation (10).

$$\Gamma(v)=\int_{0}^{+\infty} t^{z-1}e^{t-1}dt \qquad (10)$$

**Power Density Method (PDM):** In this method, the expression for power density $P$ for the Weibull distribution is given by equation (11)[10].

$$P=\frac{1}{2}\rho\int_{0}^{+\infty} v^3 f(v)dv \qquad (11)$$

Where: $\rho$ is the density of the air (kg/m$^3$).

The energy model factor is defined by the equation (12).

$$E_{pf}=\frac{\overline{V^3}}{\overline{V}^3}=\frac{\frac{1}{n}\sum_{i=1}^{n}v_i^3}{\left(\frac{1}{n}\sum_{i=1}^{n}v_i\right)^3} \qquad (12)$$

Where: $\overline{V}$ is the mean wind speed, n is the number of intervals.

The value of the shape parameter k is obtained using $E_{pf}$:

$$k=1+\left(\frac{3,69}{E_{pf}^2}\right) \qquad (13)$$

Then, c is determined with equation (14).

$$c=\frac{\overline{V}}{\Gamma(1+\frac{1}{K})} \qquad (14)$$

To test each of the three methods, we will determine the statistical analysis parameters which are the Coefficient of Determination ( $R^2$ ) and the Root of the Mean Square Error (RMSE). The Coefficient of Determination is calculated by equation (15).

$$R^2=1-\left(\frac{\sum_{i=1}^{N}(y_i-x_i)^2}{\sum_{i=1}^{N}(y_i-\overline{y})^2}\right) \qquad (15)$$

And the Root Mean Square Error by the equation (16).

$$RMSE=\left(\frac{1}{N}\sum_{i=1}^{N}(y_i-x_i)^2\right)^{0.5} \qquad (16)$$

Where: $N$ is the total number of intervals, $y_i$ is the observed frequency value, $x_i$ is the value of frequency obtained by the Weibull distribution and $\overline{y}$ the mean value of $y_i$ .

A model is said to be ideal, if it is characterized by a zero value for the RMSE and 1 for the parameter $R^2$ .

**Vertical extrapolation of Weibull parameters and mean wind speed:** The wind speed data we use in this study are measured at 10 meters from the ground. It is necessary to estimate Weibull parameters and wind speed at different altitudes[22]. The extrapolation of the Weibull parameters is obtained by equations (17), (18) and (19).

$$k_1 = \frac{k_0}{\left(1 - 0.00881\ln\left(\frac{z}{10}\right)\right)} \qquad (17)$$

$$c_1 = c_0\left(\frac{z}{z_0}\right)^n \qquad (18)$$

$$n = \frac{0.37 - 0.0088\ln c_0}{1 - 0.00881\ln\left(\frac{z}{10}\right)} \qquad (19)$$

Where: $k_0$ is the shape parameter at the height of measurements (generally 10 m); $k_1$ is the shape parameter at the height at which shape parameter is estimated (height of the hub of the wind turbine); $c_0$ is the scale parameter at the height of measurement; $c_1$ is the scale parameter at the height at which scale parameter is estimated; $z_0$, height of measurement (generally 10 m); z is the height at which the shape parameter k and the scale parameter c are estimated.

The extrapolation of wind speed for different altitudes is obtained by equations (20) and (21)[7,9].

$$v = v_0\left(\frac{z}{z_0}\right)^{a_J} \qquad (20)$$

$$\begin{cases} a_J = \dfrac{1}{\ln\left(\dfrac{z_g}{r_0}\right)} \\ z_g = \sqrt{z_0 z} \end{cases} \qquad (21)$$

Where: v is the estimated speed at height z, $v_0$ is the speed at the measurement height, z is the height at which speed is estimated (height of the wind turbine hub), $z_0$ is the measurement height 10 m), $a_J$ is an empirical factor expressing the influences of surface roughness and atmospheric stability, $z_g$ is the geometric mean of height and $r_0$ is the roughness of the soil.

Measurements of wind speed are carried out at airports and the soil roughness is of the open country type[23]: $r_0 = 0.07$ m.

**Average Wind Power Density:** The power available in a wind speed flow is obtained by the relation (22).

$$P(v) = 0.5\rho S v^3 \quad [W] \qquad (22)$$

Where: ρ is air density, S is cross-section through which the wind flows perpendicularly, v is the wind speed.

