EVALUATION OF THE WIND POTENTIAL FOR REGIONS OF THE STATE OF ESPÍRITO SANTO

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Abstract. *The environment deterioration caused by the exploration of diverse power sources, increase the necessity of better exploring other natural resources for electric energy generation, particularly the renewable source fighting ambient problems, dependence of the traditional sources and reducing the increasing scarcity of energy. Among the renewable sources, the wind energy demonstrate some advantages in relation to the other sources, as easy operation, technological simplicity and long useful life of equipment. The evaluation of wind potential of a site is the first step to install a wind generator of electric energy. For this, it is necessary to treat data with statistical tools and, knowing the characteristics of the generator and of the local winds, evaluate the amount of electrical energy that is possible to generate. In this work a synthesis of the theory used for the estimation of energy potential is made and, from real data of speed and direction of wind, a first evaluation for the existing wind potential in some regions of State of Espirito Santo.*

Keywords*: Alternative source, wind energy, statistical method, wind rose, Weibull's distribution.*

1. Introduction

With gradual environment degradation due to increasing industrial society of consumption along the years, including the pollution of the rivers and the deforestation of the river's woods, the problems deriving from this ecological disequilibrium had multiplied, as the sanding of the river beds and the fall of capacity of the traditional hydroelectric plants, for example.

Thus appeared the necessity of better explorer other natural resources, as the winds, to increase the amount of available electric energy, supplying the demand coming from the population and industry increasing and reducing the dependence of traditional sources, as hydroelectric energy (Anjos and Ramos, 2005).

This article aims to clarify the possible ways to get the potential of energy in any region, knowing the characteristics of speed and direction of local wind, measured with certain precision in a proper height, the geographic characteristics of the region and the characteristics of generated power by a "weather-vane" (also called aero-generator or wind turbine) as function of speed and frequency of incident wind.

Using such knowledge, was realized an estimation of the amount of energy that is possible to generate in some places in State of Espírito Santo.

2. Characteristics of the exploitation

Wind energy is used since remote times for some populations, as the Persians and the Egyptians, as motor source for the navigation and milling of grains.

The winds come from the solar radiation, due to the not uniform heating of the Earth's surface. Fig. 1a shows an estimative, where 0,2% of the solar energy absorbed by Earth is converted into kinetic energy of the winds. From such analysis, there is approximately the energy of 600 Hydroelectric Plants of Itaipu available in the Brazil's surface (Acioli, 1994).

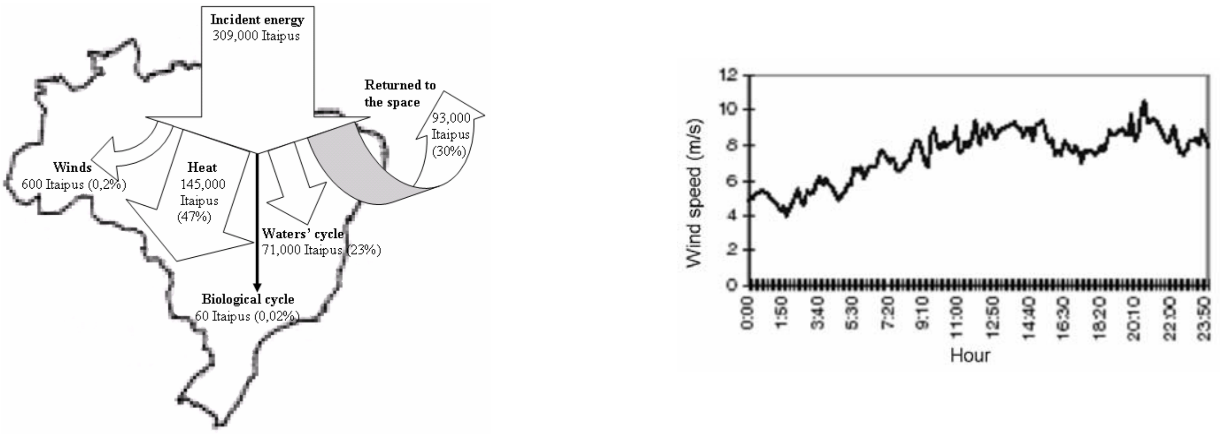
The following topics are part of the extensive existing theory on the estimation of the wind potential available for a region.

