 


# DETERMINATION OF A WIND TURBINE CAPACITY FACTOR RELATED TO A CERTAIN WIND SITE

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***Abstract.*** This work aims to apply a simple methodology to determinate the capacity factor of wind turbines. To calculate the wind turbine capacity factor, it is first necessary the knowledge of the wind density probability function and its parameters. The terrain roughness or the roughness by sectors, if the terrain is not homogeneous with respect to the wind obstacle, is also important to make the determination of parameters at any desired height. These last values are easy to obtain when there are two anemometers in the place in analysis, but, if there is only one anemometer in the station a preliminary study may be done by the use of a suggested method, the Wieringa method. Afterwards, with some technical and performance data, turbine analysis may be done. The capacity factor is calculated by the relation between the energy obtained from the turbine in a certain time interval and the possible energy obtained from the wind turbine at the same time interval. Two commercial turbines were studied. It was concluded that the windy place had good results in relation to the turbines studied and the medium capacity factors of 0.44 and 0.42 were obtained for each one.

***Keywords****. wind density probability function****,*** *wind energy, electricity generation, wind turbines, capacity factor.*

## 1. Introduction

The capacity factor of wind turbines has as objective to define the relation between the electric energy that will be generated in a certain wind place and the energy that this same machine has conditions of producing under some ideal conditions that are determined by the manufacturer, that is, the energy that it would produce if the wind velocity was the nominal velocity during the entire period. The capacity factor therefore provides a measure of the energy efficiency of a machine in terms of its nominal power (Stull, 1988). This analysis is important in order to obtain sufficient data to choose the ideal machine to a certain place, that is, a machine that will give us the energy we need, working in its highest efficiency and having a good economic analysis too.

To calculate the capacity factor it is first necessary to know the wind density probability function in the period of time that the evaluation is desired. In this work we used mensal curves using Weibull distribution because it seems this is the most indicated time period to a seasonal phenomenon, and the kind of distribution that has the most fitness to the place in study. That can be observed in the comparison between the windspeed data histogram and the generated curve in this work. The knowledge of the power curve of the manufacturer, the cube height and the swept area are also necessary. Owning these data it is possible to determinate the relationship between the wind energy obtained from the wind machine in a certain time period and the nominal energy furnished by the machine in the same time period.

## 2. Hypotheses and adopted concepts

### 2. 1. Weibull distribution

For several years, the Weilbull distribution model was applied to represent the wind distribution to be used in structural calculation (Justus and Hargreaves, 1977), going through later to the wind power to be determined from this distribution (Hennessey, 1977), whose probability density function is determined by:

$$f_X(x) = \left(\frac{c}{b}\right)\left(\frac{x}{b}\right)^{c-1} \exp\left[-\left(\frac{x}{b}\right)^{c}\right] \tag{1}$$

where**:**
$f_X(x)$ is the density probability function,
***c*** is the shape parameter (dimensionless)
***b*** is the scale parameter in m/s

The Weibull distribution has its mean and its standard deviation in terms of gamma function (Newland, 1993) according to Eq. (2) and Eq. (3)

$$\mu = b\Gamma(1+1/c) \tag{2}$$

$$\sigma^2 = b^2\left[\Gamma(1+2/c) - \Gamma\left(1+1/c\right)^2\right] \tag{3}$$

If the sample mean and the standard deviation are known, the shape parameter ***c*** may be valued using several methods (Hennessey,1977).Taking into consideration the simplicity of the attainment method, as well as the attained positive results, the approach (Koeppl,1982) was applied, to the present work:

$$c = \left(\sigma/\mu\right)^{-1.086} \tag{4}$$

From this on, the scale factor may be calculated through the equation to the mean, Eq. (2), attaining the distribution curve.

Thus, owning the mean and the standard deviation, all the necessary parameters to build up the probability density function are known.

In addition to this, the Weilbull distribution is a powerful tool with several utilizations (Hennessey,1977), among them, the possibility to know the wind distribution in another different height from the one was used by the anemometer (Justus,1977), through the hypothesis of the logarithmic wind profile.

