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STATISTICAL ANALYSIS OF WIND DATA AND ASSESSMENT OF WIND POTENTIAL IN BURKINA FASO

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ABSTRACT

This paper reports the assessment of Burkina Faso wind potential. To achieve this, measurements were made over a period of 11 years (2006-2016) by Burkina Faso National Meteorological Agency (ANAM) using an anemometer established on a 10m mat above the ground. Weibull distribution was used to model the average monthly and annual wind speed. A comparative study by Weibull on three parameter estimation methods (shape and scale parameter) is presented in order to minimize errors in estimating the power and energy density available on ten sites in Burkina Faso. These include the standard deviation method (empirical method), the energy pattern factor and the maximum likelihood. The results of the study show that the average monthly wind speed at 10 m above the ground varies from a minimum of 0.61 ms^{-1} at Dori (September) to a maximum of 3.57 $m.s^{-1}$ in Bobo (May). The minimum and maximum annual average speeds are recorded at Dori, 1.06 $m.s^{-1}$ and Bobo-Dioulasso, 3.02 $m.s^{-1}$, respectively. The standard deviation method and the maximum likelihood method give the best overall adjustment of the actual wind data distribution. Weibull parameter estimation results show that the shape parameter varies between 1.47 at Dédougou (June) and 5.11 in Bobo-Dioulasso (January) while the scale parameter varies between 0.68 $m.s^{-1}$ at Dori (October) and 3.90 $m.s^{-1}$ (May) in Bobo-Dioulasso. The average annual value of the scale parameter varies from 1.19 $m.s^{-1}$ (Dori) to 3.34 $m.s^{-1}$ (Bobo-Dioulasso) while the average annual value of the shape parameter varies from 1.66 (Dori) to 3.77 (Bobo). The results of the average monthly power density show that the minimum value of 0.3390 W / m^2 is recorded at Dori (November) while the maximum value of 34.5070 W / m^2 is recorded in Bobo-Dioulasso (May). On an annual scale, the results of the average annual power density vary from a minimum value of 1.794 W / m^2 on the Boromo site to a maximum value of 22.529 W/m^2 for that of Bobo-Dioulasso. Statistical indicators show that the maximum likelihood method and the standard deviation method best adjust the real wind data with a determination coefficient (R^2) and an average squared error (RMSE) higher than 0.95 and less than 1.5, respectively for all study sites.

KEYWORDS: Wind, wind potential, Weibull distribution, power density, standard deviation, maximum likelihood.

1. INTRODUCTION

The development of any human activity implies energy consumption[1]. The increasing demand for energy coupled with the depletion of fossil fuels in the more or less long term together with the increase in environmental pollution, lead countries throughout the world to gradually move towards new and renewable energies. Least developed countries in the world, endowed with renewable resources, are the most affected by the global energy crisis[2]. Burkina Faso is one of the countries the most affected by an acute energy crisis. It is estimated that electricity demand increases by an average of 13 yearly while the average annual growth rate of Burkina Faso National Electricity Company (SONABEL) is 10 %[3]. Considering the energy deficit, it is necessary and even urgent that Burkina Faso find alternate solutions to cover energy demand with a clean source of energy. One of the possibilities that we review through this study consists in assessing the wind resource for decision-making on a possible implementation of wind power generation systems. With the stochastic nature of

the wind resource, engineers in the field rely most often on mathematical models to predict the energy available in the wind [4]. To do so, it is important to find an appropriate statistical model of wind speed distribution frequency to predict the resource. Wind turbine manufacturers use information obtained from speed distribution to optimize their design and minimize power generation costs [5]**.** However, investors need this information to plan wind farm productivity. Over these recent years, several distribution functions are developed and tested by several researchers around the world. Among these, Weibull distribution function with two parameters (shape parameter and scale parameter) developed in 1951 by Waloddi Weibull [2] is one of the most widely used functions [6]. Several studies have assessed and analyzed the performance of various probability distribution functions to identify those best suited to wind energy applications. To compare theses distribution functions, several statistical indicators of model performance are used in literature, such as the coefficient of determination (R^2), the root mean square error (RMSE), the relative error percentage, etc. Yilmaz et al (2008) [7] conducted a comparative study of ten probability density functions (beta, Erlang, exponential, gamma, log-logistic, normal log, Pearson V, Pearson VI, uniform and Weibull). They found that Weibull is better fit to wind speed in the study area in Turkey. We also mention Carta et al. (2009) [8] who examined the use of various probability distribution functions of wind speed at four stations on the Canary Islands. Their results showed that Weibull's function offers advantages over several other distribution functions. However, its disadvantage is that it cannot accurately estimate the distribution of wind speed in places with high percentages of zero wind speeds. Sohoni et al. (2016) [9] also compared the distribution of Rayleigh, Gamma, Weibull, log-normal and inverse Gaussian in India. They reported that Weibull has minimal errors. Wais (2017) [10] conducted a study on the applicability of the Weibull distribution to two and three parameters (shape, scale and location) in wind energy analysis and also on the comparison of different probability density functions. The results show that for the higher rate of wind speed equal to zero or less than 2 $m.s^{-1}$,the three-parameter Weibull model is more advantageous compared to the two-parameter Weibull distribution that can be proposed as an alternative to the wind energy estimate technique. In a similar study, Tizgui et al (2018) [11] model the distribution of wind speed in Agadir, Morocco, using four distribution functions (Weibull, Rayleigh, Gamma, and normal log). Adjustment quality tests show that Weibull bear minimum errors. In addition, several researchers have proved that Weibull distribution accurately matches most of wind distributions around the world [12], [13], [14]. The brief review of the literature on distribution functions shows that the use of the Weibull function has some limits in the modeling of some wind regimes; but it is widely used and recommended by several studies because of its simplicity and offers high performance for many sites. As part of our work, the Weibull distribution will be used to model wind speed on the ten sites in Burkina Faso.

To minimize uncertainties in wind speed modeling, some researchers have proposed several methods for estimating distribution parameters, notably those of Weibull, such as the graphical method (GM), the maximum likelihood method (MLM) , the Modified Maximum Likelihood Method (MMLM), the Energy Pattern Factor Method (EPFM), the Moment Method (MoM), the Justus Empirical Method, the power density method (PDM) [5] .To compare these methods, different statistical analysis tests are used in literature [15]. In different studies, for specific sites and climatic conditions, researchers tried to compare the different methods in order to select the best one. Usta et al. (2016) [16] added the method of weighted probability moments based on the power density method (PWMBP) to the previous methods. The author compared the proposed method with six other methods, namely maximum likelihood, modified maximum likelihood, graphical, moments, power density and weighted moments. Quality criteria proved that the proposed method gave better results than the others. Kidmo et al. (2015) [17] compared seven numerical methods to provide the most accurate method for determining Weibull parameters in Garoua, Cameroon. It appears that the energy pattern factor method (EPFM) ranked first. Tizgui et al. (2017) [5] studied the performance of the graphical method, the maximum likelihood, the energy configuration factor method and the method of moments (MoM) and reported that the maximum likelihood method (MLM) gives the best results. Katinas et al (2018) [4] reviewed methods for estimating Weibull parameters adapted to different wind conditions (high and low winds) and proposed a more precise estimate of Weibull parameters in order to reduce the uncertainties to forecast wind energy production. Weibull distribution was used to model the average monthly wind speed, using four methods, namely the maximum likelihood method, the modified maximum likelihood method, the WAsP method and the Rayleigh distribution. The maximum likelihood method and the WAsP method were the most reliable for estimating Weibull parameters at these places.Usta et al (2018)[18]have developed a new approach to estimate Weibull parameters which might