2.1. Available Wind potential

The existing power in air flow, in *Watts*, is given by:

$$P_d = 0{,}5 \cdot \frac{dm}{dt} \cdot V^2 \tag{1}$$

Being dm/dt the mass outflow, in *kg/s*, of air with density ρ, in kg/m^3, passing for an area A, in m^2, with a speed V, in *m/s*:



(a) (b)

Figure 1 - (a) Distribution of the incident solar energy in Brazil and (b) Speed of the wind by one any day

$$\frac{dm}{dt} = \rho \cdot A \cdot V \tag{2}$$

Inserting eq. 2 into eq. 1:

$$P_d = 0,5 \cdot \rho \cdot A \cdot V^3 \tag{3}$$

Multiplying the power, in *W*, for the time, in *hours*, it is gotten the flow kinetic energy, in *W.h*:

$$E_d = 0,5 \cdot \rho \cdot A \cdot V^3 \cdot t \tag{4}$$

To get the maximum power that can be extracted from the wind, the German physicist Albert Betz applied the theory of momentum conservation in the air draining passing through a rotor (Golding, 1955).

The flow retardation occurs in two stages, one before and another after its passage through the rotor; which is considered as a disk with some blades that produces uniform alterations in the speed of the flow.

Being V_1, V and V_2 the speeds of the wind before, during and after its passage through the rotor, respectively, and M the air mass in a unit of time, the momentum loss of the wind is:

$$\Delta Q_{mov} = M \cdot (V_1 - V_2) \tag{5}$$

The power absorbed by the rotor is:

$$P = M \cdot (V_1 - V_2) \cdot V \tag{6}$$

The kinetic energy transferred by the wind is:

$$\Delta E_c = 0,5 \cdot M \cdot (V_1^2 - V_2^2) \tag{7}$$

Equaling eq. 7 with eq. 6, it is gotten:

$$V = 0,5 \cdot (V_1 + V_2) \tag{8}$$

By the definition of M, the eq. 2 becomes:

$$M = \rho \cdot A \cdot V \tag{9}$$

Inserting the eq. 8 and 9 in the eq. 6:

$$P = 0,25 \cdot \rho \cdot (V_1 - V_2) \cdot (V_1 + V_2)^2 \tag{10}$$

The power of the wind before passing through the same turbine of area A is:

$$P_o = 0,5 \cdot \rho \cdot A \cdot V_1^3 \tag{11}$$

Then, the ratio *P/Po* becomes:

$$\frac{P}{P_o} = 0,5 \cdot \left(1 - \frac{V_2^2}{V_1^2} \right) \cdot \left(1 + \frac{V_2}{V_1} \right) \tag{12}$$

Deriving eq. 12 in relation to the ratio V_2/V_1, it is verified that the maximum of the function is reached in *0,5926* when $V_2/V_1 = 1/3$, and the maximum power extracted of the wind is *59,26%* (or *16/27*) relative to the total power of the incident wind; this percentage is called "Betz's Limit" (Golding, 1955).

2.2. Usable real potential

It is also necessary evaluate the amount of electric energy that is really possible to be generated. Since the speed of the wind varies at every moment and the power, as much as generated energy, depends on the cubic speed, it has to be determined using a trustworthy method from the speed and direction data collected by an anemometer.

The anemometer makes possible the collection of an endless number of speed data and direction and, through these, it is possible to observe the existence of significant variations between distinct periods of time. In analogous way, the winds do not blow in equal way year after year, needing at least 5 years of daily collected data, in periods of 1 hour between readings to have a more accurate estimative upon the local potential (Anjos, 2005).

Moreover, it is noticed (Fig. 1b) that it is complex and laborious to relate the speed in function of the time. Then, how to correctly use a database to estimate the wind potential of a region?

In the related articles (Hirata et al, 1999, Sahin and Aksakal, 1998, Khan et al, 2004), statistical largeness are used, as average and standard deviation of the collected data as well as the probability density functions (*pdf's*) for the estimation. Among several existing *pdf's*, those that better indicate the wind potential of a region are the Weibull's and Rayleigh's function.