### 2.2. Logarithmic wind profile

In the atmospheric inertial sublayer, which is the lowest part of the planetary boundary layer with exception of a thin wall layer immediately adjoining the surface, the wind can be assumed to vary with height according to the logarithmic wind profile (Wieringa, 1975) according to Eq. (5), in which we can find the wind velocity at any height ($z_2$) as a function of the velocity at a reference height ($z_1$) and the roughness length $z_0$ that is the distance above the ground level where the wind velocity would be theoretically zero (Sadhu, 1981).

$$U2/U1 = \left[\ln\left(z2/z0\right)\right] / \left[\ln\left(z1/z0\right)\right] \tag{5}$$

where:

$U_2$ = wind velocity at the height $z_2$ (m/s)
$U_1$ = wind velocity at the height $z_1$ (m/s)
$Z_2$ = point 2 height (reference height) (m)
$Z_1$ = point 2 height (m)
$Z_0$ = roughness length (m)

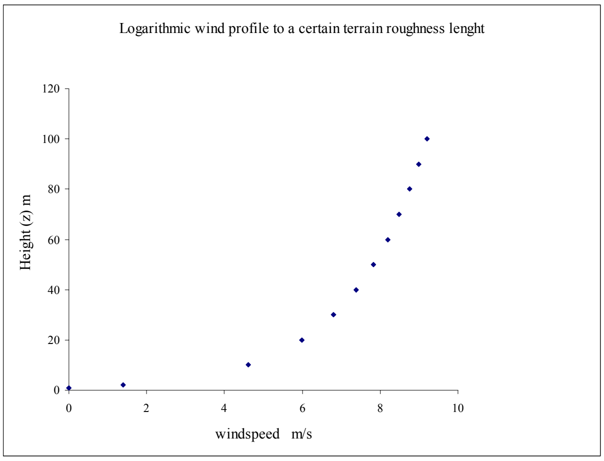



Figure 1. Logarithmic wind profile.

If the velocities in two different heights ($z_1$ e $z_2$) are known it is possible to determine an average roughness length $z_0$ to the station in question. Having the roughness length value, it is possible to find the mean velocity and the standard deviation at any height from the Eq. (5), and, therefore to determinate the new Weibull parameters to make the probability curve in the new studied altitude where:

c(z) is the shape parameter at height z,
$c_a$ is the shape parameter at anemometer height
b(z) is the scale parameter at height z
$b_a$ is the scale parameter at anemometer height

Besides the Weibull distribution the histograms relative to the wind velocity were monthly made.

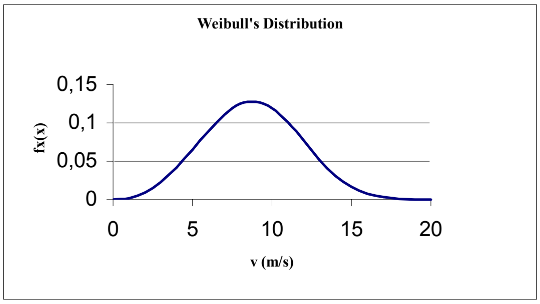
## 3. Calculation made from the wind turbine data and local Weibull distribution

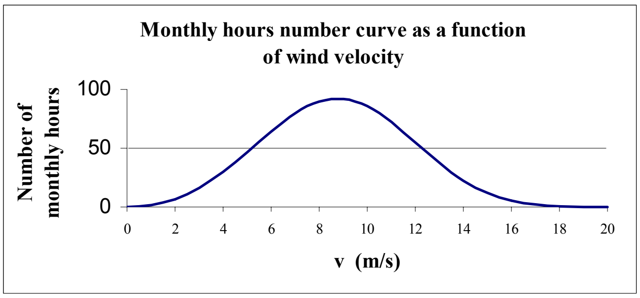
### 3.1. Monthly hours number curve as a function of wind velocity N(x)

This curve is obtained from the multiplication of the Weibull's probability density function obtained to the wind site by the desired number of hours. It depends, therefore, if the calculations are monthly or annual made. In this work it was multiplied by 720, that corresponds to the number of hours of a 30 days month, as it is shown in Eq. (6):

$$N(x) = f_x(x).720 \tag{6}$$

Figures (2) and (3) show respectively a Weibull's probability density function example and the monthly hours number curve as a wind velocity function belonging to a certain wind site.