be use to estimate wind energy. This new approach, called the Multi-Objective Moment Method (MUOM) is compared with well-known estimation methods such as Maximum Likelihood Method (MLM), Modified Maximum Likelihood (MLM), Power Density Method (PDM). Results obtained show that the new method provides more accurate estimates than other well-known methods of estimating wind energy based on the Weibull distribution. Shoaib et al (2017) [2] estimated using four statistical methods, namely the Maximum Likelihood Method (MLM), the Method of Moment (MoM), the Energy Factor Method (EPFM) and the Power Density Method (PDM) of Weibull distribution. The test results shows that the method of moments (MoM) and power density Method (PDM) are more reliable in estimating Weibull distribution parameters. A literary review of methods to estimate Weibull parameters in wind energy studies shows that several studies have focused on estimating Weibull parameters. However, there is no consent on the choice of the best estimation method because it depends on the climatic conditions of the studied site. Yet, it is noticed that the maximum likelihood method, the Justus moment method (standard deviation method) and the power density method are part of most studies conducted worldwide in first, second or third position in terms of details. These three methods are therefore used in the context of our study to review Weibull parameters.

The work by Landry and al (2011) [19] presents Burkina Faso wind atlas, consisting of three maps of the wind resource at 30, 50 and 80 m above ground level, as well as the topography and soil roughness for the whole country, using the Anemoscope commercial software. The results showed that the wind resource at 80 m above the ground is fairly good in the northeastern regions of the country (9.01 $m.s^{-1}$ and above), as well as in the North and West of the country. However, the work presented in [19] gives the vertical wind profiles at the meso level and a micro-level profile determination is required using in situ data. In addition, the previous work by Landry and al on the establishment of wind atlases does not address the power density, which is an essential indicator of the assessment of the wind resource on a site. Considering the deficit of studies on wind resource in Burkina Faso, the general objective of this paper is to assess the wind potential on 10 sites distributed throughout the country while the specific objectives include the following:

- Identify the most accurate method of modeling wind distribution in Burkina Faso using the Weibull model (standard deviation method, energy pattern factor and maximum likelihood);
- Estimate the monthly and annual power and energy density on the site under study. This paper is divided into 4 parts: after reviewing the introduction in the first part, the second part presents the study environment and data used. The third part is devoted to a description of the Weibull model, the methods of parameter determination as well as the estimation of power density and energy. Then, the fourth part presents the results of the calculations and discussions. The paper also include a conclusion. We hope that this study will contribute to a better knowledge of the available wind energy density over the whole country.

2. PRESENTATION OF THE STUDY AREAS AND DATA USED

Burkina Faso, a vast country of 274,200 square kilometers, is located in the heart of West Africa, between parallels 9°20' and 15°05' latitude north and meridians 2°20' longitude east and 5°30' longitude west at an average altitude of 300m above sea level. Landlocked country, Burkina Faso is surrounded by six (06) other countries: Mali in the West and the North, the Niger in the East, and in the South by Benin, Togo, Ghana and Cote d'Ivoire. Climate division reveals 03 major climate zones depending on rainfall and temperature in Burkina Faso:

- The Sahelian climate zone, located in the North of the 14^{th} parallel, characterized by an annual rainfall of less than 650 mm.
- The Sudano-Sahelian climate zone, located between the parallels 11°30 and 14° latitude north characterized by an annual rainfall ranging between 650 and 1,000 mm.
- The Sudanese climate zone in the South of 11°30' latitude north characterized by the annual rainfall exceeding 1,000 mm [20]. In these three climate zones, the average wind speeds were collected in ten synoptic stations throughout the country and provided by the Burkina Faso National Meteorological Agency thanks to wind sensors (anemovane). Measuring intervals such as 60 minutes or daily intervals

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are used only to obtain a reliable estimate of the wind potential, an interval of 10 minutes is recommended in literature [2]. In this paper, gross data are collected every three hours, i.e. eight (8) measurements (00h-03h-06h-09h-12h-15h-18h-21h) per day to obtain a daily average at 10 m from the

ground over the period going from January 1, 2006 to December 31, 2016. Figure 1 gives an overview of the study area and Table 1 gives the geographic coordinates of the sites selected for the study.

Table 1: Geographic coordinates of the sites studies

Site	Longitude	Latitude	Altitude(m)
Dori	00°02' W	14° 02'N	282
Ouahigouya	02° 19' W	13° 31'N	328
Bogandé	00°08'W	12°59'N	295
Fada N'goura	00°25' E	12° 4' N	298
Po	01°09'W	11°10'N	305
Ouagadougou	01° 40'W	12° 19'N	299
Dédougou	03°28'W	12°28'N	302
Boromo	02°56'W	11°45'N	325
Bobo Dioulasso	04°18'W	11°10'N	423
Gaoua	03°12' W	10°18 N	329

Figure1: Geographic location of the ten study sites.

3. METHOD

3.1. Mathematic modelling of wind frequency distribution: Weibull function

Given the difficulty to use all the data related to wind frequency distribution, it is more suitable for theoretical considerations to model the frequency histogram of wind speeds by a continuous mathematical function than by a table of discrete values. We can therefore choose the Weibull model. Indeed, for periods ranging from a few weeks to one year, Weibull function reasonably represents the speeds observed [21], [22]. In the Weibull distribution, wind speed variations are characterized by two functions, namely the Probability Density Function (PDF) and the Cumulative Distribution Function (CDF). The probability density function shows the part of time or the probability for which a wind speed is given. The probability density function is given 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 $f(v)$ is the probability density of the speed v ; k is the shape parameter of the curve (dimensionless) and c the scale parameters of the curve in $m.s^{-1}$. The distribution function or the speed cumulative distribution function gives the fraction of time or the probability for a wind less than or equal to v; therefore, the dividing distribution function is the primitive of the density function of distribution given in the equation (2).

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

The average wind speed may be calculated by integrating the probability density function, or the formula (1):

$$\bar{v} = \int_0^{\infty} v.f(v)dv \quad (3)$$

Thus, Weibull distribution can facilitate several calculations made necessary by the analysis of wind data.

3.2 Calculation of Weibull parameters.

There are several methods to calculate k and c from a given wind distribution. We used three commonly used methods: standard deviation, power density and maximum likelihood.

3.2.1 Standard Deviation Method (empirical method)

This method is suggested by Justus et al [23], [24]. If the average speed and the standard deviation are available, the estimation of parameters is done using formulas (3) and (4).

$$k = \left(\frac{\sigma}{\bar{v}}\right)^{-1,086} \quad (4)$$

$$c = \frac{\bar{v}}{\Gamma\left(1+\frac{1}{k}\right)} \quad (5)$$

With σ the standard deviation of the random variable, $\Gamma(x)$ Gamma Function defined by:

$\Gamma(x) = \int_0^{\infty} \exp(-t).t^{x-1}dt$; $\Gamma(1+x) = x\Gamma(x)$, where t is a real variable on which makes the integration.

3.2.2. Energy pattern Factor Method.

The energyfactor was defined by Golding [22], [25] as the ratio of the total value of available wind energy and the energy calculated from the curve of the mean wind speed.