The Weibull's function is given by:

$$f(v)_W = \frac{k}{C} \cdot \left(\frac{v}{C} \right)^{k-1} \cdot exp\left[-\left(\frac{v}{C} \right)^k \right] \tag{13}$$

The factor *C* is called scale factor and possess speed dimension, characterizing the distribution. Factor *k* is the form factor, dimensionless, that indicates the distribution's uniformity of the speed values.

The method that has presented the most accurate way to evaluate these two factors is the method of the average speed and the standard deviation (Hirata et al, 1999), where:

$$k = \left(\frac{Vm}{\sigma} \right)^{1,086} \tag{14}$$

$$C = \frac{Vm}{\Gamma(1 + 1/k)} \tag{15}$$

In the equations above, *Vm* is the average wind speed in the considered period, σ is the standard deviation and $\Gamma(z)$ is the Gamma Function, defined as:

$$\Gamma(z) = \int_0^\infty T^{z-1} \cdot exp(-T) \cdot dT \tag{16}$$

If the value of *k* is equal to *2*, Weibull's function reduces itself to Rayleigh's function:

$$f(v)_R = \left(\frac{\pi \cdot v}{2 \cdot V_m^2} \right) \cdot exp\left(-\frac{\pi \cdot v^2}{4 \cdot V_m^2} \right) \tag{17}$$

Comparing the graphs of the two distributions with the representative histogram of the site, it is verified which one represents the best probability density function for the estimation. The Weibull's distribution generally is the best curve for the characterization of the local winds (Sahin and Aksakal, 1998).

Thus, all the results in this article will be gotten by using the Weibull's function, with the method to attainment of *k* and *C* before shown.

To evaluate the sum of possible amount of electric energy that can be generated in a certainty interval of time by a turbine, it is necessary to know the average wind power in such interval from the average cubic speed:

$$P_m = 0{,}5 \cdot \rho \cdot A \cdot V_m^3 \tag{18}$$

From the definition of probability density function, the average speed is given by:

$$V_m = \int_0^\infty v \cdot f(v)_W \cdot dv \tag{19}$$

Consequently:

$$V_m^3 = \int_0^\infty v^3 \cdot f(v)_W \cdot dv \tag{20}$$

When substituting the eq. 20 in the eq. 18, the average power will be:

$$P_m = 0{,}5 \cdot \rho \cdot A \int_0^\infty v^3 \cdot f(v)_W \cdot dv \tag{21}$$

The turbine rotor converts kinetic energy into mechanic energy in function of the incident wind speed and, in this way, it is possible to know the efficiency of the turbine – *N(v)* – or its generated power – *P(v)* – in function of the speed.

If *N(v)* is known, eq. 21 becomes:

$$P_m = 0{,}5 \cdot \rho \cdot A \int_0^\infty v^3 \cdot N(v) \cdot f(v)_W \cdot dv \tag{22}$$

On the other hand, if the formula of *P(v)* is known:

$$P_m = \int_0^\infty P(v) \cdot f(v)_W \cdot dv = \int_{Vi}^{Vf} P(v) \cdot f(v)_W \cdot dv \tag{23}$$

In the equation above, *Vi* and *Vf* are, respectively, the speed of "cut in", in which the turbine starts to produce energy and "cut off", when turbine ceases the energy generation to prevent problems on its structure.

Generally, the manufacturers provide the rated power of the equipment, the speeds of "cut-in" and "cut-off" and the relation between generated power and incident speed; if they don't provide the last information, it can be simulated from the output power of the turbine, as shown in eq. 24 (Khan et al, 2004):

$$P(v) = 0,\ if\ 0 \le v < Vi; \quad P_n \cdot \frac{v^k - Vi^k}{Vr^k - Vi^k},\ if\ Vi \le v < Vr; \quad Pn,\ if\ Vr \le v < Vf \tag{24}$$

In this equation, *Vr* is the speed where the turbine produces the maximum or rated power *Pn* for which it was projected. With the real average power found, it is simple to calculate the sum of generated electric energy in one determined period Δt, as follows:

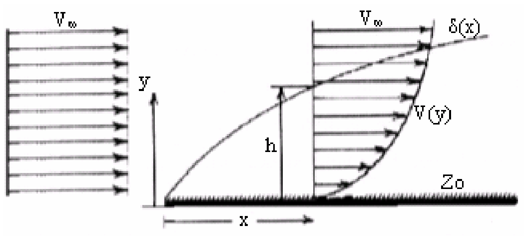
$$E_g = P_m \cdot \Delta t \tag{25}$$

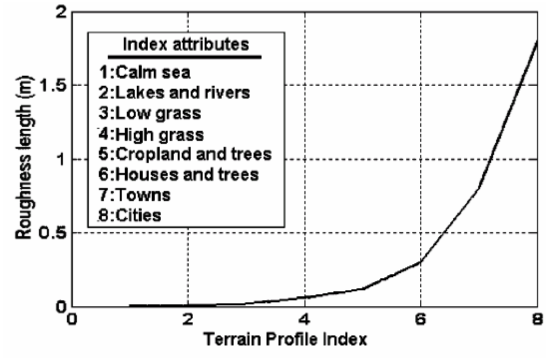
2.3. Potential in diverse heights

As in a draining on a fixed plain, the wind speed also varies in accordance with the height from the plan (fig. 2a).

Thus, if data have been collected in only one simple altitude, it can be necessary to evaluate the sum of energy that can be generated in higher heights, better using the available energy in the winds.

There are two main methods for such estimation (Khan et al, 2004), described below:





(a) (b)

Figure 2 – (a) Profile of draining of a fluid in a plain plate and (b) *Zo* for some types of lands

2.3.1. Power Law

The speed (*Vz*) in a desired height *Z* is given by:

$$Vz = Vr \cdot \left(\frac{Z}{Zr} \right)^{\alpha} \tag{26}$$

In the equation above, *Vr* is the known speed at one determined height *Zr*, and *α* is an exponent that can be evaluated knowing the characteristics of the local land. For this, the roughness length (*Zo*) of the land is estimated as shown in fig. 2b.

With *Zo* evaluated, *α* is obtained using the following relation:

$$\alpha = 0{,}096 \cdot log(Zo) + 0{,}016 \cdot log^{2}(Zo) + 0{,}24 \tag{27}$$

2.3.2. Logarithmic Law

The speed (*Vz*) at the desired height *Z* is given by:

$$Vz = Vr \cdot \frac{ln(Z / Zo)}{ln(Zr / Zo)} \tag{28}$$

The land roughness length (*Zo*) could be gotten through the graph in fig. 2b.

The most accurate method does not exist, for the estimation of the wind potential in various heights, except where the installation of various anemometers at different heights in one same tower is available.

However, using the Power Law it can be obtained small errors between the estimated and the real measurement, as shown in the tab. 1 (Khan et al, 2004):

Table 1. Comparison between the evaluated speeds by Power Law and the real measures.

Site	Meteorological data		Measured velocity at 25 m	Estimated velocity at 25 m	Error (%)	Terrain profile index	Roughness length (m)
	Velocity (m/s)	Height (m)					
Cox's Bazar	2.42	10	3.34	3.22	- 3.61	6.50	0.6245
Kutubdia	2.16	5	4.18	3.69	- 11.77	6.25	0.5139
Patenga	2.45	5	3.85	4.04	5.12	6.00	0.4160
Teknaf	2.16	5	2.96	3.33	12.62	5.50	0.2580

In the present work, from the anemometric data measured at 10 meters of height from the ground, it will be made the evaluation of the wind potential using the Power Law. It is interesting to notice that only the parameter of Weibull *C* change with the height, because this depends on the average speed, which will change with the height according with Eq. 15).

2.4. Wind Rose

It is of high importance for the full knowledge of local winds characteristics to know how the direction of wind varies in a given period of time. For the turbines of horizontal axis, less direction variation means less consumption of generated energy to change its orientation. In regions where exists some preferential wind direction, turbines with simpler direction control and lesser angle of turn may be used. However, if vertical turbines, the variation in the wind direction is not so significant.

