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Evaluation of the Wind Energy Potential of a Mountainous Region in the Ceará State, Brazil

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ABSTRACT

The aim of this work is to evaluate the wind energy potential of two sites in the Ibiapaba Mountain situated in the Ceará State, Brazil. Techniques and parameters used for the assessment of wind energy in those sites are described and statistical analysis of wind speed and direction is performed in data collected of two meteorological stations. It was observed that the Ibiapaba Mountain presents significant wind energy potential and adequate to satisfy the demand for electricity at the region and consequently may be suitable to complement the energy matrix of the Ceará State.

1. Introduction

The demand for electric energy in Brazil and in the world will practically double by the year 2030 (IEA, 2004). Most of this demand will be met by fossil fuels intensifying the greenhouse effect. Presently about 75% of the produced electric energy in Brazil comes from hydropower plants (ANEEL, 2009). Even being a renewable and sustainable source of energy at least in terms of emission of greenhouse gases, the implementation of commercial hydropower plants requires considerable volume of water and height of the dam. This

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potentially causes the inundation of large extension of land and the retention of sediments. The construction of new hydropower plants in the near term will not satisfy the growing Brazilian demand at the year 2008 was roughly 100 GW. Therefore it is necessary that Brazil diversify its ways of electric energy production considering the natural characteristics of each region, preferentially making use of electric energy sources that produce the minimum impact on nature and population, and at the same time being economically competitive with traditional forms of energy production. The Brazilian Government took one step in this direction in 2002, through the creation of the Program of Incentives for Alternative Electricity Sources (PROINFA). This program had as objective the increase of the participation of renewable energy sources for the production of electricity aiming to increase up to 10% of the total demand until the year 2022. Among the renewable sources, wind energy looks as the most prominent, mainly due to its already commercial use as for example in Europe (Burton *et. al.*, 2001) and other parts of the World.

As highlighted in the Brazilian Wind Atlas (Amarante *et. al.*, 2001) and in the Wind Energy Resource Map launched by the Ceará State Infrastructure Secretary, the state of Ceará plays an important role in the future of the national energy policy, since it has one of the greatest wind energy potential in Brazil, comprehending 25 GW onshore and 10 GW offshore. The Geographic Information System based software WindMap™ (Brower & Co, EUA) has been used for the elaboration of the Brazilian Wind Atlas. It requires the insertion of locally measured wind data, and through interpolations and the solution of a set of partial differential equations such as continuity, momentum, energy and others, it constructs maps with graphical indication of wind intensity and direction in the region of interest. However in the elaboration of both the Brazilian Wind Atlas and the Ceará Wind Energy Resource Atlas not enough measured data were used for mountainous regions, in particular in the Ibiapaba Mountain region situated in the northwest of the Ceará State, as indicated in the Figure 1. Such lack of data may cause errors at the estimation of the wind speed. Excluding some particular sites in the coastal region of the state, meteorological stations are relatively spread and it may result in significant error in the parameters estimated for regions far from such stations.

On the other hand, it is known that mountainous regions may intensify the wind speed (Turnipseed *et. al.*, 2004) as a result of the circulation due the coupling of the valley-mountain system with other meteorological systems, with consequent tunneling effect that arise when valleys are lined with the wind flow direction. It is also known that the topography may produce areas with low wind intensity, for example when valleys are circled by mountains, or the leeward effect of hills or sites where the wind creates stagnation points. The literature has been pointing the potential of such regions as viable for wind energy project (Turnipseed *et. al.*, 2004; Palma *et. al.*, 2008).