The distribution density of wind energy is expressed by equation (23).

$$\frac{P(v)}{S} f(v,k,c) = 0.5\rho v^3 f(v,k,c) \quad [W/m^2] \qquad (23)$$

Where: $f(v,k,c)$ is the frequency of occurrences of wind speeds (%).

By integrating equation (23) for a study period, we obtain the average wind power density using equation (24).

$$\overline{P} = 0.5\rho \int_0^{+\infty} v^3 f(v,k,c)\,dv \qquad (24)$$

According to the Betz limit, the maximum recoverable power density of wind at a site becomes equal to $16/27$ (59.26%) of the available power. Equation (25) expresses this relationship.

$$P = \frac{16}{27}\overline{P} \quad [W/m^2] \qquad (25)$$

**Wind rose:** A wind rose makes it possible to know, for a given point, the frequencies of observation of the wind according to criteria of direction and strength[15]. The provenance of wind is determined according to the following directions: between 0° and 90°, the winds come from the Northeast (N-E); between 90° and 180°, the winds come from the Southeast (S-E); between 180° and 270°, the winds come from the Southwest (S-W); between 270° and 360°, the winds come from the Northwest (N-W).

## Results and discussion

The average monthly wind speeds at 10 m altitude at the three sites are shown in Figure-2. Wind speed has a maximum value of 4.63 m/s at Ouahigouya (in June), while the minimum wind speed of 1.26 m/s is recorded in November at Dori (Figure-2). The average annual minimum wind speed is observed at Dori, with a value of 1.85 m/s, while the average annual wind speed is recorded at Ouagadougou with a value of 3.53 m/s. From monthly averages and wind speed distribution, monthly averages of wind speed are less than 4 m/s at 10 m from the ground except for the months of June and July at the Ouahigouya site.

For the Dori site, average monthly speeds are below 2.5 m/s; there is a significant variation in monthly mean wind speeds during the year. The Ouagadougou site has virtually constant monthly average speeds of about 3.5 m/s. Monthly average wind speeds vary little from month to month during the year. The average monthly speeds at the Ouahigouya site vary greatly during the year; An average of 2.20 m/s in November, it was 4.63 m/s in June (Figure-2). We can say that the sites studied are not windy enough.

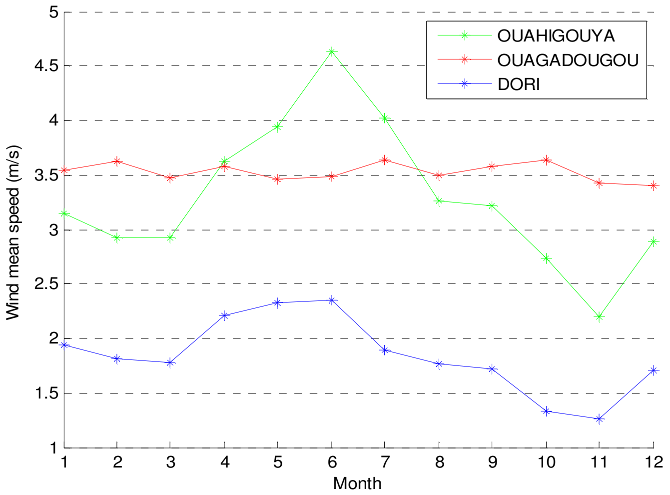

**Figure-2:** Monthly wind speed for the three sites at 10 m altitude.

The curves representing the cumulated frequencies measured and the estimated cumulative Weibull frequencies (Equation (2)) are given in Figures-3, 4 and 5, respectively. For all sites, there is no great difference between the cumulative frequency curves estimated by the Justus and graphic methods and the cumulated frequency measured.

The cumulative frequencies estimated by the Justus and graphical methods are very similar for three sites. The cumulative frequencies estimated by these two (2) methods are then very close, while the cumulative frequencies estimated by the power density method differ, especially at the Dori site (Figures-3, 4 and 5). For all sites, the cumulative frequency curves given by the power density method were the closest to the measured distribution.