The cubic wind speed is: $\bar{v}^3 = c^3\Gamma^3(1+1/k)$ (6)

The average cubic wind speed is: $\overline{v^3} = c^3\Gamma(1+3/k)$ (7)

The energy model factor is defined by:

$$k_E = \frac{\overline{v^3}}{\bar{v}^3} = \frac{\Gamma(1+3/k)}{\Gamma^3(1+1/k)} \quad (8)$$

In addition, based on observations, the energy factor may be calculated with the (9).

$$k_E = \left(\frac{1}{n}\sum_{i=1}^{n} v_i^3\right) \Big/ \left(\frac{1}{n}\sum_{i=1}^{n} v_i\right)^3 \quad (9)$$

The equation (8) is fairly given by the relation (10).

$$k = 1 + \frac{3{,}69}{(k_E)^2} \quad (10)$$

3.2.3 Maximum likelihood method.

Weibull distribution can adjust a series of wind data using the maximum likelihood method suggested by Stevens and Smulders [26]. The shape parameter k and scale parameter c are estimated using equations (11) and (12).

$$k = \left(\frac{\sum_{i=1}^{n} V_i^k \ln V_i}{\sum_{i=1}^{n} V_i^k} - \frac{1}{n}\sum_{i=1}^{n} \ln V_i \right)^{-1} \quad (11)$$

$$c = \left(\frac{1}{n}\sum_{i=1}^{n} V_i^k\right)^{1/k} \quad (12)$$

Where v_i is the wind speed at time i and n is the non-zero wind speed observation number. Equation (11) can be solved using an iterative procedure (k = 2 is the appropriate initial conjecture), then equation (12) can be solved explicitly. Equation (11) must be only used to non-zero wind speed data points. In order to try the various methods, the calculation of the statistical analysis parameters of equation (13) and (14) is used [23]:

- The determination coefficient: $R^2 = 1 - \left[\sum_{i=1}^{n}(y_i - x_i)^2 \Big/ \sum_{i=1}^{n}(y_i - \bar{y})^2\right]$ (13)

-the root mean square error: $RMSE = \left[\frac{1}{n}\sum_{i=1}^{n}(y_i - x_i)^2\right]^{1/2}$ (14)

Where n is the total number of intervals, y_i is the frequency of the values observed, x_i is the frequency of the values obtained with Weibull distribution and $\bar{y}$ is the average value of y_i . A model is considered as the ideal, if it is characterized by a null value for RMSE and 1 for the parameter R^2.

3.3. Available wind energy density.

The power density of wind energy is the most important feature of wind. It represents the amount of energy produced by wind. Assuming that S is the cross-section through which the wind rotates perpendicularly, the wind power density is given by equation (15) [27]:

$$\bar{P} = \int_0^{\infty} P(v) f(v)\, dv \quad (15)$$

Where $P(v) = \frac{1}{2}\rho S v^3$

By integrating the equation (15), we obtain the expression of the average available energy density given by equation (16).

$$\bar{P} = \frac{1}{2}\rho c^3 \Gamma\left(\frac{k+3}{k}\right) \quad (16)$$

Where ρ is the density of the air according to the altitude. In this study, we will use the density of the constant air because its variation is insignificant so that it does not influence the calculation of the wind resource [28].

4. RESULTS AND DISCUSSION

Based on the wind speeds provided by the Burkina Faso National Meteorological Service for the period from January 2006 to December 2016, the average monthly wind speeds at 10m on the ground surface of the ten sites are given in **Figure 2**. It should be noted that the average monthly wind speeds of the ten sites studied vary with space and time. The average monthly wind speed, with a maximum value of 3.57 m/s is recorded in Bobo (in February) while the minimum speed of 0.61m/s is recorded at Dori (in November). The average annual minimum and maximum wind speeds are got at Dori, with a value of 1.06m/s and Bobo-Dioulasso, with a value of 3.02m/s, respectively. Weibull shape and scale parameters distribution are estimated using the standard deviation, energy factor and maximum likelihood methods. **Table 2** summarizes the annual shape (k) and scale (c) parameters for the ten study sites. The curves representing the measured (empirical) frequencies and the estimated Weibull theoretical frequencies are given **in Figure 3**. For each site, there is not much difference between the parameters estimated with the three methods. However, the parameters estimated with the standard deviation method and the maximum likelihood method are very close in terms of accuracy, so that the curves obtained by both methods are superimposed, and thus better adjust data measured.

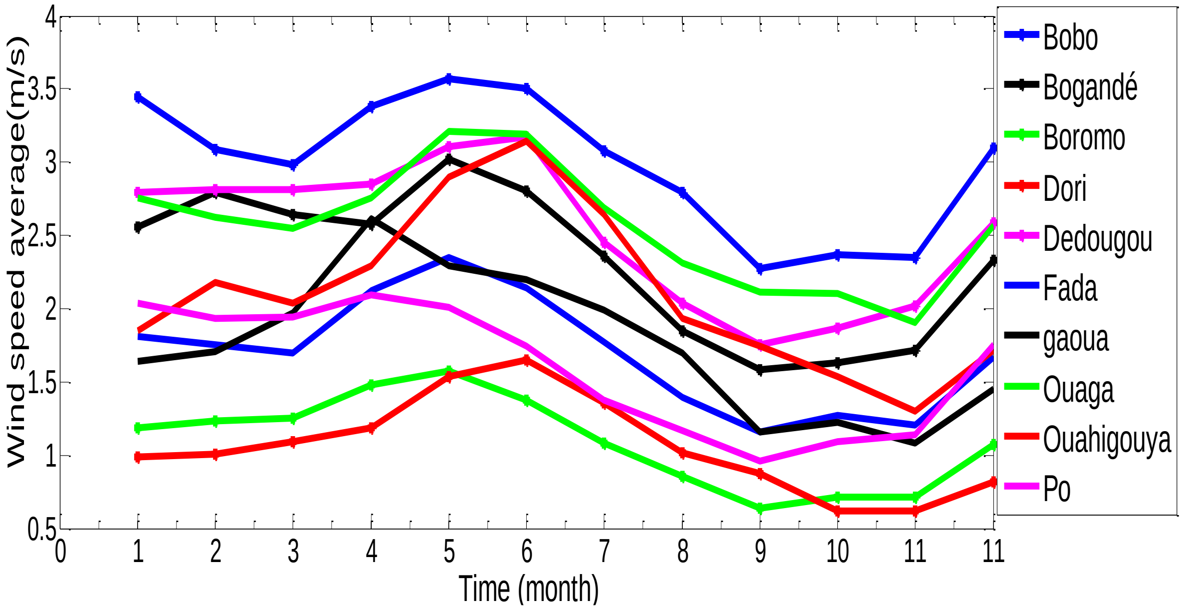

Figure 2 :Variation of the monthly average speed at 10m of altitude.

Table 2: Shape and scale parameters for the ten (10) sites using the three estimation methods.