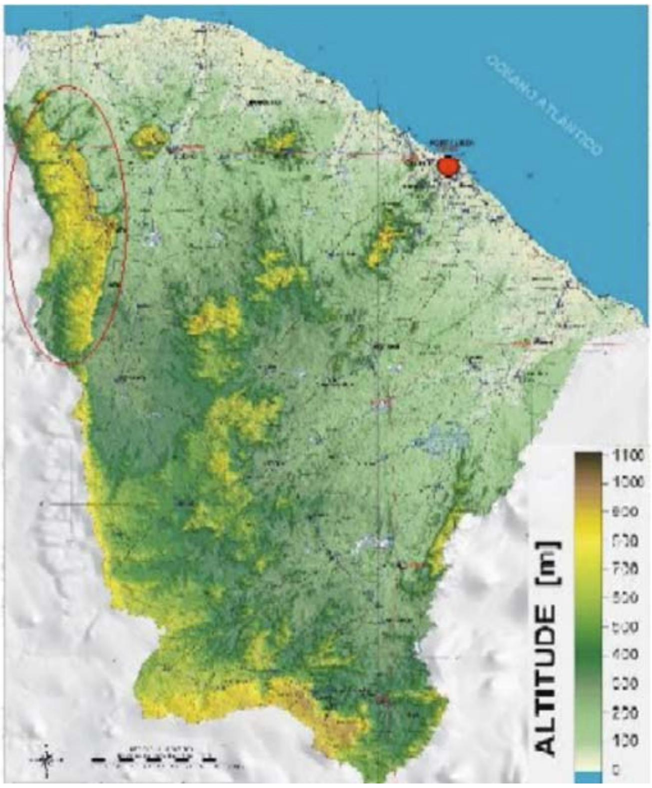

Figure 1: Ceará State topography map, indicating the Ibiapaba Mountain region situated in the northwest region. Source: Ceará State Infrastructure Secretary.

It is, therefore, interesting to make more detailed studies on the wind power potential of mountainous regions aiming to increase the accuracy of existing wind atlas. In this paper an evaluation of the wind energy potential in the Ibiapaba Mountain is made through an analysis of the data recorded by two meteorological stations installed in this region by the Meteorology and Water Resource Agency of the Ceará State (FUNCEME).

2. Wind energy potential characterization

In order to characterize the wind energy potential of a region it is necessary to know the

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structure and conditions of the wind. It is also important to know the physical parameters used to characterize the wind resources as well its classes. The most remarkable characteristic is the variability. The wind is highly variable in space and time. In the large scale, this spatial variability results from the fact that there are different climatic regions in the World as consequence of the irregular incident solar radiation on the globe depending on the geographical situation. The variation inside a certain climatic region is caused by aspects such as the relative portion of land and water and the presence of flat or mountainous regions. In this scale, vegetation has a significant influence as a medium for absorption and reflection of solar radiation, which affects surface temperature and humidity. As the scale decreases, the topography becomes more and more important. The fact is that on the top of the hills and mountains the wind speed is greater than in the leeward side or in the protected valleys. Depending on the topography relative to the incident wind, air can be constricted causing an increase on its speed. In even smaller scales, obstacles such as trees and buildings reduce significantly the wind speed.

The wind temporal variability scale decreases with the decrease in the considered space scale. In a certain large-scale domain, for example, the wind intensity temporal variability can vary from one year to even decades or more. Although studies (Meneses Neto et. al., 2006) show that the annual variation is caused in part by the El Niño and La Niña phenomena, the long term variations are not yet well understood and may turn difficult to achieve the exactness in the analysis of the feasibility of a wind power project in a particular region.

In time scales smaller than one year there are seasonable variations, which are very much foreseeable. However there are still large variations in a relatively short time scale. These variations can be caused by the passage of climatic systems, or due to the diurnal surface heating and cooling cycles. In the time scale of months, days and hours the forecasting of the wind speed is very important for the management of wind energy systems connected to the electric grid, allowing the electric energy concessionary and the National Operator of Electric System (ONS in Brazil) the decision to use an alternative form of energy to supply the grid. Variations of wind speed in the time scale smaller than a minute or a second are usually originated from turbulence and may be even more significant for the design of a wind turbine and for the quality of the electric energy delivered to the power grid.

2.1 Parameters used for wind energy potential characterization

Wind energy is the energy associated with the movement of a certain quantity of air. Part of this energy is captured by a wind turbine, which basically consists of a rotor with two or three blades coupled to an electric generator. The energy dE associated with the movement of a certain air mass dm is given by

$$dE = \frac{1}{2} dm \cdot v^2 , \tag{1}$$

Where v is the wind speed. Considering a turbine with axis parallel to the wind direction, and its blades sweeping a surface area A, one can see that $dm = \rho A v dt$, where ρ is the air specific mass. Substituting in Equation (1) and taking the derivative with respect to time one obtain the wind speed dependence for the power available to the generator

$$P = \frac{dE}{dt} = \frac{1}{2} \rho A v^3 . \tag{2}$$

The power can also be expressed in terms of the power density D_P, defined as the available power divided by the swept area,

$$D_P = \frac{P}{A} = \frac{1}{2} \rho v^3 . \tag{3}$$

The average wind speed is then used to evaluate the average power density. Together these two parameters constitute the main parameters used in the evaluation wind energy potential in a region. The specific annual electric energy production is estimated and this data are usually represented using contour curves superposed to the region map (Patel, 1999).