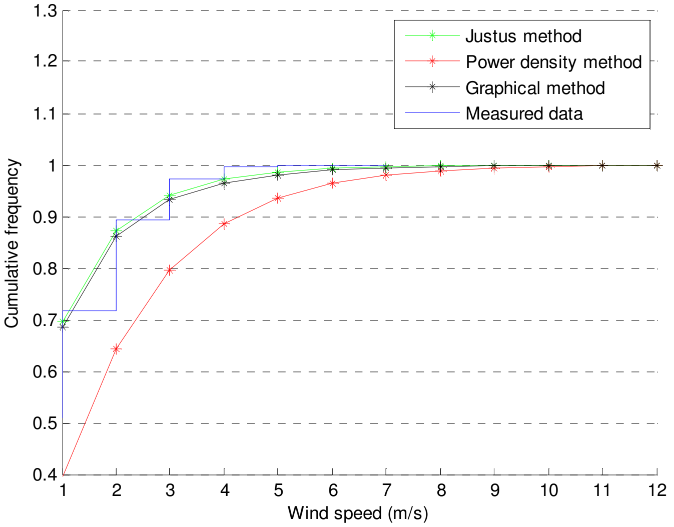

**Figure-3:** Estimated and measured cumulative frequency for the Dori site.

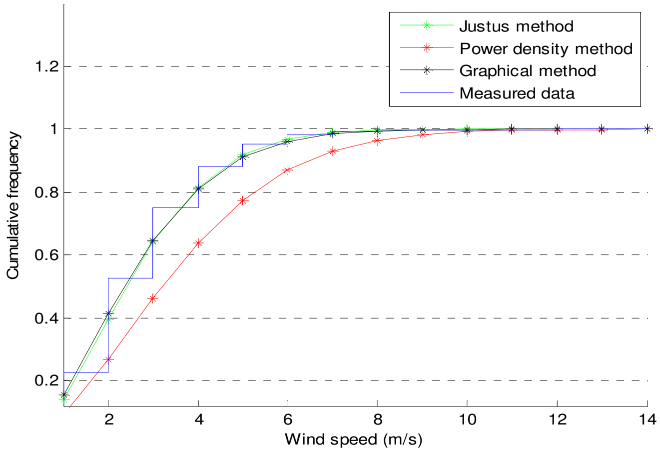

**Figure-4:** Estimated and measured cumulative frequency for the Ouagadougou site.

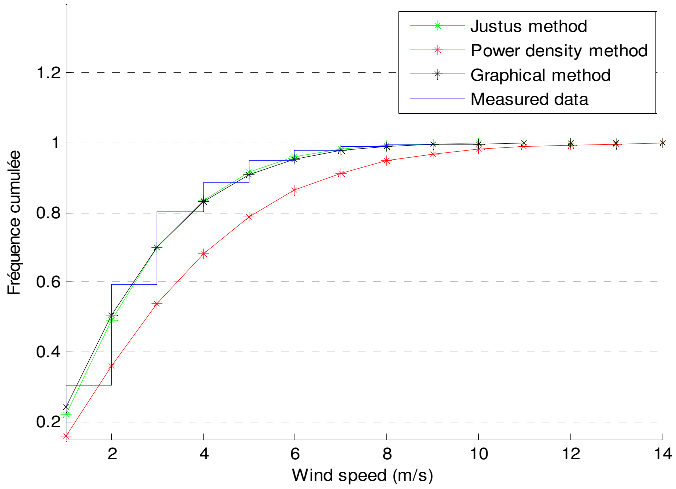

**Figure-5:** Estimated and measured cumulative frequency for the Ouahigouya site.

Table-2 presents the shape and scale parameters (k and c) for the three sites, as estimated using the Graphical Methods, Justus Methods and Power Density Method, (Equations (4)-(14)).

For each site, there is not much difference between the parameters estimated by the three methods. For all sites, the parameters estimated by the graphical method and the Justus method are close, while the parameters estimated by the power density method are different from the parameters estimated by the other two methods.

The results of the statistical indicators of precision RMSE and $R^2$ are given in Table-3 for the three sites and for the three methods used (Equations (15) and (16)). Comparison of the three methods with the measured values shows that the power density method gives the best estimate of the distribution measured for the three sites. The value of the RMSE closest to zero and the value of $R^2$ closest to 1 are obtained with the power density method for the studied sites.

The monthly variation of the Weibull shape parameter k and scale parameter c estimated by three methods used for the three sites studied is shown in Tables-4, 5 and 6. The shape parameter k varies between 0.47 at Dori (in November) and 2.007 at Ouahigouya (in July). So wind speed is more uniform at Ouahigouya during the month of July, whereas it is less uniform at Dori during the month of November. The scale parameter c varies between 0.146 m/s at Dori (in November) and 5.046 m/s at Ouahigouya (in June), which shows that the Ouahigouya site is the most windy for this period.