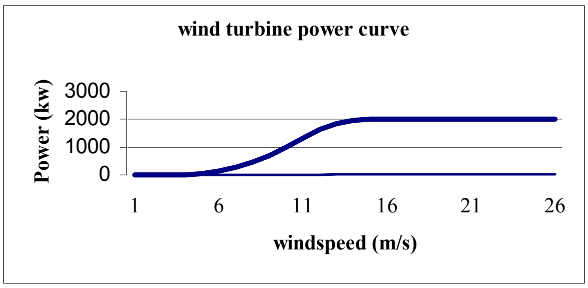



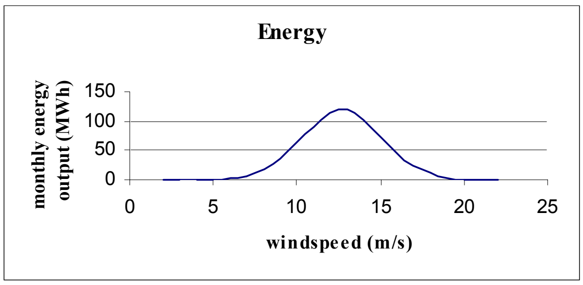

Figures 2 and 3. An example of Weibull probability density function and the monthly hours number curve as a wind velocity function.

### 3.2. Monthly energy output from a wind turbine as a function of wind velocity, $E_c$ (x)

Through the wind turbine power curve presented by the manufacturer *P(x)* it is possible to make the energy output curve yield as a function of windspeed in a certain period of time. This calculation is made from the multiplication of the windspeed probability density function as a function of monthly hours number by the power curve of the wind turbine in analysis.

$$E_c(x) = f_x(x).P(x).720 \quad \text{or} \quad E_c(x) = N(x).P(x) \tag{7}$$




Figures 4 e 5. Power curve of a wind turbine and the monthly energy output curve captured by a wind turbine as a function of wind velocity to a certain wind site examples.

### *3.3.* Total energy captured by a wind turbine in a certain time period *Ect (x)*

It is the area under the captured energy curve by the wind turbine in a certain time period, a month in this work.

$$E_{tc}(x) = \sum_{x=x_{\min}}^{x=x_{máx}} E_c(x) \tag{8}$$

where
$x_{min}$ = minimum work velocity of the wind turbine (cut-in)
$x_{máx}$ = maximum work velocity of the wind turbine (cut- out)

## 4. Wind turbine capacity factor $F_c$

The wind turbine capacity factor is obtained through the relation between the total energy captured by the wind turbine in a certain local and period of time and the number that results of the multiplication of the machine nominal power (*Pn*) by the number of hours in analysis, a month or 720 hours in this work.

$$F_c = \frac{E_{tc}(x)}{P_{no\min al} \cdot 720} \tag{9}$$

## 5. Data, instrumentation and local analyzed

The data applied in this paper are from a farm situated in Santa Vitória do Palmar (RS, Brazil) where it was installed a tower holding two anemometers from Ammonit, model "Classic", with resolution of 0.05 m/s and uncertainty in the measurement of 2 % or 0.3 m/s. They were situated at 25 and 50 m high, with a sample period of 10 minutes and acquiring data at each 1s. In this paper were analyzed the data that were obtained in a period of four months (December 2001 to March 2002). Also were presented data from the wind turbines that are in manufacturers catalogs like power curve as a function of wind velocity. So, the analysis were made in accordance with these values from the models that are part of Tab (1) bellow.