The local wind speed distribution can be used to estimate the average wind velocity over a region in a certain period of time. Usually expressed in terms of the occurrence percentage, the wind velocity data are usually fitted using an empirical probability density function (Burton *et. al.*, 2001; Patel, 1999). The two-parameter Weibull distribution has been widely used to model wind speed distributions (Escalante-Sandoval, 2008; Ettoumi et. al., 2003; Garcia-Bustamante et. al., 2008; Genc et. al., 2005; Justus et. al., 1976, Justus et. al., 1978; Tuller and Brett, 1984; Ucar and Balo, 2009; Vallee et. al., 2008). The Weibull probability density function gives the probability to find wind speeds between v and $v + dv$ as

$$f\left(v\right)dv = \frac{k}{c}\left(\frac{v}{c}\right)^{k-1} \exp\left[-\left(\frac{v}{c}\right)^{k}\right]dv, \tag{4}$$

Where k and c are the shape and scale factors, respectively. The corresponding cumulative probability function is given by

$$F\left(v\right) = \int_0^v f\left(v'\right)dv' = 1 - \exp\left[-\left(\frac{v}{c}\right)^{k}\right]. \tag{5}$$

The average wind speed can be evaluated by

$$\overline{v} = \int_0^\infty v f(v) dv. \tag{6}$$

Using Equation (4) in (6), one can relate the average wind speed to the Weibull scale and form parameters by

$$\overline{v} = c\Gamma\left(1 + \frac{1}{k}\right), \tag{7}$$

Where Γ is the Gamma function. The standard deviation can be expressed in terms of theses parameters as

$$\sigma^2 = c^2\left[\Gamma\left(1 + \frac{2}{k}\right) - \Gamma\left(1 + \frac{1}{k}\right)^2\right] \tag{8}$$

The wind data are typically measured over a one-year period and recorded as hourly averaged speed, which lead to a set of discrete values. The probability density function is obtained by fitting the data using a histogram. The measured data are divided into N intervals, or wind classes, centered on the speed values v_i. Let the frequencies of data on each interval be f_i, and the cumulative frequencies F_i. Then, by plotting the data with the transformations

$$x_i = \ln v_i,$$

$$y_i = \ln\left[-\ln\left(1 - F_i\right)\right], \tag{9}$$

One can determine the Weibull parameters by fitting with Equation (5) which transforms to a linear form $y = a + bx$ with $k = b$ and $c = \exp(-a/b)$.

It is equally necessary to the evaluation of a wind energy project to know the wind direction and its variability. The importance of this knowledge relies on the fact that the wind turbines present optimal performance when they receive frontal winds. Modern turbines incorporate a system that rotates the structure of its hub in order to face frontally incident wind. The lower the variability of the wind direction, the greater will be the turbine performance. The preferential wind direction is also fundamental for the installation of a wind farm, since it will be used to minimize problems such as shadow or wakes from one turbine to another.

All statistical treatment given to the wind speed can be also given to its direction. However, it is common practice to represent the frequency or probability of the wind direction in a polar (circular) graph of 360°. On this graph 0° represents the North, 90° the East and so on. In general such graph is called Wind Rose.

3. Vertical profile of wind speed and the surface boundary layer

The wind near the terrestrial surface is subjected to shear stresses that attenuate its speed. Lower atmospheric layers in direct contact with the soil will experience reduction in its acceleration. As consequence the speed of higher layers will be attenuated resulting in a vertical speed profile.

The farther an air layer is from the surface, the smaller it will be the effect of the shear stress. At the height of approximately 3 000 m, the terrestrial atmosphere is not affected by the shear stresses at the surface. The atmospheric layer in this height is called Planetary Boundary Layer (PBL). Inside the PBL there is a sub layer, which characterizes the region of interest to the evaluation of wind energy potential, which extends from the soil to the height of approximately 100 m.

The region above the PBL is the free Atmosphere. Inside it, air flows without the direct influence from the terrestrial surface characterizing the geostrophic wind. However, in the Surface Boundary Layer (SBL) the wind intensity is highly influenced by the terrestrial surface and its variations with the altitude may be obtained by following the logarithmic equation

$$\bar{v}(z) = \frac{v_*}{\kappa} \ln\left(\frac{z}{z_0}\right), \tag{10}$$

Where $\bar{v}(z)$ is the average wind speed at the altitude z, v_* is the friction velocity, κ is the von Karman constant and z_0 is the rugosity length.

Due to the difficulty in determining the friction velocity, since it depends on different factors such as soil rugosity, the wind speed and the atmospheric stability, Equation (10) is commonly used to find the wind speed in a certain height based on the knowledge of the average wind speed $\bar{v}_R$ in a reference altitude z_R

$$\bar{v}(z) = \bar{v}_R \frac{\ln z - \ln z_0}{\ln z_R - \ln z_0}. \tag{11}$$

4. Classification of Wind Energy Potential

In order to classify the wind resources of a region normally it is used the available annual average density of probability or the wind speed divided in categories called wind classes on which are attributed colors for subsequent elaboration of contour graphs.