**Table-2:** Annual shape and scale parameters (k and c) for the three study sites using three methods.

| | Dori | | Ouagadougou | | Ouahigouya | |
|---|---|---|---|---|---|---|
| Methods | k [-] | c [m/s] | k [-] | c [m/s] | k [-] | c [m/s] |
| Graphical Method | 0.7654 | 0.8230 | 1.6515 | 2.9322 | 1.3413 | 2.6027 |
| Justus Method | 0.7905 | 0.8003 | 1.7426 | 2.9609 | 1.4278 | 2.6382 |
| Power Density Method | 1.0613 | 1.9366 | 1.6124 | 3.7993 | 1.3561 | 3.6160 |

**Table-3:** Comparison of the three methods for the three sites.

| | Dori | | Ouagadougou | | Ouahigouya | |
|---|---|---|---|---|---|---|
| Methods | RMSE | $R^2$ | RMSE | $R^2$ | RMSE | $R^2$ |
| Graphical method | 0.0601 | 0.9962 | 0.0414 | 0.9986 | 0.0154 | 0.9998 |
| Justus method | 0.0635 | 0.9959 | 0.0747 | 0.9954 | 0.0109 | 0.9999 |
| Power density method | 0.0026 | 0.9999 | 0.0050 | 0.9995 | 0.0024 | 0.9999 |

**Table-4:** Estimation of the monthly shape and scale parameters for the three sites by the Graphical Method.

| Graphical Method | | | | | | |
|---|---|---|---|---|---|---|
| | Dori | | Ouagadougou | | Ouahigouya | |
| Month | k [-] | c [m/s] | k [-] | c [m/s] | k [-] | c [m/s] |
| January | 0.7033 | 0.8367 | 1.6988 | 2.9635 | 1.3344 | 2.4376 |
| February | 0.6992 | 0.7211 | 1.7025 | 3.0671 | 1.7065 | 2.2600 |
| March | 0.7165 | 0.7081 | 1.7544 | 2.8919 | 1.6535 | 2.2644 |
| April | 0.8419 | 1.2273 | 1.6752 | 2.9815 | 1.4585 | 3.0025 |
| May | 0.9642 | 1.4259 | 1.7284 | 2.8746 | 1.6552 | 3.3946 |
| June | 1.0340 | 1.4861 | 1.5711 | 2.8765 | 1.6029 | 4.1547 |
| July | 0.7770 | 0.8709 | 1.6411 | 3.0484 | 1.9452 | 3.5224 |
| August | 0.8300 | 0.8034 | 1.6335 | 2.8845 | 1.4224 | 2.5839 |
| September | 0.8636 | 0.7825 | 1.6817 | 2.9842 | 1.6597 | 2.5918 |
| October | 0.7722 | 0.3914 | 1.5813 | 3.0415 | 1.3474 | 2.0065 |
| November | 0.7845 | 0.3356 | 1.7564 | 2.8316 | 0.8071 | 1.1640 |
| December | 0.7983 | 0.7229 | 1.4964 | 2.7603 | 1.3248 | 2.1553 |

**Table-5:** Estimation of the monthly shape and scale parameters for the three sites by the Justus Method.

| Justus Method | | | | | | |
|---|---|---|---|---|---|---|
| | Dori | | Ouagadougou | | Ouahigouya | |
| Month | k [-] | c [m/s] | k [-] | c [m/s] | k [-] | c [m/s] |
| January | 0.7499 | 0.8432 | 1.7692 | 2.9854 | 1.5394 | 2.5043 |
| February | 0.7104 | 0.6937 | 1.7475 | 3.0724 | 1.8634 | 2.2926 |
| March | 0.7021 | 0.6581 | 1.8155 | 2.9076 | 1.7200 | 2.2795 |
| April | 1.0184 | 1.3014 | 1.8548 | 3.0354 | 1.4627 | 3.0043 |
| May | 1.1313 | 1.4799 | 1.7709 | 2.8859 | 1.7440 | 3.4266 |
| June | 1.1961 | 1.5313 | 1.6769 | 2.9112 | 1.5414 | 4.1333 |
| July | 0.7994 | 0.8465 | 1.7234 | 3.0758 | 2.0079 | 3.5401 |
| August | 0.8430 | 0.7677 | 1.7738 | 2.9269 | 1.5472 | 2.6267 |
| September | 0.8764 | 0.7451 | 1.7722 | 3.0150 | 1.7492 | 2.6152 |
| October | 0.5283 | 0.2198 | 1.5969 | 3.0532 | 1.5231 | 2.0494 |
| November | 0.4738 | 0.1461 | 1.8741 | 2.8630 | 0.8959 | 1.1968 |
| December | 0.7943 | 0.6105 | 1.6105 | 2.7990 | 1.4620 | 2.1949 |