Table 1. Analyzed wind turbine data.

| Manufacturer | Nominal Power (kw) | Rotor Diameter (m) | Hub Height (m) | cut-in windspeed (m/s) | cut-out windspeed (m/s) | Nominal wind speed (m/s) |
|---|---|---|---|---|---|---|
| NORDEX | 2300 | 90 | 80 | 3 | 25 | 12.0 |
| DEWIND | 2000 | 80 | 80 | 3 | none | 13.5 |

## 6. Wieringa method

If there is only one anemometer in the station, the Wieringa method is suggested to make the values of the wind turbine cube height known. In 1975, J. Wieringa published in the periodic Quart. J. R. Met. Soc. an article titled "An objective exposure correction method for average wind speeds measured at a sheltered location", where proposed a method to improve the windspeed measure representativity made in a local with shelter effects caused by small-scale obstacles. With his method, starting with data at certain height, it is possible to "transfer" them to another height and "clean" them of the sheltering effects. This method proposes that the corrections applied to the wind data can be made without a subjective evaluation of the surroundings and without needing reference stations.

### 6.1. Wieringa method hypotheses and basic concepts

Wieringa uses like hypotheses the logarithmic wind profile (already described in item 2.2) and the assumption that the contribution of individual roughness elements to the general wind retardation becomes difficult to localize above a certain roughness blending height $z_b$. The wind speed at that height, $U_b$, will then be a smoothed result of the retardation influences imposed on the driving wind by the upwind surface roughness at mesoscale (horizontal dimension ≤ 10 Km), and the wind velocity will be the same that it would be in open-terrain. Over ordinary countryside, with maximal roughness element heights of 20 to 30 m, a suitable choice seems to be $z_b$ = 60 m. Over a suitable wind station it then can be assumed that strong winds vary between $z_s$ and $z_b$ according to a logarithmic profile , and it becomes possible to derive $U_r$ from $U_s$, by way of estimating $U_b$ above the station, using the transformation illustrated in Fig. (6).

With the assumption that the analyzed station is situated in a moderate open field and having an average windspeed $U_s$ measured at a height $z_s$, where the "*s*" subscript indicates the real station values and it is desired to know which would be the average windspeed $U_r$ in the same localization, in a reference terrain hypothetically plane and clear at a reference height $z_r$, with a reference roughness length $z_{or}$ .

It becomes possible to derive $U_r$ from $U_s$ by estimating $U_b$ above the station, using the transformation illustrated in Fig (6).This transformation can be formalized as follows in Eq (10):

$$Ur = Us \frac{\ln(zb/zos)\ln(zr/zor)}{\ln(ze/zos)\ln(zb/zor)} \tag{10}$$

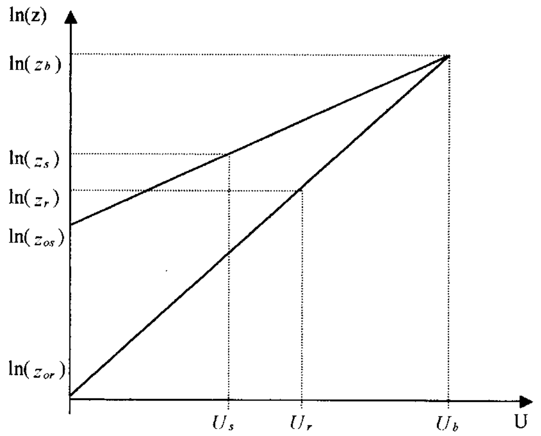



Figure 6. Derivation of the hypothetical wind speed $U_r$ at reference height $z_r$ over open terrain, from the known wind velocity measured at station height.

In the determination of $U_r$ from the Eq. (10), all the values are either known or can be postulated in advance, like $z_{or}$. The only parameter that needs to be calculated before $U_r$ determination is the station roughness length by sectors, $z_{os}(\theta)$, that can be obtained by the method to be described in the section 6.2.

### 6.2. Determination of the station roughness length by sectors from the gust factors values measured at the wind station height.