There is no standard related to wind classes. However, the classification of the National Renewable Energy Laboratory (NREL), USA, is used in many researches. The NREL classification is shown in Table 1.

Table 1: Wind classes as function of average power density and wind speed measured at the heights of 10 m and 50 m above the soil surface. Source: NREL.

Wind Class	D_{PM} at 10 m (W/m^2)	$\bar{v}$ at 10 m (m/s)	D_{PM} at 50 m (W/m^2)	$\bar{v}$ at 50 m (m/s)	Description
1	0 - 100	0.0 - 4.4	0 - 200	0.0 - 5.6	Poor
2	100 - 150	4.4 - 5.1	200 - 300	5.6 - 6.4	Marginal
3	150 - 200	5.1 - 5.6	300 - 400	6.4 - 4.0	Satisfactory
4	200 - 250	5.6 - 6.0	400 - 500	7.0 - 7.5	Good
5	250 - 300	6.0 - 6.4	500 - 600	7.5 - 8.0	Excellent
6	300 - 400	6.4 - 7.0	600 - 800	8.0 - 8.8	Prominent
7	400 - 1000	7.0 - 9.4	800 - 2000	8.8 - 11.9	Splendid

The power density is proportional to the third momentum of a distribution of wind speed and the air density. Therefore, there is not a unique relationship between the power density and the average wind speed, which comprehends the first momentum of the distribution. Using the distribution of Weibull for the wind speed and a standard specific mass for the air at the sea level (1.22 kg/m^3) the average wind speed can be determined for each limit of classes of wind power. The decrease of the air specific mass with the altitude requires that the mean speed must be increased by 3% for each 1000 m of elevation for maintaining the same power density.

5. Methodology for the Evaluation of the Wind Energy Potential

The simplest way of evaluating the wind power potential of a region consists of effectuating measurements in the region of interest through a net of anemometers and sensors of wind direction. These measurements must be taken during a period of 3 to 5 years, to avoid the risk of considering one year particularly calm or windy. After that, the recorded data must be interpolated and extrapolated in time and space in order to have a general picture of the wind resources of the considered region.

6. Meteorological Data

For the present study the data recorded in two FUNCEME meteorological stations situated in the Ibiapaba Mountain in the Ceará state was used. One of the sites situates in the São Benedito district and the other in the Ubajara district.

The meteorological stations are data collecting platforms from Campbell Scientific, model MO-034a, with a starting threshold of 0.4 m/s and an accuracy of ±0.11 m/s for measurements below 10.1 m/s. FUNCEME was responsible for their initial certification as it is for the periodic maintenance.

Data recorded in the meteorological stations consist of hourly averaged measurement performed in 10 min time intervals. The measurements are made at 10 m height from the ground level. Validation tests are made at FUNCEME for verification of data errors and inconsistencies.

For the present study one considered wind speed and direction measurements taken from the year 2004 to the year 2006, more than two years of total measurements. There are no other meteorological stations in region of the Ibiapaba Mountain. In Table 2 it is shown the geographical coordinates of the two stations used in this study.

Table 2: Geographical coordinates of meteorological stations. Source: FUNCEME.

District	Longitude	Latitude	Altitude (m)
São Benedito	W 040° 54' 39.5"	S 04° 01' 28.6"	901
Ubajara	W 041° 07' 02.9"	S 03° 51' 44.9"	847

7. Wind Power Potential

The monthly averaged wind speed for each station is plotted in Figure 2. It shows that during the first semester the average wind speeds are lower. This period correspond to the rainy season in the region. In the second semester the average winds are higher, which in its turn coincides with the drought period in the region. The same correlation between wind speed and rain seasons is found in other localities in the Ceará State (Camelo, 2007).