**Table-6:** Estimation of the monthly shape and scale parameters for the three sites by the Power Density Method.

| Power Density Method | | | | | | |
|---|---|---|---|---|---|---|
| | Dori | | Ouagadougou | | Ouahigouya | |
| Month | k [-] | c [m/s] | k [-] | c [m/s] | k [-] | c [m/s] |
| January | 1.0541 | 2.0252 | 1.7332 | 3.9819 | 1.6028 | 3.5144 |
| February | 1.0443 | 1.8812 | 1.7001 | 4.0706 | 1.9281 | 3.2951 |
| March | 1.0380 | 1.8432 | 1.8031 | 3.9067 | 1.6922 | 3.2770 |
| April | 1.1933 | 2.3711 | 1.8932 | 4.0377 | 1.3981 | 3.9846 |
| May | 1.2369 | 2.5159 | 1.7343 | 3.8825 | 1.7410 | 4.4263 |
| June | 1.3024 | 2.5615 | 1.6798 | 3.9115 | 1.3323 | 5.0467 |
| July | 1.0575 | 1.9810 | 1.6964 | 4.0726 | 1.9757 | 4.5390 |
| August | 1.0796 | 1.8647 | 1.7932 | 3.9286 | 1.5444 | 3.6262 |
| September | 1.0978 | 1.8242 | 1.7104 | 3.5732 | 1.7459 | 3.6149 |
| October | 1.0083 | 1.4006 | 1.4640 | 4.0235 | 1.5824 | 2.3077 |
| November | 1.0046 | 1.3251 | 1.9016 | 3.8644 | 1.0944 | 1.3082 |
| December | 1.0673 | 1.7889 | 1.6124 | 3.7993 | 1.4910 | 3.2004 |

A maximum value of average monthly recoverable power density of 115.86 $W/m^2$ is recorded at Ouahigouya (in June) at 10 m altitude (Table-7). While, a minimum value of 4.90 $W/m^2$ is recorded at Dori (November) (Table-7). The maximum value of 42.10 $W/m^2$ of average annual recoverable wind power density at 10 m altitude is recorded in Ouahigouya, while the minimum value of 12.77 $W/m^2$ is recorded at Dori (Table-7). The estimated average recoverable annual power density in Ouagadougou is 36.40 $W/m^2$ (Table-7). The power density values in Ouagadougou and Ouahigouya are clearly better than in Dori.

The annual recoverable power densities are evaluated at heights of 20 m to 130 m in 10 m steps with the soil roughness $r_0 = 0.07$ m (Equations (17)-(25)). Figures-6 and 7 show the results obtained from the extrapolated wind characteristics (Equations (17)-(25)). Wind speed and power density increase with altitude; The average annual minimum wind speed of 3.29 m/s and the average annual minimum power density of 65.16 $W/m^2$ are recorded at Dori, while the average annual maximum speed of 5.54 m/s is recorded in Ouagadougou and the average annual maximum power density of 161.97 $W/m^2$ is recorded in Ouahigouya. The average annual wind speed in Ouahigouya is 5.25 m/s and the mean power density is 138.56 $W/m^2$ in Ouagadougou (Table-7), (Figures-6 and 7). At 130 m altitude, the average annual minimum wind speed of 4.20 m/s and the average annual minimum power density of 127.19 $W/m^2$ are recorded at Dori, while the average annual maximum speed of 6.76 m/s is Recorded in Ouagadougou and the average annual maximum power density of 279.04 $W/m^2$ is recorded in Ouahigouya. The average annual wind speed in Ouahigouya is 6.39 m/s and the mean power density is 248.36 $W/m^2$ in Ouagadougou (Table-7), (Figures-6 and 7). At an altitude of 60 m, the Ouagadougou and Ouahigouya sites have an average wind speed higher than 5 m/s (Figure-6), which is sufficient for the interesting production of electricity using wind turbines (Table-7), (Figures-6 and 7). For the Dori site, however, it is necessary to go above 130 m altitude to obtain wind speeds values greater than 5 m/s.