Method	Bobo	Bogandé	Boromo	Dori	Dédougou
Vm	3.02	2.31	1.09	1.06	2.52

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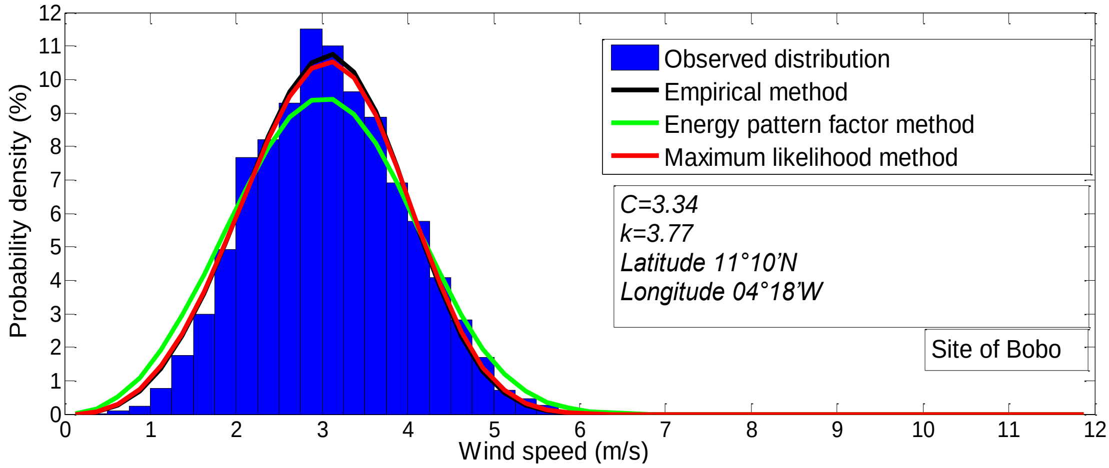
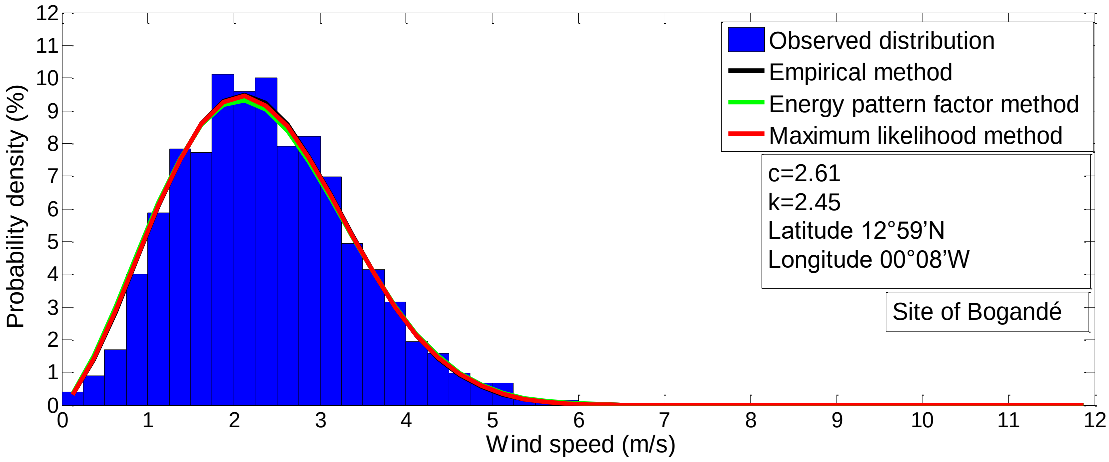
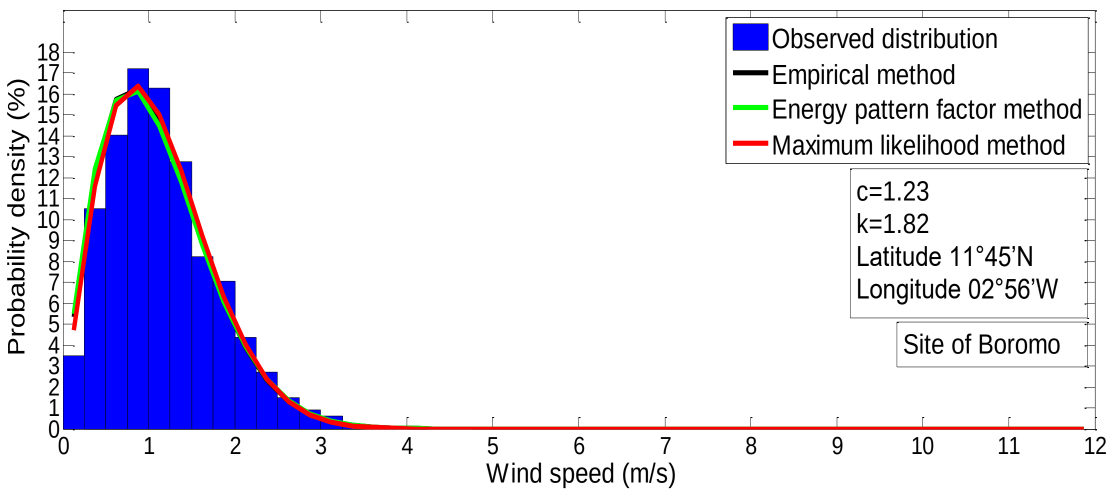
	k	c (m/s)	k	c (m/s)	k	c (m/s)	k	c (m/s)	k	c (m/s)
Standard deviation	3.77	3.34	2.45	2.61	1.82	1.23	1.66	1.19	2.45	2.84
Energy pattern factor	3.30	3.37	2.40	2.61	1.80	1.23	1.63	1.18	1.95	2.84
Maximum likelihood	3.70	3.34	2.44	2.61	1.88	1.25	1.72	1.21	2.22	2.81

Method	**Fada**		**Gaoua**		**Ouaga**		**Ouahigouya**		**po**	
Vm	1.69		1.75		2.56		2.10		1.60	
	k	c (m/s)	k	c (m/s)	k	c (m/s)	k	c (m/s)	k	c (m/s)
Standard deviation	2.21	1.91	2.12	1.97	3.26	2.86	2.16	2.37	2.23	1.80
Energy pattern factor	2.20	1.91	206	1.97	3.00	2.87	2.08	2.37	2.19	1.80
Maximum likelihood	2.20	1.91	2.13	1.98	3.18	2.86	2.16	2.38	2.23	1.81

The results of the precision statistical indicators, RMSE and R2, are given in **Table 3** for the ten sites and for the three methods used. By comparing the three methods used with the values measured, this shows that the standard deviation method gives the best estimate of the distribution measured for all sites followed by the maximum likelihood method. The RMSE values of the standard deviation method for all sites are closest to zero (0) and the R2 values for this method are closest to one (1) for all sites. As a result, the latter will be used to estimate the power and energy density for all sites. It should also be noted that the maximum likelihood method gives better results than the energy pattern factor method.Bobo-Dioulasso is the site with the highest annual shape parameter estimated at 3.77 while the lowest shape parameter is 1.66 recorded at the site of Dori. Therefore, wind speed is more uniform at the site of Bobo, less uniform at the site of Dori. As for the annual scale parameter, it varies between 1.19 m/s at Dori and 3.34 m/s in Bobo-Dioulasso, which shows that Bobo-Dioulasso is the windiest site on an annual scale. The monthly variation of the Weibull shape and scale parameters, which are estimated by the three methods used, is shown in **Table 4, 5, 6** for the ten sites studied. It can be observed that the shape parameter varies between 1.47 in Dédougou (June) and 5.11 in Bobo-Dioulasso (January). Thus, the wind speed is more uniform in Bobo-Dioulasso in January, whereas it is less uniform at Dédougou in June. The scale parameter varies between 0.68 $m.s^{-1}$ at Dori (October) and 3.90 m/s (May) in Bobo-Dioulasso which is the windiest site in May. **Table 7** gives the different monthly average values of power density and energy available. We note that the maximum value of the average monthly wind power density of 34.5070 W/m^2 is recorded in Bobo-Dioulasso (May), while, the minimum value of the average power density of 0.3390W/m^2 is recorded at Dori (November). **Table 8** presents the different annual average values of power density and energy available. It should be recalled that the annual minimum and maximum wind speeds are registered at Dori, 1.06m/s and in Bobo-Dioulasso, 3.02m/s, respectively. In addition, the lowest power density and energy density are recorded in Boromo at 1.7941W/m^2 and 15.73 kWh / m^2 / year, respectively. However, the highest power density and energy density are recorded in Bobo-Dioulasso, or 22.5299W/m^2 and 197.50 kWh/m^2 / year, respectively.