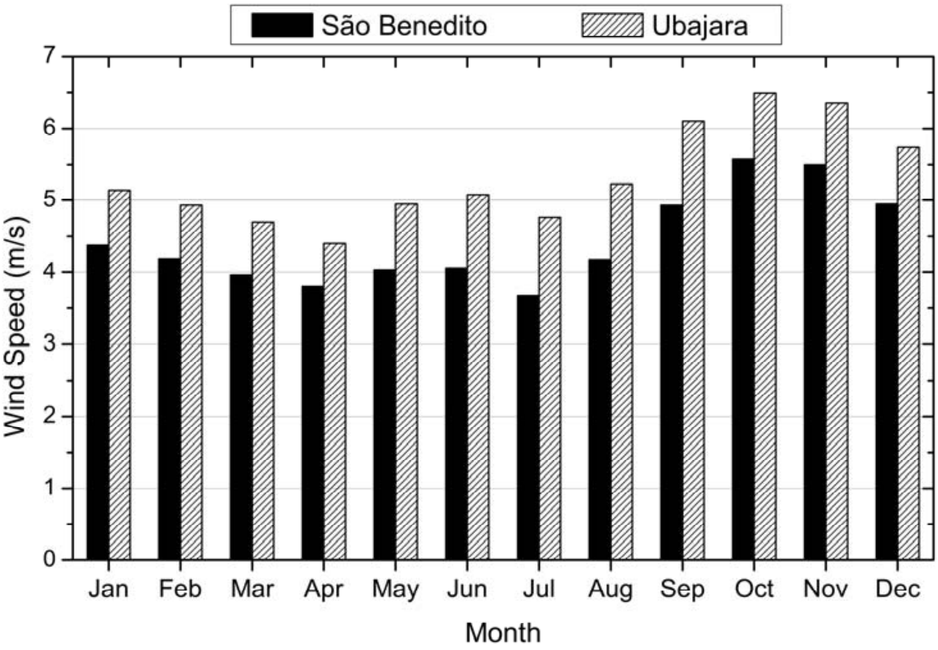
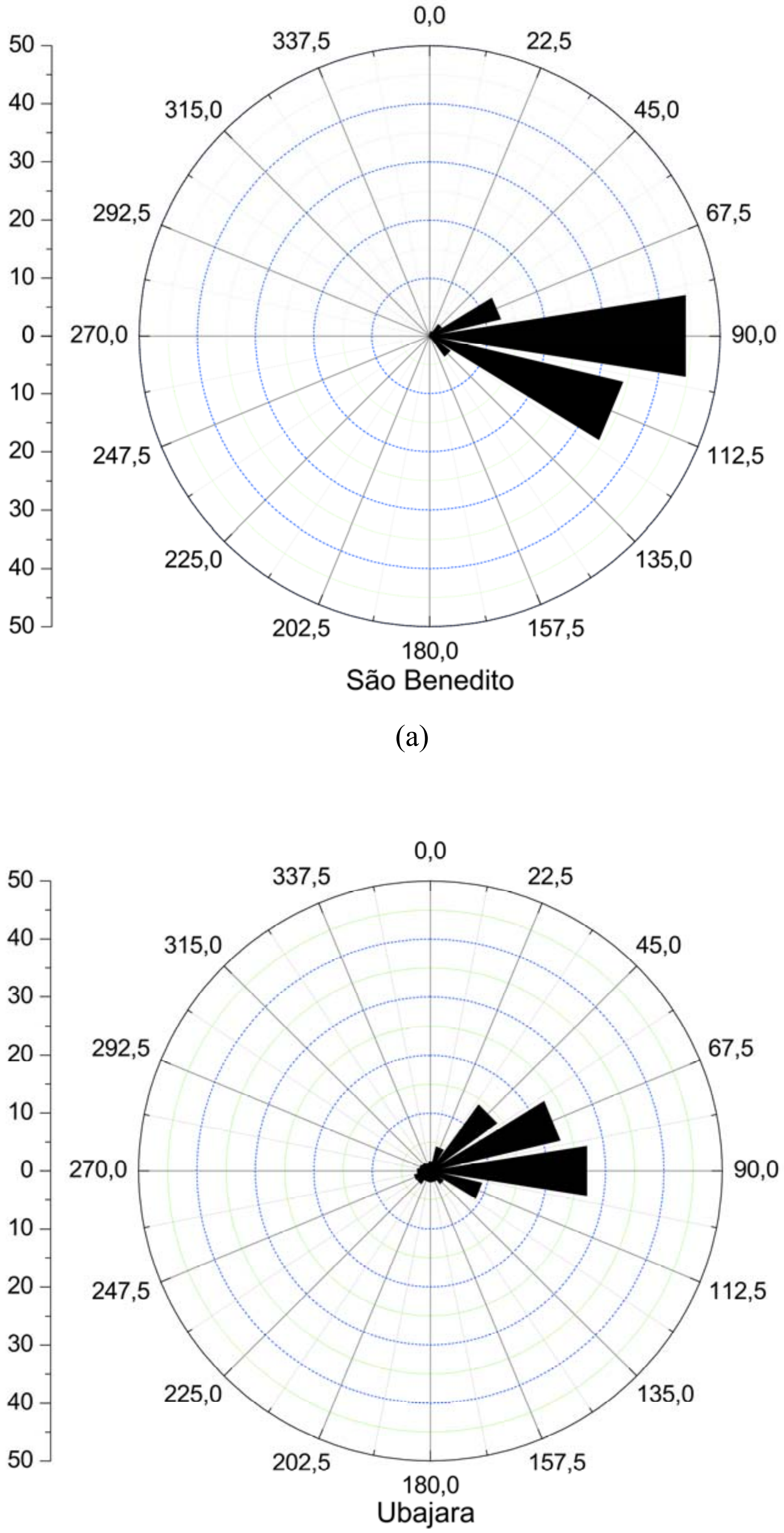


Figure 2: Monthly average wind speed at the height of 10 m.