**Table-7:** Estimated recoverable power density for the three selected sites.

| | Dori | Ouagadougou | Ouahigouya |
|---|---|---|---|
| Month | Recoverable power density values [W/m²] | Recoverable power density values [W/m²] | Recoverable power density values [W/m²] |
| January | 14.7118 | 35.6957 | 27.6287 |
| February | 12.1832 | 38.2319 | 17.6756 |
| March | 11.7057 | 31.9583 | 20.5916 |
| April | 16.0684 | 33.2145 | 51.8816 |
| May | 17.4208 | 33.0585 | 48.7211 |
| June | 16.1612 | 35.4043 | 115.8606 |
| July | 13.6209 | 39.3833 | 44.9674 |
| August | 10.5953 | 32.7331 | 32.3103 |
| September | 9.3945 | 37.1105 | 26.4362 |
| October | 5.7084 | 48.6900 | 18.5843 |
| November | 4.9004 | 28.9678 | 18.9358 |
| December | 9.7390 | 34.5687 | 23.6726 |
| Annual | 12.7776 | 36.4076 | 42.1056 |

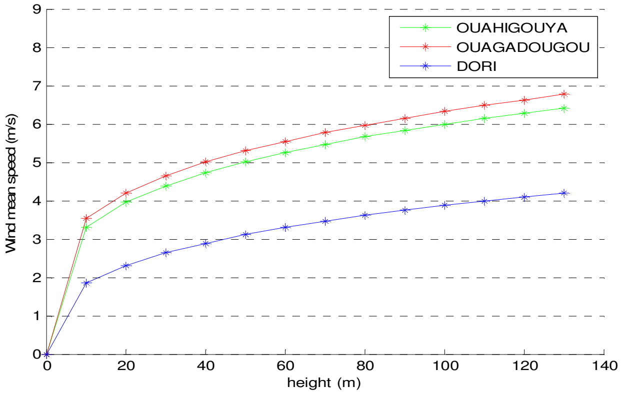

**Figure-6:** Average annual wind speed for different altitudes.

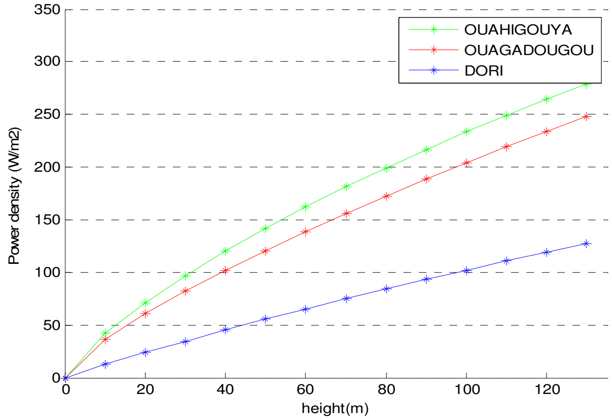

**Figure-7:** Evolution of recoverable power density at different altitudes.

The wind roses at the Dori, Ouagadougou and Ouahigouya sites are shown in Figures-8, 9 and 10, respectively. The observations and analyzes made on the wind statistics of the three sites shows predominance in the following directions: i. Northeast direction, in the third sector (between 60° and 90°) for the Dori site (Figure-8); ii. South-east direction, between the fifth and sixth sectors (between 120° and 180°) for the Ouagadougou site (Figure-9); iii. Southwest direction, in the ninth sector (between 240° and 270°) for the Ouahigouya site (Figure-10).