To design the wind rose of a region, some more calculations of the speed at higher heights have to be performed, since wind speed depends on the roughness of the land, which in turn varies with the direction.

3. Evaluation of the regional potential

Using the calculation tools previously presented, the potential of some places in state of Espírito Santo was estimated, using collected data from the companies Aracruz Celulose and Rodosol.

Aracruz Celulose provided data between October/2001 and November/2002, automatically registered in intervals of half hour, from three measurement stations named Serra, Fábrica and Santana. The anemometers are installed at 10 meters from the ground.

On the other hand, Rodosol provided data between January/2001 and December/2003, registered in intervals of one hour by an anemometer situated in the central gap of the Third Bridge, at 70 meters from the sea level. The localization of each studied station is shown in fig. 3a.

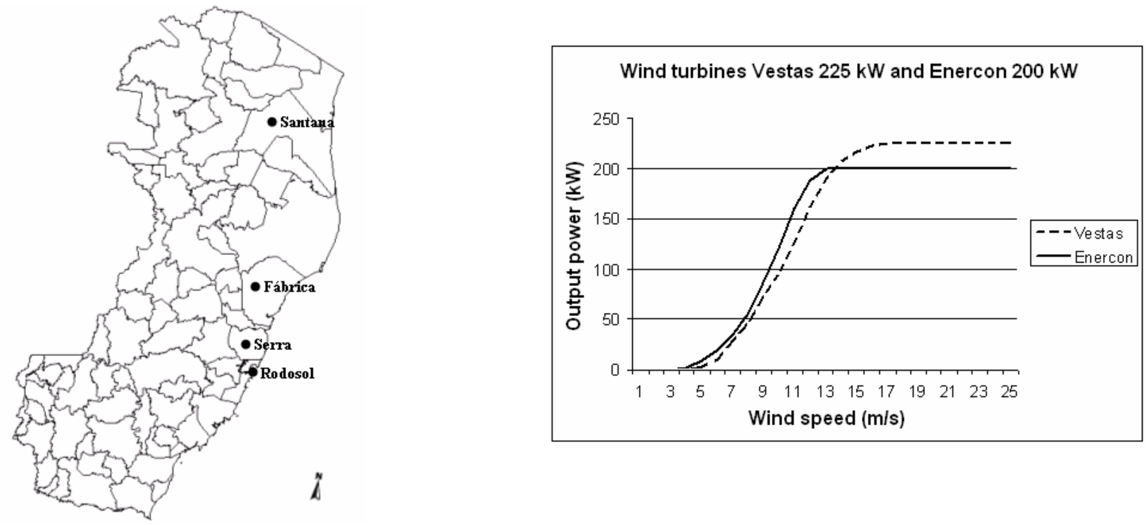
From the given data, average speed, standard deviation and parameters of Weibull function for each month had been calculated, making possible estimate the monthly production of energy. For the calculations and comparisons, it were analyzed seven existing turbines available in the market, whose characteristics are available from manufactures.

Assuming that the regions where the stations are located are covered by grass and trees, from fig. 2b it is observed the value of *0,12245* for *Zo*, which implies in α equal *0,16575* after substitution in Eq. 27; the last result was used for estimate the potential at *10*, *20*, *30* and *100* meters from the ground, this last one only in the total of the months.

Using the software *AllWin for Windows* (1995), the frequency histogram was mounted for comparing the distributions of Weibull and Rayleigh with the measured data, as well as the wind rose for eight main directions – North, Northeast, East, Southeast, South, Southwest, West and the Northwest.

For the estimation of the wind potential in *MWh* and *kW* for each station, the power versus wind speed curves of two turbines existing in market had been used. One with *200 kW* of normal rated power, manufactured for Enercon company, and another with *225 kW*, manufactured for Vestas company. The graph of each one is shown as in fig. 3b (Enercon, 2003, Vestas, 2003).

Thus, all the gotten values had been listed to make easy the comparison between turbines, months in distinct heights, shown as described in the studies of cases, sections 3.1-3.2.