Observed distribution
Empirical method
Energy pattern factor method
Maximum likelihood method
C=3.34
k=3.77
Latitude 11°10'N
Longitude 04°18'W
Site of Bobo
Probability density (%)
Wind speed (m/s)


Observed distribution
Empirical method
Energy pattern factor method
Maximum likelihood method
c=2.61
k=2.45
Latitude 12°59'N
Longitude 00°08'W
Site of Bogandé
Probability density (%)
Wind speed (m/s)


Observed distribution
Empirical method
Energy pattern factor method
Maximum likelihood method
c=1.23
k=1.82
Latitude 11°45'N
Longitude 02°56'W
Site of Boromo
Probability density (%)
Wind speed (m/s)

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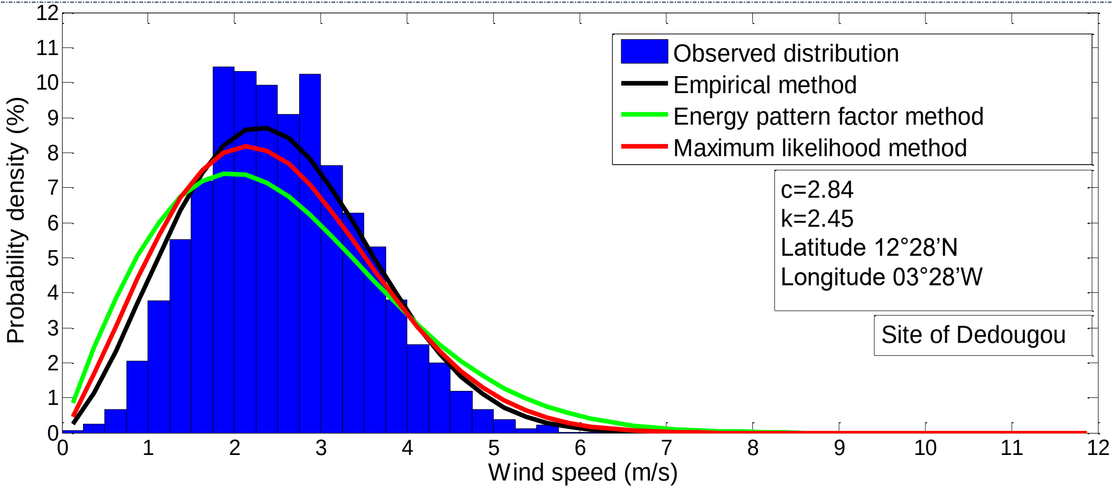

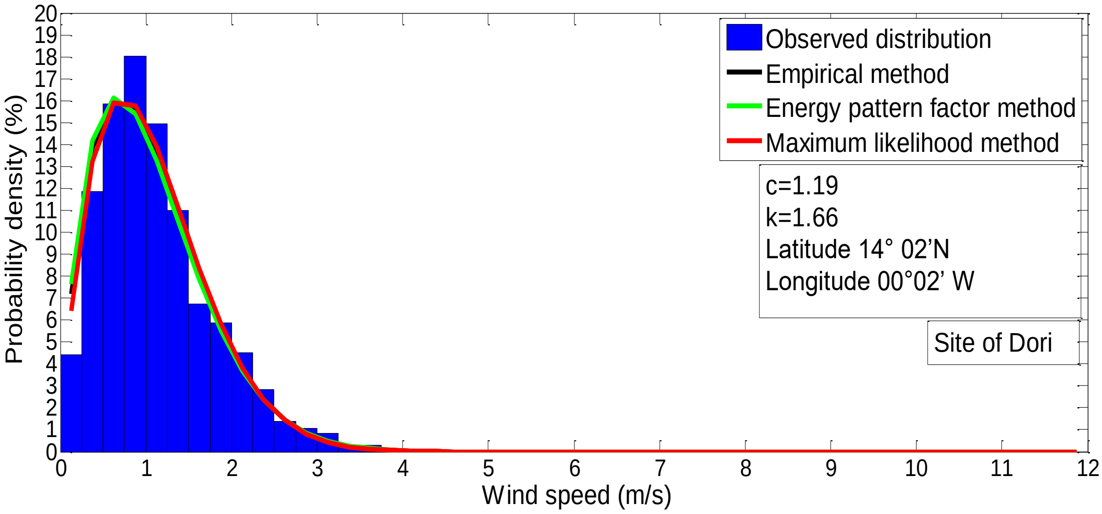

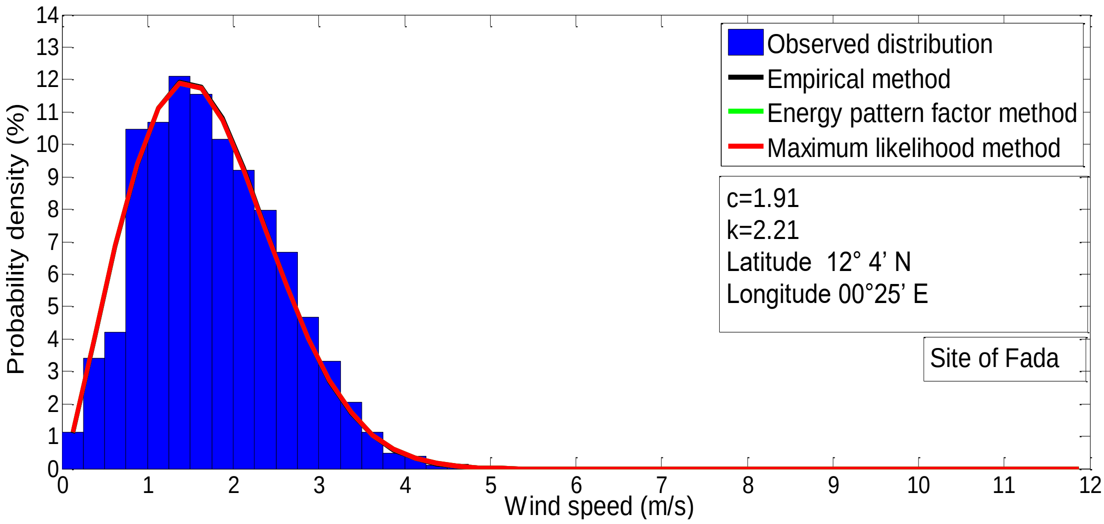

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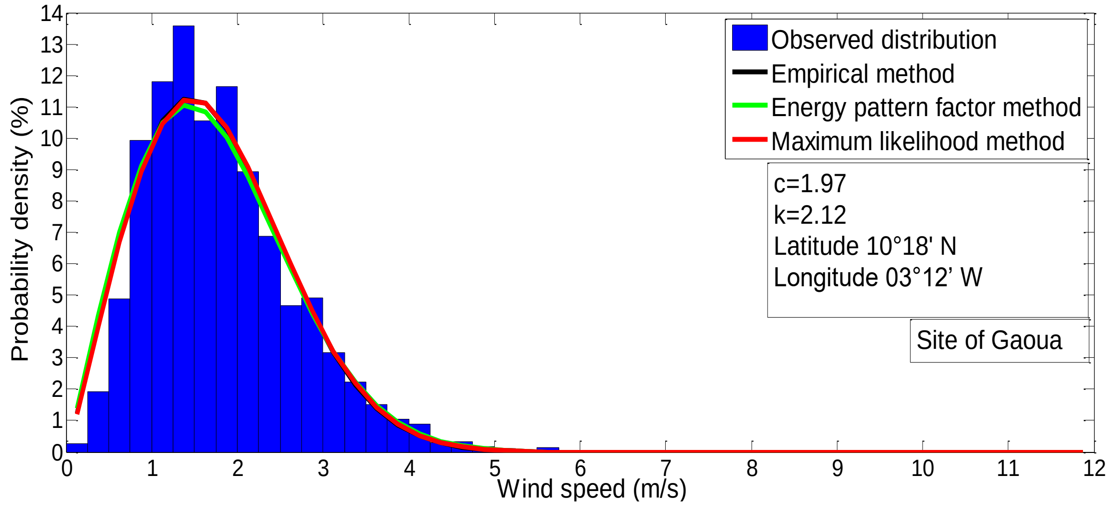