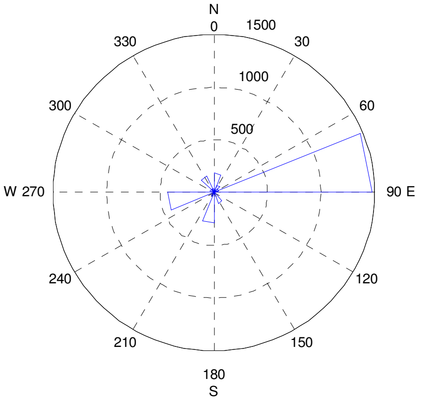

**Figure-8:** Wind roses for Dori site.

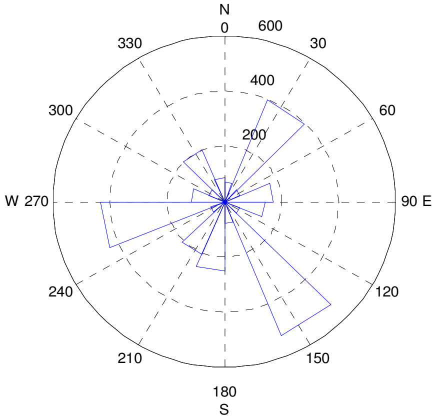

**Figure-9:** Wind roses for Ouagadougou site.

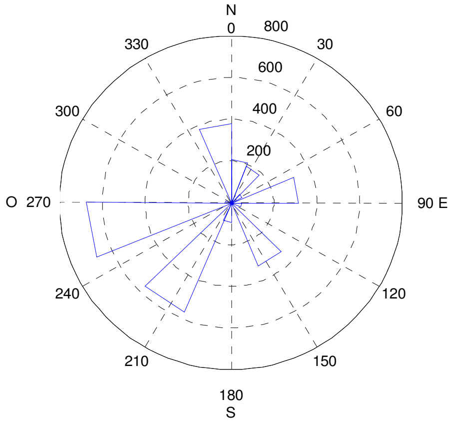

**Figure-10:** Wind roses for Ouahigouya site.

In order to validate the power density method for the evaluation of the Burkina Faso wind resource, the results obtained have been compared with Burkina Faso wind atlas[7]. These comparisons demonstrated that the average speed and the recoverable wind power density, for the three sites with Power Density Method, represent the wind resource for the sites studied in Burkina Faso.

## Conclusion

Three-hourly wind speed data in time-series for three sites of Burkina Faso have been statistically studied using the Weibull Power Density Function. The objective was to select the most accurate and efficient method to evaluate how closely the measured data follow the two-parameter Weibull Power Density Function.

The performance of three Weibull methods were assessed using the Root Mean Square Error (RMSE) and correlation coefficient ($R^2$) goodness of fit to precisely rank and acknowledge the methods that are adequate for the specific wind data, collected in the airport of Dori, Ouagadougou and Ouahigouya. Based on the analysis, the most important results of the study can be presented as follows: i. wind speeds for three sites are modeled using Weibull Power Density Function (PDF). The shape parameter k and the scale parameter c are shown in Table-2; ii. the Power Density Method ranked as the most accurate and efficient method for determining the value of k and c to approximate wind speed distribution; as a result, the Power Density Method (PDM) is recommended for the better and more accurate estimation of the Weibull parameters for three sites of this study, in objective to reduce uncertainties affiliated to the wind energy output calculation for these sites; iii. the recoverable wind power density varies between 42.11 W/m$^2$ in Ouahigouya and 12.78 W/m$^2$ in Dori for the maximum and minimum value and 36.41 W/m$^2$ in Ouagadougou at 10 m height; at 60 m height, the power density is 65.16 W/m$^2$ at Dori, 138.56 W/m$^2$ at Ouagadougou and 161.97 W/m$^2$ at Ouahigouya; iv. favorable winds are in the direction: Northeast for the site of Dori, Southeast for the site of Ouagadougou and Southwest for the site of Ouahigouya; v. we can conclude that the potential for wind energy development in Dori is not fitted for generating electrical energy and a very fruitful use would be achieved if windmills were installed for producing community water supply, farm irrigation and livestock watering; wind energy can be exploited at the sites of Ouagadougou and Ouahigouya, but from a height of 80 meters in height.

This study is a first step in the development of wind energy. The results obtained make it possible to obtain excellent recommendations for projects to install medium and large-scale wind turbines in Burkina Faso.

## Acknowledgements

The authors want to thank the University Nazi BONI of Bobo-Dioulasso and the University of Lomé for providing enabling environment during the research.