(a) (b)

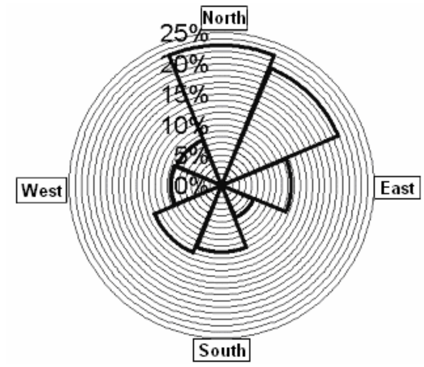
Figure 3 – (a) Geographical division of the State of Espirito Santo and the location of studied stations and (b) Power curves of the used turbines Vestas and Enercon

3.1. Study of Case – Aracruz Celulose

The tables and figures below show the results for the characteristics for winds and wind potential in three measurement stations available by Aracruz Celulose. Unfortunately, Station Fabrica did not have the potential calculated because it rare presents wind speed above *3 m/s* which is the minimum limit below what turbines do not generate electric energy, generally speaking.

Table 2. Station Serra – (a) Characteristics of the winds and wind potential at 30 meters from ground between October/2001 and November/2002 and (b) the respective wind rose

Month	k	C	Vm	Enercon, MWh	Enercon, kW	Vestas, MWh	Vestas, kW
Oct/01	2,330	5,366	4,755	20,2	27,2	16,3	21,9
Nov/01	2,272	5,309	4,703	23,4	32,5	19,0	26,4
Dec/01	2,326	6,135	5,436	29,5	39,6	24,2	32,5
Jan/02	2,025	5,798	5,137	27,3	36,7	22,5	30,2
Feb/02	2,109	5,651	5,005	22,5	33,5	18,3	27,3
Mar/02	2,070	5,266	4,665	20,8	27,9	16,8	22,6
Apr/02	2,165	4,715	4,175	14,0	19,5	11,2	15,5
May/02	2,178	5,388	4,772	21,4	28,8	17,3	23,3
Jun/02	2,609	4,304	3,823	9,1	12,6	6,9	9,6
Jul/02	2,406	5,190	4,601	17,9	24,1	14,4	19,3
Aug/02	2,434	5,236	4,643	18,3	24,6	14,7	19,7
Sep/02	2,336	5,587	4,950	22,0	30,5	17,8	24,7
Oct/02	2,807	6,985	6,220	39,0	52,4	32,1	43,1
Nov/02	2,963	7,073	6,312	38,5	53,5	31,7	44,0
Total	2,227	5,585	4,946	274,9	31,4	223,1	25,5



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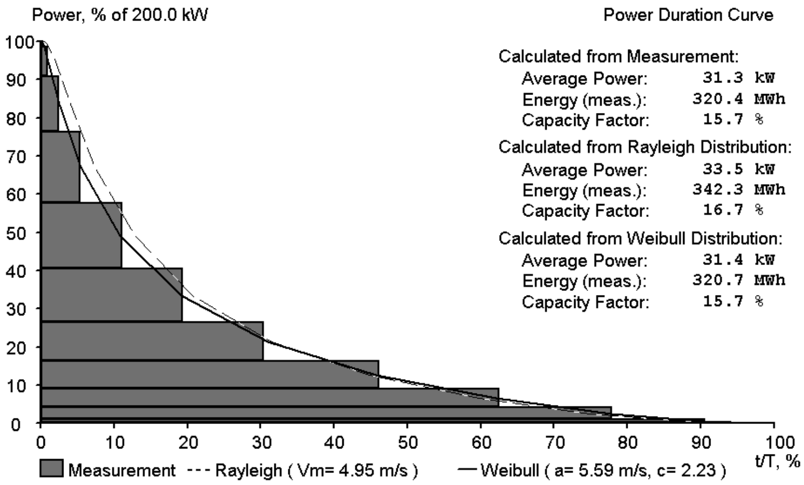
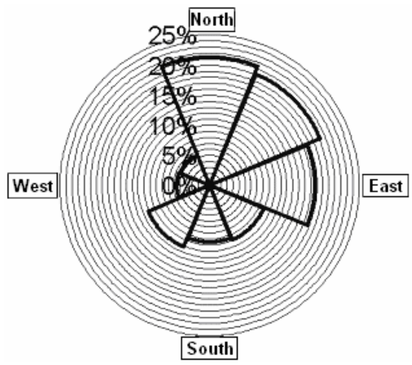