In 1973, studies made by J. Wieringa, proved that gust velocity values suffer less influence with height than average winds. Gusts must be understood as short time (around 3 seconds) variations in windspeed. Based in this testifying, Wieringa, concluded that the difference between gust and average velocities values rise with increasing terrain roughness and developed a method to determinate the roughness length of a wind station from the gust values measured by the referred station. Assuming the logarithmic wind profile applicability, Wieringa showed that if at a station during a period $T$, with average wind speed $\overline{u}$ and a maximum velocity registered value (gust) $u_{\max}$ (T,t) of duration $t$ is recorded, for T = 10 min at a height $z$ over a homogeneous terrain wit roughness length $z_o$ the following relation is valid:

$$\langle G\rangle = 1 + \{1{,}42 + 0{,}30\ln[(1000/\overline{u}\,t_p) - 4]\}/\ln(z/z_0) \tag{11}$$

where:

$\langle G\rangle$ is the median value of a number of gust factors registered during strong winds. The use of median values is preferable to arithmetic averaging values, due to trends and fronts effects in G distribution that influences less the first one. Equation (11) was deducted assuming a wind velocity normal distribution, that can be admitted to wind speeds of 6m/s and higher.

Equation (11) term, where we assume that the distribution around the mean is gaussian, it is the distribution eccentricity $E$, that is represented by the Eq. (12).

$$E = 1{,}42 + 0{,}30\ln\left[(1000/\overline{u}.t_p) - 4\right] \tag{12}$$

where $\overline{u}.t_p$ is the gust wavelength length $\lambda$ . This last value corresponds to the gust period $t_p$ multiplied by mean wind velocity $\overline{u}$ . It basically depends on the anemometer capacity of "follow" the gust, that is, of its length response

$L^{*}$ (instrument characteristic value). The higher is the length response the lower is the anemometer capacity of registering the gusts, that corresponds to a step change of the wind velocity variable. Wieringa suggests a gust wavelength length value of 100 m, because it is typical for ordinary wind instrumentation. After the substitution of suggested $\lambda$ , $E$ value results in 1,96.

Replacing Eq. (11) in Eq. (12) leads to Eq. (13):

$$\ln z_O = \ln z - E/(\langle G\rangle - 1) \tag{13}$$

Replacing Eq. (13) in Eq. (10) we obtain Eq. (14) that calculates the correction factors by sectors::

$$\frac{Ur}{Us} = F(\theta) = \left[\frac{(\langle G(\theta)\rangle - 1)\ln(zb/zs)}{E} + 1\right]\frac{\ln(zr/zor)}{\ln(zb/zor)} \tag{14}$$

Therefore, the roughness length is only an intermediate parameter in the model, since it does not feature explicitly in Eq. (14). However it makes its effect in the median $\langle G\rangle$ parameter.

## 7. Application of methodologies

### 7.1. Methodology using data obtained from wind station towers with two anemometers situated at different measurement heights

In this situation, the roughness length $z_0$, can be obtained for different angles around the terrain station of the anemometers tower. These angles must be conveniently separated according to the similarities of the obstacle heights, or, if the terrain is homogeneous (that is this work case), it can be considered as a unique value. The anemometric tower was situated in an open field without nearby obstacles able to modify windspeed profile at a distance of 3 or 4 Km.. With the two velocities, at 25 and 50 m it was possible to obtain the terrain roughness length from the Eq. (5) and, afterwards it was possible to calculate the windspeed at 80 m height, from the Eq. (5), too. Owning these last two values it was possible to determinate the shape and scale Weibull parameters using Eq. (4) and (2), respectively. With these parameters obtained, it was possible to determine the Weibull density probability function from Eq. (1).