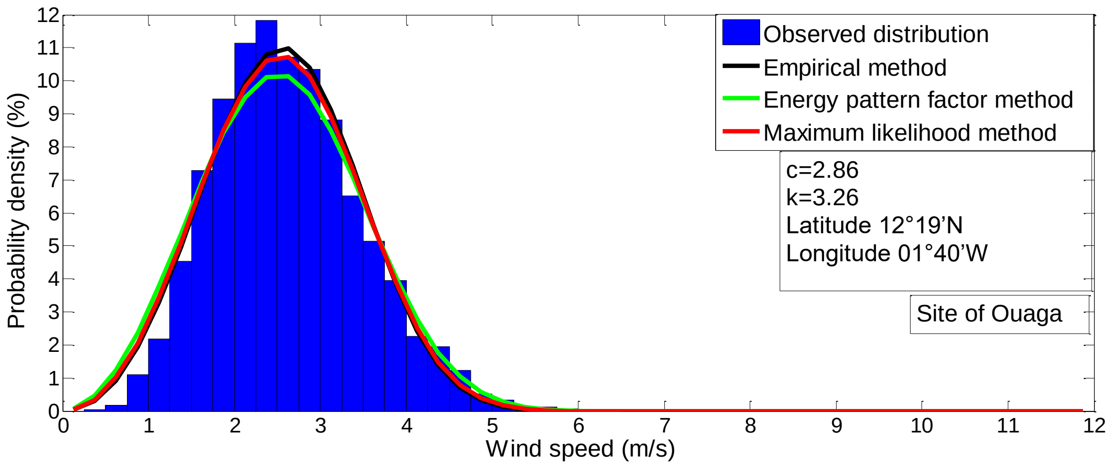

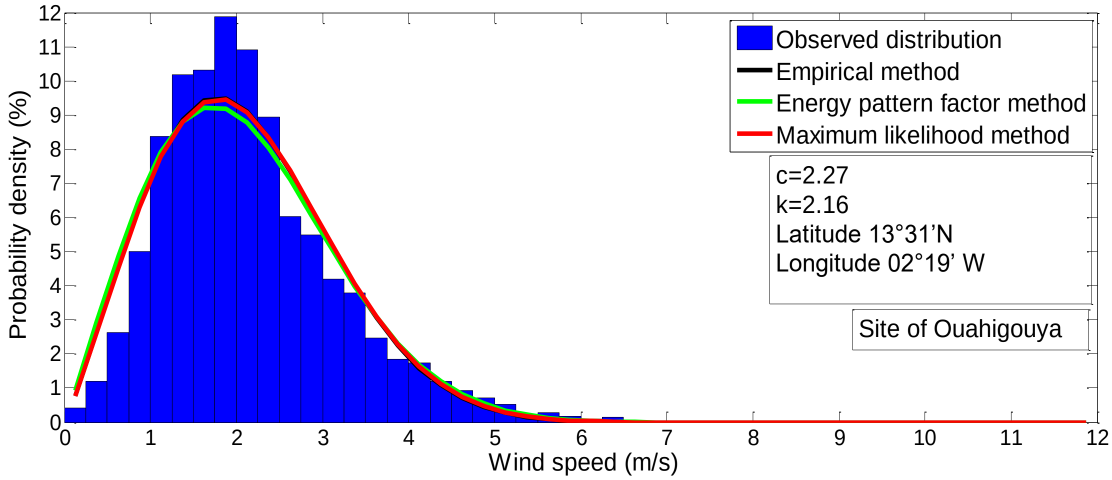

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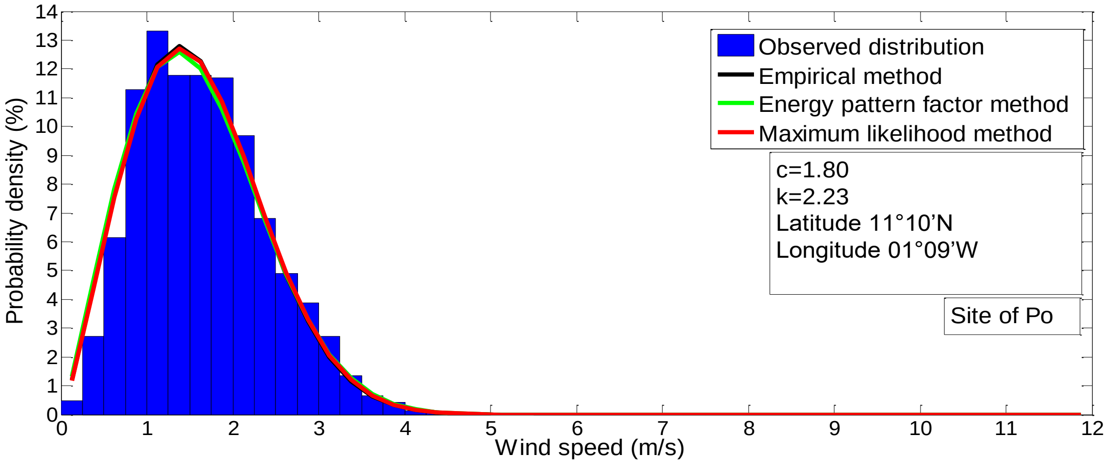

Figure 3: Comparison of distributions calculated and theoretical distributions with the three calculation methods of Weibull parameters for (10) sites.

Table 3: Comparison of methods for the ten (10) sites studied

Site		**Standard deviation method**	**Energy pattern factor method**	**Maximum likelihood method**
Bobo	RMSE	0.3151	0.5591	0.5591
	R^2	0.9917	0.9739	0.9913
Bogandé	RMSE	0.3398	0.3750	0.3750
	R^2	0.9889	0.9865	0.9884
Boromo	RMSE	0.5671	0.6005	0.6005
	R^2	0.9843	0.9824	0.9909
Dori	RMSE	0.6897	0.7655	0.7655
	R^2	0.9768	0.9714	0.9844
Dédougou	RMSE	0.7387	1.3713	1.3713
	R^2	0.9523	0.8355	0.9104
Fada	RMSE	0.4892	0.4919	0.4919
	R^2	0.9826	0.9824	0.9824
Gaoua	RMSE	0.6719	0.7255	0.7255
	R^2	0.9682	0.9629	0.9685
Ouaga	RMSE	0.4184	0.5568	0.5568
	R^2	0.9865	0.9760	0.9848
Ouahigouya	RMSE	0.7076	0.7842	0.7842
	R^2	0.9572	0.9474	0.9566
Po	RMSE	0.4786	0.5134	0.5134
	R^2	0.9853	0.9830	0.9859

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Table 4: Estimation of the monthly shape and scale parametersfor the standard deviation method of the ten sites