Figure 4. Station Serra – Comparison between the estimated potentials at 30 meters using a 200 kW turbine

Table 3. Station Santana – (a) Characteristics of the winds and wind potential at 30 meters from ground between October/2001 and November/2002 and (b) the respective wind rose

Month	k	C	Vm	Enercon, MWh	Enercon, kW	Vestas, MWh	Vestas, kW
Oct/01	1,964	4,356	3,862	15,6	21,0	12,5	16,8
Nov/01	2,268	4,706	4,169	17,2	23,9	13,9	19,3
Dec/01	2,226	4,916	4,354	21,0	28,2	17,1	23,1
Jan/02	2,303	4,924	4,362	19,7	26,5	15,9	21,4
Feb/02	1,975	4,061	3,600	14,1	21,0	11,4	16,9
Mar/02	2,643	3,164	2,812	10,3	13,8	8,1	10,9
Apr/02	2,779	3,665	3,263	8,7	12,1	6,8	9,5
May/02	3,112	4,031	3,606	12,6	16,9	9,8	13,1
Jun/02	2,768	3,184	2,834	5,7	7,9	4,3	6,0
Jul/02	2,984	3,892	3,475	11,1	14,9	8,6	11,5
Aug/02	2,918	4,188	3,735	12,3	16,5	9,5	12,8
Sep/02	2,789	4,633	4,125	15,3	21,3	12,0	16,7
Oct/02	2,865	5,215	4,648	24,9	33,4	20,0	26,9
Nov/02	2,786	5,041	4,488	23,6	32,8	19,0	26,4
Total	2,333	4,301	3,811	179,5	20,6	143,3	16,4

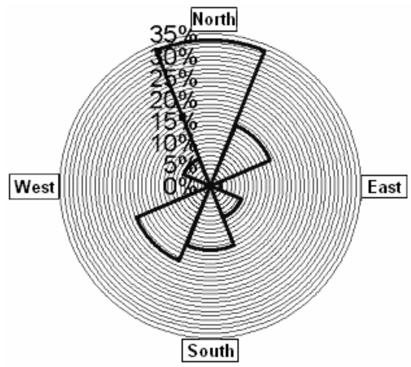


(a) (b)

Table 4. Station Fábrica- (a)Characteristics of the winds at 30 meters from ground between October/2001 and November/2002 and (b) the respective wind rose

Month	k	C	Vm
Oct/01	1,680	2,247	2,007
Nov/01	1,719	2,616	2,333
Dec/01	2,158	2,731	2,418
Jan/02	1,865	2,624	2,330
Feb/02	1,888	2,440	2,165
Mar/02	1,589	1,897	1,702
Apr/02	1,779	2,001	1,780
May/02	1,565	2,039	1,832
Jun/02	1,681	1,632	1,457
Jul/02	1,716	2,278	2,032
Aug/02	1,842	2,080	1,848
Sep/02	1,923	2,607	2,313
Oct/02	2,235	2,894	2,563
Nov/02	2,452	3,270	2,900
Total	1,767	2,381	2,119

(a)



(b)

3.2. Study of Case – Rodosol

Table 5 and fig. 5 show the results gotten of the characteristics for winds and wind potential in the measurement station of Rodosol, in the Third Bridge.

Table 5. Station Rodosol – 2001.