The estimation may be monthly our yearly made, the most adequate to the data set at disposal. It's known that data set of at least one year is considered sufficient to evaluate the wind resources viability of a certain place. However, this work has not this analysis as its objective, but only to show wind turbines capacity factor calculation steps, owning just a data set at different heights (or not, like the situation of item 7.2). Monthly calculations were made to show the differences among Weibul parameters, as well this function density probability distribution and the monthly hours number curve as a function of wind velocity *N(x).*

With the results obtained so far, two commercial wind turbines were chosen. It is necessary to elucidate that costs were not taken in account, the machines were random chosen and the necessary parameters were acquired via internet to make possible the calculations continuity. Being in possession of the wind turbine catalogs data, it was possible to evaluate monthly energy output from a wind turbine as a function of wind, $E_c$ (x), the total energy captured by a wind turbine in a certain time period $E_{ct\,(x)}$, and, finally the wind turbines capacity factor $F_c$.

### 7.2. Wieringa application method

The utilization of Wieringa method with the acquired data set that were used in this work is senseless due to the possibility of the knowledge of the terrain roughness length, since there are two velocity measurements at two different heights. However, it is certainly very useful to evaluation situations when only one anemometer is installed, that is, measurements are made in only one height above the terrain level. There are works published using this method, including Olinto (2001), Lopes and Almeida (2002) and, Olinto, Lopes, et al. (2001).

In this work only the necessary steps to the method application are presented that are listed as follows:

- The azimuth sectors around the station tower ($\theta$ ) must be chosen with vegetation around it in similar conditions, that is, the elected sectors must pursue the same wind obstruction characteristics. These sectors must be determined trough a topographical work around the station anemometer. To find the wind velocity correction factors $F(\theta)$ to each sector it is first necessary to find the median gust factor $\langle G(\theta)\rangle$, according to the following steps
- Separation of the wind data velocity separation in blocks of 6 m/s and higher values, their directions and respective gusts.
- Separation of the preceding data in their respective directions in correspondent elected sectors.
- Evaluation of the median of gust factor $G(\theta)$ by sector, which is the median value of the reason between $u_{\max}$ and $U$ by sectors.

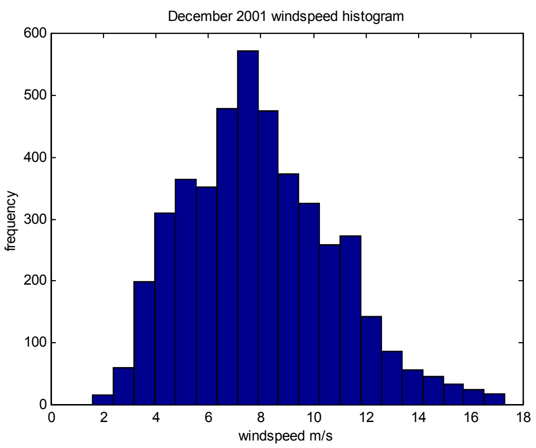
In sequence the application of the correction factors to the original data by sectors must be done. A new data set will be utilized to calculate the mean velocity, standard deviation, and the Weibull parameters. Finally, all calculation related to the energy output mentioned in item 3 may be done.

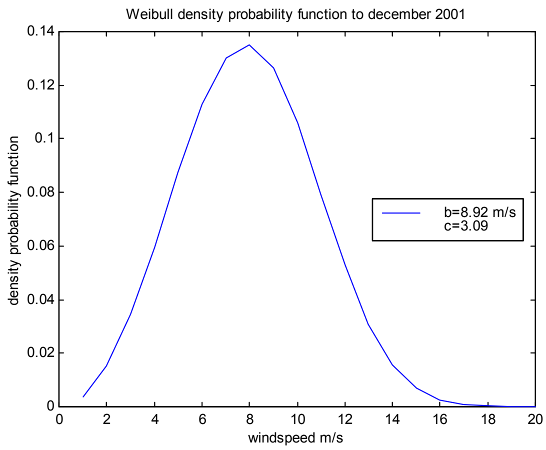
## 8. Results.

Forthcoming will be presented the obtained results to the monthly-analyzed data.