Polar graphs of the wind direction frequency distribution for the same region are shown in Figure 3. Graphs are divided 16 parts in order to include cardinal points, collateral and sub collateral points in the wind rose. Sector 0° corresponds to the North and sector 90° corresponds to the East.

Analysis of Figure 3 shows clearly that the main prevailing wind in the Ibiapaba mountain region is easterly, with low variability in the wind direction. In São Benedito practically 50% of the wind direction data is east, 32% of the wind direction is east-southeast. In the Ubajara district about 30% is east, with a little more variability to the north. This low variability in the wind direction is a good indication as discussed in Section 2.1.

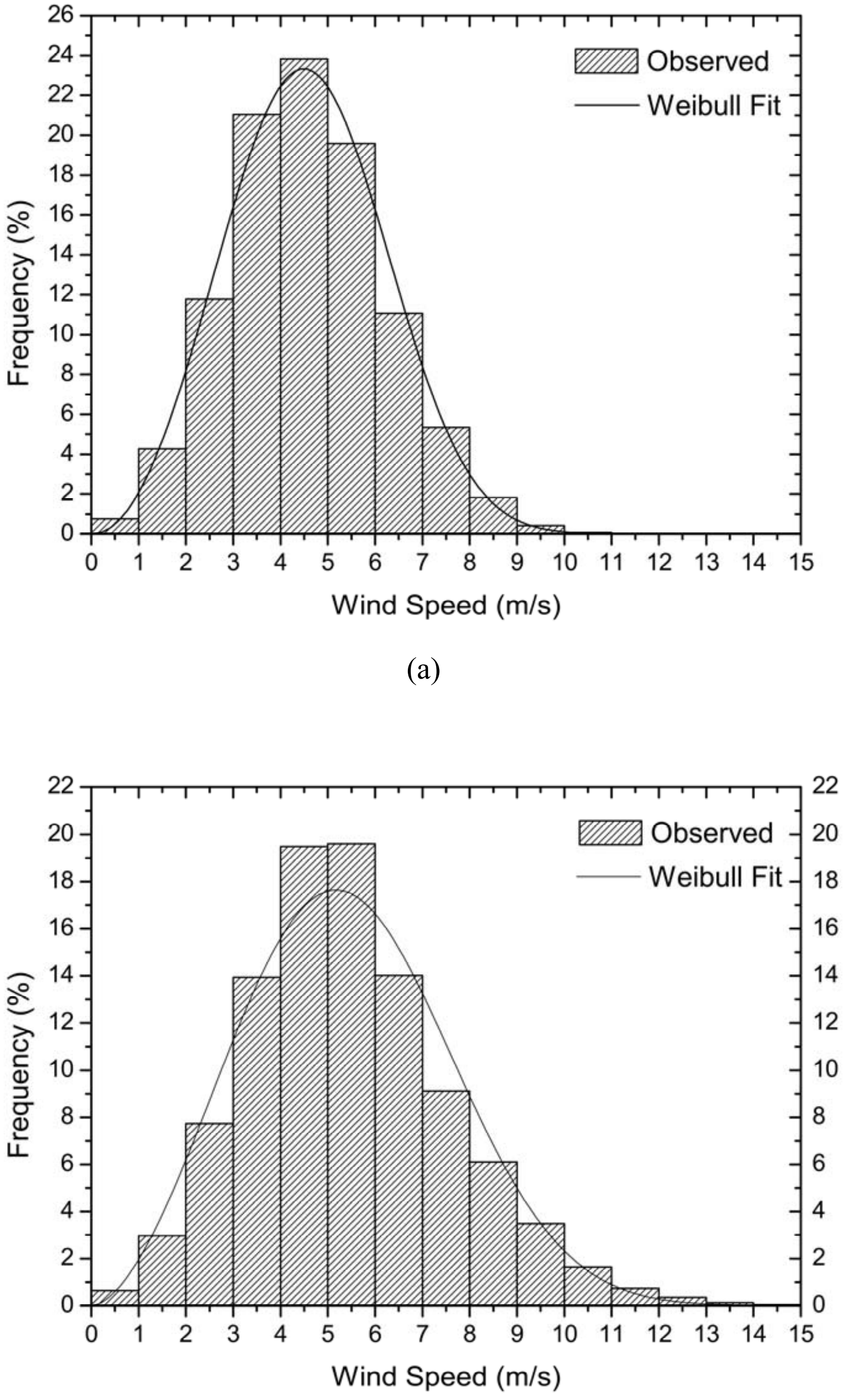
The histograms of the wind speed for the considered period are depicted in Figure 4. There is also a curve fitting made by the use of a probability density function. As stressed in Section 2.1, the best function for the evaluation of wind energy potential is the Weibull function, Equation (4), being characterized by two parameters: the shape factor *k* and the scale factor *c*.