Year:	2001							2002						
Month	k	C	Vm	Enercon, MWh	Enercon, kW	Vestas, MWh	Vestas, kW	k	C	Vm	Enercon, MWh	Enercon, kW	Vestas, MWh	Vestas, kW
Jan	1,661	6,605	5,900	40,7	54,7	35,6	47,8	1,768	6,184	5,510	34,9	46,9	29,8	40,0
Feb	1,601	5,820	5,220	29,1	43,3	24,9	37,1	1,743	5,710	5,090	26,7	39,7	22,4	33,4
Mar	1,658	5,542	4,950	28,4	38,2	24,0	32,2	Anemometer in maintenance						
Apr	1,716	4,599	4,100	16,8	23,4	13,6	18,9	Anemometer in maintenance						
May	1,601	4,072	3,650	13,5	18,1	10,8	14,5	1,927	4,278	3,800	12,5	16,8	9,8	13,2
Jun	1,468	3,601	3,260	10,4	14,4	8,3	11,5	1,567	3,633	3,260	9,6	13,4	7,6	10,6
Jul	1,653	4,864	4,350	18,8	25,3	15,3	20,5	1,582	3,663	3,290	10,0	13,5	8,0	10,7
Aug	1,386	4,308	3,930	19,8	26,6	16,7	22,5	1,537	4,686	4,220	20,3	27,3	16,9	22,7
Sep	1,672	5,099	4,560	22,5	31,2	18,6	25,9	1,550	4,728	4,250	19,9	27,7	16,6	23,0
Oct	1,641	4,479	4,010	17,0	22,8	13,8	18,5	1,914	7,402	6,570	48,8	65,6	42,8	57,5
Nov	1,828	5,797	5,150	28,8	40,0	24,1	33,5	2,080	7,510	6,650	48,1	66,8	41,7	57,9
Dec	1,939	6,469	5,740	37,1	49,9	31,5	42,4	1,793	5,630	5,010	28,1	37,8	23,4	31,5
Total	1,579	5,029	4,520	276,8	31,6	231,3	26,4	1,563	5,290	4,750	313,6	35,8	265,4	30,3

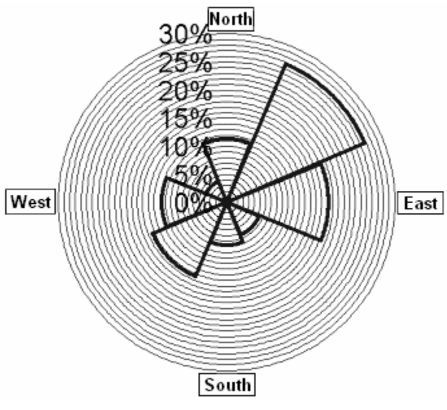


Figure 5. Station Rodosol – Wind Rose between 2001 and 2002

In order to visualize the economic advantage of the use of wind energy, an analysis of the station Serra was made for installation of a wind turbine at 100 meters from the ground, as described in tab. 6, where the installation cost include the sum of turbine costs, transport and installation, disrespecting the preventive and corrective maintenance.

Table 6. Station Serra – Simple economic analysis of the energy production.

Turbine costs (as shown in Fig. 3b)	Vestas	Enercon
Rated Power (kW)	225	200
Installed kW cost (R$ / kW)	3.321,00	3.732,00
Turbine total cost (R$)	747.203,00	746.418,00
Annual turbine's production (MWh)	384	459
Average annual consumption of one house (MWh)	2,4	2,4
Houses supplied for each turbine annually	160	191

4. Conclusions

Analyzing the results, it can be concluded that:

1) The distribution of Weibull express the wind frequency better than the distribution of Rayleigh for all studied places, as shown in tab. 2 for station Serra. The calculated energy for the distribution of Weibull (*320,7 MWh*) is closer to the real distribution (*320,4 MWh*) than the distribution of Rayleigh (*342,3 MWh*);
2) The distribution of Weibull is not perfectly equal to the real distribution, suggesting for future works, the necessity of optimization of Weibull parameters (Hirata et al, 1999), that will increase the trustworthiness of the estimation;
3) The estimation made with Rodosol's data shows that the sampling of one year's data is not representative to use to take the decision for installation a wind turbine;
4) It is verified that the energy generation reaches, in one year, a maximum value and a minimum value depending on the season; this suggests the period where the break necessary for preventive maintenance must be programmed. By tab. 5, the most appropriate months for maintenance in the Rodosol station are April and June, for example;
5) In a first analysis, it can be thought that how much bigger is the rated power of the turbine generates more energy is produced. However, the evaluations do not show that bigger turbine will generate more energy. For example, the comparison between the turbines, as seen in tab. 5 - year *2002*, show that the turbine of *200 kW* generates per year *278,6 MWh*, while the turbine of *225 kW* generates *234,8 MWh* in the same period.

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7. Responsibility notice

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