	Bobo		Bogandé		Boromo		Dori		Dédougou	
Months	k	c (m/s)	k	c (m/s)	k	c (m/s)	k	c (m/s)	k	c (m/s)
Standard deviation method										
January	5.11	3.75	2.98	2.87	1.93	1.33	1.94	1.11	4.08	3.07
February	3.66	3.43	2.74	3.13	1.88	1.39	1.71	1.12	3.65	3.12
March	3.60	3.31	2.94	2.96	2.31	1.41	2.02	1.23	3.92	3.11
April	4.53	3.71	3.03	2.89	2.44	1.67	1.75	1.33	3.54	3.16
May	4.90	3.90	3.60	3.35	2.79	1.76	2.31	1.73	3.89	3.43
June	4.18	3.85	2.71	3.15	2.18	1.55	2.32	1.86	1.47	3.50
July	4.36	3.38	2.73	2.65	2.09	1.22	2.09	1.52	2.91	2.75
August	4.44	3.06	2.52	2.08	1.78	0.96	1.91	1.14	2.84	2.28
September	3.71	2.51	2.69	1.78	1.53	0.71	1.78	0.98	2.72	1.96
October	4.02	2.62	2.63	1.83	1.97	0.80	1.52	0.68	3.20	2.08
November	4.12	2.60	2.66	1.93	2.27	0.80	1.73	0.69	2.88	2.25
December	4.83	3.40	2.71	2.62	2.26	1.21	1.91	0.91	3.58	2.86

	Fada		Gaoua		Ouaga		Ouahigouya		Po	
Months	k	c(m/s)	k	c(m/s)	k	c(m/s)	k	c(m/s)	k	c(m/s)
Standard deviation method										
January	2.38	2.04	2.21	1.85	3.27	3.07	2.48	2.08	2.71	2.28
February	2.33	1.98	2.19	1.92	3.16	2.92	2.56	2.45	2.58	2.17
March	2.43	1.91	2.52	2.21	3.37	2.84	2.90	2.28	2.92	2.17
April	2.86	2.38	2.70	2.93	3.68	3.05	2.34	2.58	3.58	2.32
May	3.03	2.62	2.91	2.56	4.77	3.50	2.81	3.25	3.15	2.24
June	2.71	2.40	2.75	2.46	4.33	3.50	2.98	3.51	2.63	1.96
July	2.49	1.99	2.81	2.23	3.84	2.97	2.61	2.97	2.57	1.55
August	2.16	1.57	2.71	1.91	3.91	2.55	2.19	2.17	2.43	1.31
September	2.23	1.30	2.14	1.31	3.78	2.34	2.51	1.96	2.13	1.07
October	2.57	1.42	2.46	1.38	3.62	2.32	2.32	1.73	1.81	1.23
November	2.63	1.35	2.76	1.22	3.18	2.12	2.62	1.47	2.75	1.27
December	2.42	1.87	2.96	1.62	3.87	2.83	2.72	1.92	3.11	1.95

Table 5: Estimation of the monthly shape and scale parameters using energy pattern factor method of the ten sites

	Bobo		Bogandé		Boromo		Dori		Dédougou	
Months	k	c(m/s)	k	c(m/s)	k	c (m/s)	k	c (m/s)	k	c (m/s)
Energy pattern factor method										
January	3.79	3.81	2.83	2.87	1.87	1.33	1.94	1.11	3.44	3.10
February	3.26	3.45	2.65	3.13	1.82	1.39	1.67	1.12	3.24	3.14
March	3.24	3.33	2.83	2.96	2.28	1.41	2.01	1.23	3.36	3.13
April	3.62	3.75	2.90	2.89	2.39	1.67	1.70	1.33	3.16	3.18
May	3.76	3.95	3.22	3.37	2.73	1.76	2.30	1.73	3.35	3.45
June	3.48	3.89	2.67	3.15	2.19	1.55	2.31	1.86	1.17	3.35
July	3.55	3.42	2.60	2.66	2.13	1.22	2.09	1.52	2.75	2.75
August	3.60	3.10	2.49	2.08	1.78	0.96	1.89	1.14	2.73	2.28
September	3.27	2.53	2.64	1.78	1.55	0.71	1.74	0.98	2.61	1.97
October	3.40	2.64	2.50	1.84	2.01	0.80	1.51	0.68	2.97	2.09

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November	3.47	2.61	2.60	1.93	2.30	0.80	1.74	0.69	2.78	2.26
December	3.72	3.44	2.65	2.62	2.18	1.21	1.80	0.91	3.21	2.88

	Fada		**Gaoua**		**Ouaga**		**Ouahigouya**		**Po**	
Months	k	c (m/s)	k	c (m/s)	k	c (m/s)	k	c (m/s)	k	c (m/s)
Energy density method										
January	2.41	2.04	2.14	1.85	3.00	3.09	2.46	2.08	2.64	2.29
February	2.32	1.98	2.09	1.92	2.95	2.93	2.43	2.45	2.51	2.18
March	2.38	1.91	2.44	2.22	3.05	2.85	2.74	2.28	2.71	2.18
April	2.78	2.38	2.61	2.93	3.25	3.07	2.25	2.59	3.20	2.33
May	2.89	2.63	2.80	2.57	3.69	3.56	2.70	3.25	2.99	2.24
June	2.72	2.40	2.65	2.46	3.53	3.54	2.81	3.52	2.59	1.96
July	2.46	1.99	2.69	2.23	3.31	3.00	2.52	2.97	2.53	1.55
August	2.17	1.57	2.65	1.91	3.36	2.57	2.13	2.17	2.41	1.31
September	2.27	1.30	2.09	1.31	3.30	2.35	2.46	1.96	2.14	1.07
October	2.57	1.42	2.37	1.38	3.19	2.34	2.29	1.73	1.48	1.21
November	2.60	1.35	2.66	1.22	2.93	2.13	2.55	1.47	2.65	1.27
December	2.46	1.87	2.82	1.63	3.36	2.86	2.65	1.92	2.94	1.96

Table 6: Estimation of the monthly shape and scale parameters by the maximum likelihood method of the ten sites

	Bobo		**Bogandé**		**Boromo**		**Dori**		**Dédougou**	
Months	k	c (m/s)	k	c(m/s)	k	c (m/s)	k	c (m/s)	k	c (m/s)
Maximum likelihood method										
January	4.93	3.75	2.93	2.87	1.96	1.34	2.03	1.13	3.99	3.07
February	3.97	3.66	2.69	3.13	1.88	1.39	1.76	1.14	3.61	3.12
March	4.46	3.38	2.92	2.96	2.33	1.42	2.08	1.24	3.81	3.11
April	4.44	3.71	3.04	2.89	2.43	1.67	1.77	1.34	3.43	3.17
May	4.96	3.88	3.54	3.35	2.83	1.76	2.32	1.73	3.77	3.43
June	4.18	3.78	2.73	3.16	2.22	1.56	2.34	1.87	1.67	3.57
July	4.20	3.39	2.65	2.65	2.18	1.24	2.07	1.52	2.82	2.75
August	4.42	3.06	2.57	2.10	1.86	0.98	1.92	1.14	2.81	2.28
September	3.65	2.51	2.69	1.78	1.77	0.77	1.86	1.00	2.72	1.98
October	3.87	2.62	2.60	1.84	2.12	0.83	1.68	0.72	3.13	2.08
November	4.02	2.58	2.63	1.93	2.40	0.81	1.85	0.71	2.89	2.26
December	4.79	3.39	2.71	2.62	2.27	1.21	1.98	0.93	3.53	2.86