(a)

(b)

Figure 3: Frequency distribution (%) of wind direction for (a) São Benedito and (b) Ubajara at 10 m height.



(a)

(b)

Figure 4: Frequency distribution (%) of wind speed for (a) São Benedito and (b) Ubajara, at 10 m height.

The shape parameter *k* has inverse relationship with the standard deviation of the distribution. High values of *k* indicate low variability of wind related to its average intensity. The value for São Benedito is $k = 2.94$ and for Ubajara is $k = 2.67$. Considering two years as the period of time, one sees that in São Benedito the distribution is thinner and the wind speed less variable. Taking into account that wind in the Ceará state is seasonable, as seen in Figure 2, Figure 5 shows the annual variation of the parameter *k* permitting to observe the difference between the rainy and drought periods.

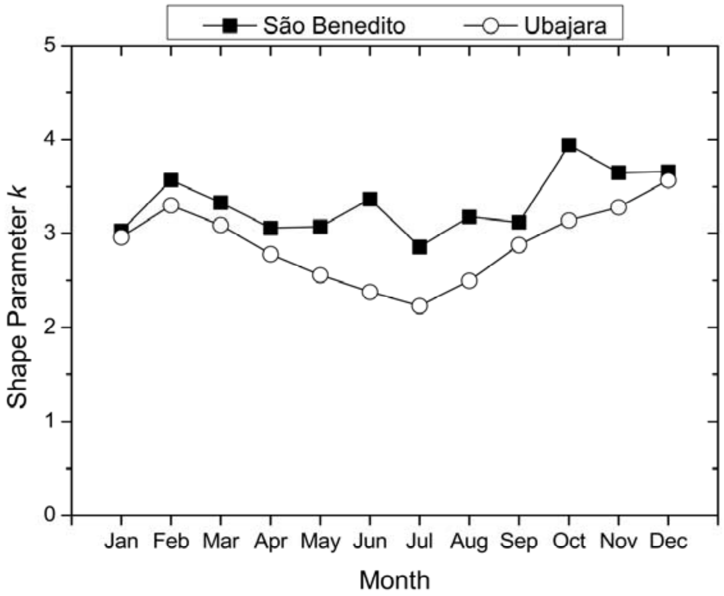


Figure 5: Monthly variation of parameter *k* of the Weibull distribution.

The scale factor in São Benedito is $c = 5.00$ m/s, while in Ubajara is $c = 6.12$ m/s. Since the scale factor directly relates with the average wind speed, it may be concluded by these results that in Ubajara the average wind speed is higher than in São Benedito. Figure 6 shows the annual variation of the parameter *c* showing again the difference between the two periods. Calculating the average speeds through the timely series from both stations one finds 4.46 m/s for São Benedito and 5.44 m/s for Ubajara, as can be observed in Figures 4(a) and 4(b).

Subsequently the average power density was calculated using Equation (3) and the wind classification is presented in Table 3. For São Benedito, the wind class was found to be 1, and for Ubajara the wind class was 2. Although they are winds of lower classes, they are appropriate to attend the local necessity for electric energy, as it will be shown hereafter.