### 8.1. Wind frequency histogram and Weibull distribution curve corresponding to December 2001

Although the four months were analyzed, in this item are only presented the results correspondent to December 2001 as representatives of the other months. It is possible to identify the adherence of the wind histogram to the cited month with the Weibull density probability function.




Figures 7 and 8. Wind velocity histogram, Weibull density probability function and correspondent parameters to the anemometers height related to December 2001.

### 8.2. Comparative tables of mean velocity, standard deviation, Weibull parameters results obtained to the studied months and turbines power curves

#### 8.2.1. Comparative results of mean velocity standard deviation and Weibull parameters at 50 and 80 m.

Table 2. Comparative results of mean velocity standard deviation and Weibull parameters at 50 and 80 m.

| | | | **Mean velocity (m/s)** $\overline{V}$ | | **Standard (m/s)** **ó** | | **Scale parameter (m/s)** ***b*** | |
|---|---|---|---|---|---|---|---|---|
| **month** | **Data number (N)** | **Rough-ness length (m)** $z_0$ | **50 m** | **80 m** | **50 m** | **80 m** | **50 m** | **80 m** |
| **December** | 4464 | 0.021 | 7.97 | 8.41 | 2.82 | 2.98 | 8.92 | 9.41 |
| **January** | 4464 | 0.017 | 7.76 | 8.22 | 2.86 | 3.03 | 8.70 | 9.21 |
| **February** | 4032 | 0.030 | 7.05 | 7.49 | 2.92 | 3.11 | 7.94 | 8.42 |
| **March** | 4464 | 0.045 | 7.78 | 8.30 | 3.09 | 3.30 | 8.75 | 9.33 |

### 8.2.2. Wind turbine power curves

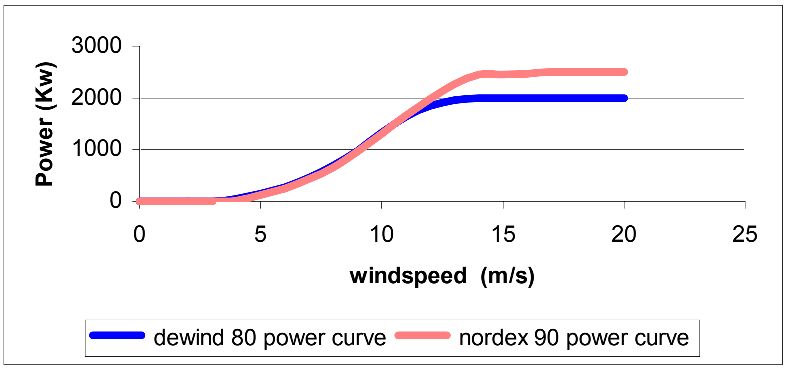



Figure 8. Wind power curves obtained from the manufacturer catalog data.

### 8.2.3. Turbine energy output and manufacturer power curve as a function of wind velocity related to January 2002

The curves presented were obtained from January 2002, to represent the other months.