## References

1. Mostafaeipour A., Jadidi M., Mohammadi K. and Sedaghat A. (2014). An Analysis of Wind Energy Potential and Economic Evaluation in Zahedan, Iran. *Renewable and Sustainable Energy Reviews*, 30, 641-650.
2. Houekpoheha M.A., Kounouhewa B., Tokpohozin B.N. and Awanou N. (2014). Estimation de la puissance énergétique éolienne à partir de la distribution de Weibull sur la côte béninoise à Cotonou dans le Golfe de Guinée. *Revue des Energies Renouvelables*, 17(3), 489-495.
3. Abdraman M., Tahir A., Lissouck D., Kazet M. and Mouangue R. (2016). Wind Resource Assessment in the City of N'djamena in Chad. *International Journal of Renewable Energy Research (IJRER)*, 6(3), 1022-1036.
4. Ministère des mines et de l'énergie du Burkina Faso (2013). Politique Sectorielle de l'Energie 2014 – 2025, Standards and Reports.
5. Fagbenle R.O., Katende J., Ajayi O.O. and Okeniyi J.O. (2011). Assessment of wind energy potential of two sites in North-East, Nigeria. *Renewable energy*, 36(4), 1277-1283.
6. Fyrippis I., Axaopoulos P.J. and Panayiotou G. (2010). Wind energy potential assessment in Naxos Island, Greece. *Applied Energy*, 87(2), 577-586.
7. Landry M., Ouedraogo Y., Gagnon Y. and Ouedraogo A. (2011). Atlas éolien du Burkina Faso. rapport de l'Université de Moncton, Canada et UFR-SEA, Université de Ouagadougou, Burkina Faso.
8. Salami A.A., Ajavon A.S.A., Kodjo M.K. and Bedja K. (2006). Etude de la variabilité mensuelle du potentiel éolien sur le site de Lomé: contribution à un choix optimal des aérogénérateurs pour ce site. *J. Rech. Sci. Univ. Lomé (TOGO)*. 8(1), 1-11.
9. Tar K. (2008). Some statistical characteristics of monthly average wind speed at various heights. *Renewable and Sustainable Energy Reviews*, 12(6), 1712-1724.
10. Al Zohbi G., Hendrick P. and Bouillard P. (2014). Evaluation du potentiel d'énergie éolienne au Liban. *Revue des Energies Renouvelables*, 17(1), 83-96.
11. Salami A.A., Tiem S., Lishou C. and Bédja K. (2007). La logique floue pour la prediction de la moyenne horaire de la vitesse du vent sur le site de Lomé. *Journal des Sciences Pour l'Ingénieur*, 8(1), 88-96.
12. Mouangue M.R., Kazet M.Y., Kuitche A. and Ndjaka J.M. (2014). Influence of the Determination Methods of k and c Parameters on the Ability of Weibull Distribution to Suitably Estimate wind Potential and Electric Energy. *International Journal of Renewable Energy Development*, 3(2), 145-154.
13. Seguro J.V. and Lambert T.W. (2000). Modern Estimation of the Parameters of the Weibull Wind Speed Distribution for Wind Energy Analysis. *Journal of Wind Energy Engineering and Industrial Aerodynamics*, 85(1), 75-84.
14. Vishnupriyan J. and Manoharan P.S. (2017). Demand side Management Approach to Rural Electrification of Different Climate Zones in Indian State of Tamil Nadu. *Energy*, Elsevier, 138, 799-815.
15. Direction Générale de la Météorologie du Burkina Faso (2015). Données climatologiques de stations météorologiques (2004–2013). Standards and Reports, Ouagadougou.
16. Akpinar S. and Akpinar E.K. (2007). Wind energy analysis based on maximum entropy principle (MEP)-type distribution function. *Energy Conversion and Management*, 48(4), 1140-1149.
17. Safari B. (2011). Modeling wind speed and wind power distributions in Rwanda. *Renewable and Sustainable Energy Reviews*, 15(2), 925-935.
18. Ramírez P. and Carta J.A. (2005). Influence of the data sampling interval in the estimation of the parameters of the Weibull wind speed probability density distribution: a case

study. *Energy Conversion and Management*, 46(15), 2419-2438.

**19.** Mathew S. and Philip G.S. (2011). Advances in wind energy and conversion technology. 20, Berlin: Springer, 74-80.

**20.** Kidmo D.K., Danwe R., Doka S.Y. and Djongyang N. (2015). Statistical analysis of wind speed distribution based on six Weibull Methods for wind power evaluation in Garoua, Cameroon. *Revue des Energies Renouvelables*, 18(1), 105-125.

**21.** Mohammadi K., Alavi O., Mostafaeipour A., Goudarzi N. and Jalilvand M. (2016). Assessing different parameters estimation methods of Weibull distribution to compute wind power density. *Energy Conversion and Management*, 108, 322-335.

**22.** Kasbadji-Merzouk N., Merzouk M. and Benyoucef B. (2007). Extrapolation verticale des paramètres de Weibull pour l'estimation du potentiel récupérable. *Revue des Energies Renouvelables*, 1CRESD-07, Tlemcen, 193-198.

**23.** Tieleman H.W. (2003). Roughness Estimation for Wind-Load Simulation Experiments. *Journal of Wind Energy Engineering and Industrial Aerodynamics*, 91(9), 1163-1173.