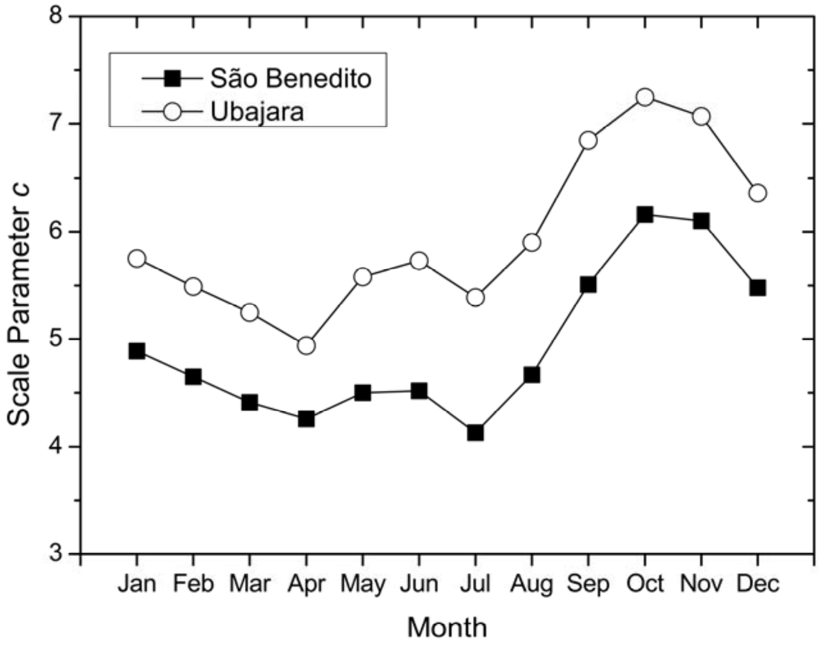


Figure 6: Monthly variation of parameter *c* of the Weibull distribution.

Table 3: Classification of wind energy potential of two sites of the Ibiapaba Mountain.

District	D_{PM} at 10 m (W/m^2)	Wind Class	Description
São Benedito	69.3	1	Poor
Ubajara	134.1	2	Marginal

In order to estimate the annual production of electric energy in those sites a commercial wind turbine, with the nominal power of 2 MW will be considered.

For the calculation of the produced electric energy in one determined year the following expression is used

$$E_{\text{eletric}} = \sum_{i=1}^{n} f_i \, P_i \; t\,, \tag{12}$$

Where f_i is the wind speed frequency relative to the class *i*, P_i is the equivalent power obtained by the power curve of the turbine and t is the time interval between measurements, in this case 1 hour. It is interesting to note that the value of the power calculated by speed class includes the power coefficient as well its mechanical efficiency, aerodynamics and others specific factors. It is also used an equation in order to make the fitting of the power curve of the turbine in order to consider the difference between the air specific mass of the site and the air specific mass where the power curve is applied as follow

$$v_{\text{effective}} = v\left(\frac{\rho}{\rho_{cp}}\right)^{1/3}, \tag{13}$$

Where v is the speed indicated in the power curve and calculated for the air specific mass ρ_{cp} while $v_{\text{effective}}$ is the speed corresponding to the power but considering the site air specific mass ρ.

Considering that the speed measurements were not performed at the turbine's rotor height, a logarithmic extrapolation have been made by the use of Equation (11) in the data in order to construct a new histogram of speed, now for the height of 70 m. Only after this procedure Equation (12) was used.

By this way, during one year, it would be generated in São Benedito about 3.674 MWh for each turbine, while for example the consumption of electric energy in the region during the year 2004 (IPECE, 2005) was of about 16.322 MWh or in other words it would be necessary 5 turbines to match the demand in that year. The annual capacity factor for this generator in that location is about 21% being considered good when compared to 22% in average for Germany considered world reference in research about wind energy, manufacture of turbines and implantation of wind farms (Carvalho, 2004).

In Ubajara only one turbine would generate 6.227 MWh and for the year 2004 the electric energy consumption was of about 14.460 MWh (IPECE, 2005) being therefore necessary only 3 turbines to attend the electricity demand. For this location the annual capacity factor was of 35.5% being considered excellent. In both cases, it was neglected turbines stops of maintenance, loss of energy by transmission and other losses that vary from case to case but which can reach about 10% of the calculated value.

Analyzing the daily cycle of wind regime it was verified that the period of greater intensity occurs in the dawning and in the start of morning. This period does not coincide with the demand peak of electric energy in the region, which uses to be in the evening. So it would be recommended for such region that jointly with the wind farm it would be installed some system of storing electric energy, which on its turn would be reconverted to the electric energy during the peak demand.

8. Conclusions

It was demonstrated in this study that there are limitations in wind maps of the Ceará state when it is necessary to evaluate the wind energy potential of mountainous region as for example the Ibiapaba Mountain. It was also shown that similar regions in other countries have already installed wind farms being therefore necessary research, which can furnish better information about the wind resources of such regions in the Ceará state.

It was also made an analysis of recorded measurements of two FUNCEME meteorological stations in the mountaintop of Ibiapaba, in São Benedito and Ubajara districts. It was revealed that there are wind resources available in that region and it would attend the local demand of electric energy or could complement the energy matrix of the Ceará state. It would be necessary 5 turbines of 2 MW of nominal power to attend the electric energy demand of São Benedito and 3 turbines of the same nominal power to attend the demand of Ubajara.

However the analysis of daily wind cycle of such regions reveals that the period of greater intensity of wind occurs during the dawning and the start of morning and that therefore does not coincide with period of more demand of electric energy. So, it is recommended for such regions that jointly with the wind farms a system of energy storage be installed.

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