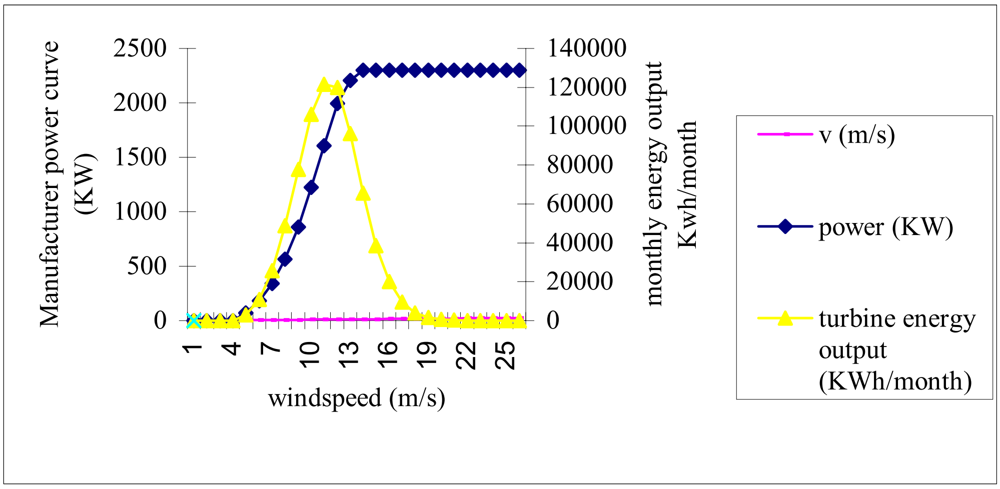



Figure 9. Curves of the Nordex 90 turbine (Jan 2002).

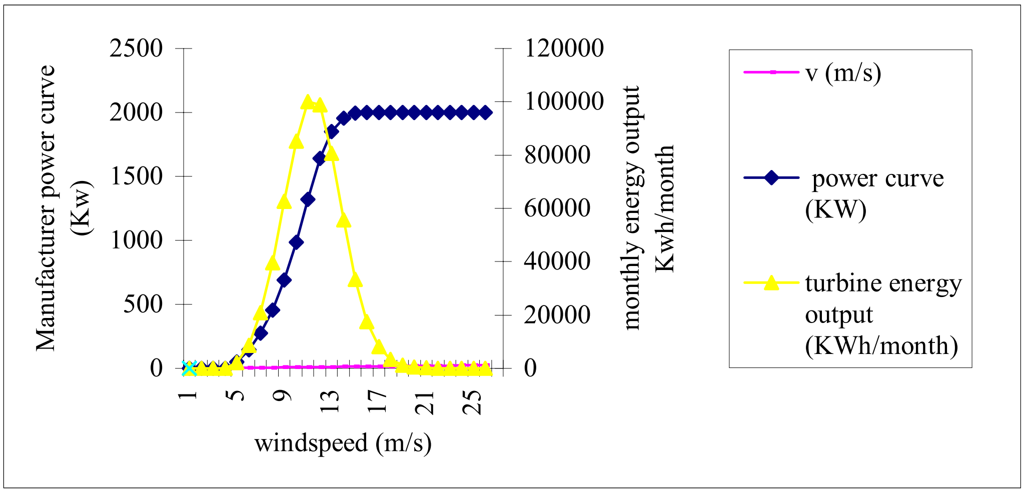



Figure 10. . Curves of the Dewind 80 turbine (Jan 2002).

### 8.3. Monthly energy output results and capacity factor of Nordex 90 e Dewind 80 turbines to the analyzed months.

Table 3. Monthly energy output results and capacity factor of Nordex 90 e Dewind 80 turbines

| | **December** | | **January** | | **February** | | **March** | |
|---|---|---|---|---|---|---|---|---|
| | *Fc* | Kwh/ month | *Fc* | Kwh/ month | *Fc* | Kwh/ month | *Fc* | Kwh/ month |
| **Dewind 80** | 0.46 | 658,262 | 0.43 | 618,442 | 0.36 | 512,761 | 0.41 | 596,565 |
| **Nordex 90** | 0.48 | 797,065 | 0.45 | 749,299 | 0.38 | 622,971 | 0.43 | 716,610 |

## 9. Conclusions

According to the obtained results it is possible to verify that the Nordex 90 turbine presents a mean capacity factor of 0.44 and the Dewind 80 turbine presents a mean capacity of 0.42 related to the wind place. This difference in capacity factor means a disparity in terms of energy output of mean 124,978 Kwh/month propitious to the first one. Unfortunately a turbine choice is not only factor capacity parameter dependent. This factor is only the first step to a economic analysis. Other factors as for example the installed wind turbine price, interest rate, inflation, the cost of routine maintenance and operation, payback time are also important to make a wind turbine choice (Nelson, 1993). Although capacity factor is important but not enough to decide which turbine is the most appropriate to the analyzed site, it is possible to ensure that it concludes the evaluation involving wind velocity performance with certain turbine in a certain location.

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