	Fada		**Gaoua**		**Ouaga**		**Ouahigouya**		**Po**	
Months	k	c (m/s)	k	c (m/s)	k	c (m/s)	k	c (m/s)	k	c(m/s)
Maximum likelihood method										
January	2.37	2.04	2.20	1.85	3.19	3.08	2.52	2.09	2.72	2.29
February	2.34	1.98	2.18	1.92	3.13	2.93	2.50	2.45	2.56	2.18
March	2.42	1.92	2.50	2.22	3.22	2.84	2.79	2.28	2.77	2.17
April	2.86	2.38	2.66	2.93	3.61	3.05	2.32	2.59	3.48	2.32
May	3.03	2.62	2.90	2.56	4.52	3.50	2.79	3.25	3.19	2.24
June	2.78	2.40	2.71	2.46	4.12	3.50	2.92	3.52	2.65	1.97
July	2.48	1.99	2.77	2.23	3.68	2.98	2.58	2.97	2.55	1.55
August	2.16	1.57	2.71	1.91	3.79	2.55	2.19	2.18	2.48	1.32
September	2.22	1.31	2.14	1.31	3.62	2.34	2.51	1.97	2.14	1.08

October	2.62	1.43	2.46	1.39	3.42	2.32	2.35	1.74	1.86	1.23
November	2.63	1.35	2.75	1.22	3.07	2.12	2.62	1.47	2.74	1.27
December	2.46	1.88	2.95	1.63	3.84	2.83	2.76	1.93	3.13	1.96

Table 7: Power density (W/m²) and energy density (kWh/m²/year) estimated for the ten sites

Months	Bobo		Bogandé		Boromo		Dori		Dédougou	
	Pd	Ed	Pd	Ed	Pd	Ed	Pd	Ed	Pd	Ed
January	30.5838	22.020	15.4098	11.095	2.1136	1.5218	1.2216	0.8795	17.2238	12.401
February	24.5709	17.691	20.8068	14.981	2.4877	1.7911	1.4740	1.0613	18.5053	13.324
March	22.1732	15.965	17.0057	12.244	2.1242	1.5294	1.5913	1.1457	18.0395	12.988
April	29.9402	21.557	15.6244	11.250	3.3904	2.4411	2.3893	1.7203	19.3791	13.953
May	34.5070	24.845	22.9868	16.550	3.6648	2.6387	3.9235	2.8249	24.2379	17.451
June	33.8333	24.360	21.3335	15.360	2.9607	2.1317	4.8599	3.4991	57.8958	41.685
July	22.7509	16.381	12.6518	09.109	1.5009	1.0807	2.9027	2.0900	13.7001	09.864
August	16.8410	12.126	6.4116	04.616	0.8781	0.6322	1.3470	0.9699	7.8977	05.686
September	9.5972	06.910	3.8650	02.783	0.4489	0.3232	0.9341	0.6726	5.1290	03.693
October	10.7340	07.729	4.2539	03.063	0.4496	0.3237	0.3990	0.2873	5.7040	04.107
November	10.4450	07.520	4.9577	03.570	0.3934	0.2832	0.3390	0.2441	7.5397	05.429
December	22.8924	16.483	12.2754	08.838	1.3661	0.9836	0.6851	0.4933	14.3242	10.313

Months	Fada		Gaoua		Ouaga		Ouahigouya		Po	
	Pd	Ed	Pd	Ed	Pd	Ed	Pd	Ed	Pd	Ed
January	6.2901	4.5289	4.9745	03.582	18.2029	13.106	6.4790	04.665	8.0898	5.8246
February	5.8432	4.2071	5.6047	04.035	15.8536	11.415	10.3745	07.470	7.1742	5.1654
March	5.0867	3.6624	7.6905	05.537	14.2704	10.275	7.8201	05.631	6.7209	4.8390
April	8.9529	6.4461	17.2031	12.386	17.2529	12.422	12.8854	09.277	7.6460	5.5052
May	11.6416	8.3820	11.0521	07.958	25.0010	18.001	22.9938	16.556	7.1653	5.1590
June	9.4355	6.7936	10.0820	07.259	25.2854	18.205	28.1886	20.296	5.2264	3.7630
July	5.6587	4.0743	7.4280	05.348	15.7778	11.360	18.2664	13.152	2.6207	1.8869
August	3.1021	2.2335	4.7559	03.424	9.9491	07.163	8.0915	05.826	1.6412	1.1816
September	1.7130	1.2333	1.8173	0.1308	7.7430	05.575	5.3785	03.872	0.9946	0.7161
October	2.0151	1.4508	1.9025	01.370	7.6242	05.489	3.9104	02.816	1.8069	1.3009
November	1.7078	1.2296	1.2274	00.884	6.0532	04.358	2.2098	01.591	1.3872	0.9988
December	4.7876	3.4470	2.7795	02.001	13.6279	09.812	4.8214	03.471	4.7501	3.4200

Table 8: Annual density and energy power for the ten study sites

Site	Annual average wind speed (m/s)	Annual power density (W/m²)	Energy density (kWh/m²/an)
Bobo	3.02	22.5299	197.50
Bogandé	2.31	12.9063	113.14
Boromo	1.09	1.7941	15.73
Dori	1.06	1.8476	16.20
Dédougou	2.52	16.6278	145.76
Fada	1.69	5.4744	47.99
Gaoua	1.75	6.2345	54.65
Ouaga	2.56	14.7324	129.14
Ouahigouya	2.10	10.6709	93.54
Po	1.60	4.5471	39.86

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5. CONCLUSION

In summary, no detailed study of this type has yet been conducted in this region to our knowledge. The assessment of wind potential is an important issue worldwide in terms of renewable energy. This detailed study can make major contributions to solve this issue. In this study, the monthly and annual distributions as well as the power and energy density were assessed during 2006-2016 on ten sites located in Burkina Faso. The analysis performed was based on Weibull distribution function with two-parameters. From the available statistical data and calculations made, the following conclusions can be drawn:

- The standard deviation method gives the best estimate of the distribution measured for all sites. However, the maximum likelihood method gives performances close to that of the standard deviation.
- The average monthly wind speed at a maximum value of $3.57 m.s^{-1}$ is recorded in Bobo-Dioulasso (February) while a minimum of 0.61m/s is registered at Dori (November). The average annual minimum and maximum wind speeds are obtained at Dori, $1.06 m.s^{-1}$ and Bobo-Dioulasso, $3.02 m.s^{-1}$, respectively.
- The average annual value of the scale parameter varies from 1.19m/s (Dori) to 3.34m/s (Bobo-Dioulasso) while the average annual value of the shape parameter varies from 1.66 (Dori) to 3.77 (Bobo-Dioulasso).
- Power density estimate for all sites shows that the highest power density values are recorded during the first months of the year (January to August) with a maximum in May and June. This corroborates the results obtained from Weibull parameter estimates.
- The sites of Bobo-Dioulasso, Ouagadougou and Dédougou are the best sites for Burkina Faso to exploit wind energy using small wind turbines to produce electricity.

However, according to the Pacific Northwest Laboratory (PNL) classification, which is widely used to list sites studied according to their wind potential, power density values on all these sites are considered as low; it is therefore necessary to conduct a survey at higher altitudes to determine the hub heights that are of significant energy interest by extrapolation. Moreover, the study recommends an analysis of wind speed data at no reduced time for a better understanding of the energy potential and the design or selection of wind turbines adapted to the sites studied. Nevertheless, the results obtained make it possible to come up with excellent recommendations for projects that wish to establish small wind turbines in Burkina.

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