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EXTRAPOLATION METHODS COMPARISON FOR WIND ENERGY PURPOSE

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Abstract. *Studies of International Agency for Renewable Energies (IRENA), conducted in 2014 indicated that the production of energy from renewable sources such as hydro, wind and solar, has become financially competitive with the production of energy from fossil fuels. Wind energy is a renewable source of energy that currently has viable technology to develop energy generation projects in large scale. For success of such projects should be substantially minimized the uncertainties associated with the project, and to this end, wind speed data used should use methods that minimize errors in processing. This study aims to compare three methods of extrapolation of vertical profiles of wind speed in order to evaluate which of them has the slightest error compared with the measured data and thus get less uncertainty. At work were determined values of Weibull distribution parameter, c and k, for the extrapolated data and measured values. After comparing the curves, were calculated errors with respect to the curve of the collected data by Root Mean Square Error (RMSE), also was performed an analysis of the wind power density.*

Keywords: *Wind Speed, Wind Potential, Extrapolation Methods, Weibull Distribution.*

1. INTRODUCTION

Of front with the energy crisis that society faces, it is important to find viable alternative of energy production. This task should not prioritize only the aspect of energy potential, but also the nature of energy sources, since there is a concern with the greenhouse effect and global warming by the Governments of Nations, especially after the creation of Kyoto Protocol, in 1997.

The sources of renewable and clean energy are the best option regarding the greenhouse effect because originate few environmental impacts and second INERA (2014) the technologies for exploitation of renewable energies such as wind and solar, has become competitive with sources of fossil fuels.

In Brazil, the energy matrix is made up mostly by hydropower, however, there is a need of expansion of energy production, as well as worldwide.

Wind energy production is a possibility to expand the energy matrix of Brazil, by exploiting a natural resource underutilized, which in addition to being a renewable source, is a source of clean energy, it is not emitting greenhouse gases.

Brasil (2008), states that the Earth has a potential of energy generation from the wind by about 500,000 TWh / year (terawatt hours per year). Theoretically ten percent of this amount is usable, which is about four times the electricity consumption in the world.

Silva (2003) states that the Brazilian Northeast has a huge potential for the exploitation of wind energy. This can boost the development of region, since there are areas where generation of energy through of hydroelectric is not feasible.

On design of a wind farm is necessary to know the characteristics of local winds, to get an estimate of wind potential in the location of wind turbines. To this end builds up anemometer towers to measure wind speeds by minimum intervals of one year, resulting in high costs in project implementation, since the higher the height of the measurement tower higher are the deployment and maintenance costs and not it is always financially feasible to build towers on height of deployment of wind turbines.

An alternative to this problem is the use of obtained data in previous measurements in the lowest height level, where the costs are lower and applying up methods of vertical extrapolation of wind speed it is possible to estimate the wind potential at the level of implantation of the wind turbines.

Lira et al (2014) used the vertical extrapolation of wind speed to calculate the wind resource in the coast of Ceará, Brazil.

The objective of this study is to compare three methods of vertical extrapolation of wind speed. The methods are: Method Logarithmic Law; Method Power Law, and Weibull Method. And determine the method that provides the highest accuracy of results, by calculating of Root the Mean Square Error (RMSE). It is also intended make an analysis of power density of extrapolated and measured data.

This research used collected data of wind speed and direction in the city of Petrolina, PE, Brazil, measured on two height levels.

The data were obtained from the database available by Sistema de Organização Nacional de Dados Ambientais (SONDA), performed by Instituto Nacional de Pesquisas Espaciais (INPE).

The data set includes measured values of wind speeds, direction and temperature during year of 2010 in intervals of 10 minutes in the levels of *25 m* e *50 m* at ground level. The geographical position of station is located at coordinates: 09º04'08” S, 40º10'11” W (WGS84) and altitude de *387 m* at sea level.

1.1 Probability distribution

On wind resource analysis are utilized probability distributions, Lima and Filho (2012) used the Weibull distribution to adjust the wind resource of São João do Cariri, Pa, Brazil. In this work the winds were adjusted by the probability distribution of Weibull.

Second Justus et al. (1977), the Weibull distribution to a wind speed V can be expressed by the probability density function given by Eq. (1):

$$p(V) = \left(\frac{k}{c}\right)\left(\frac{V}{c}\right)^{k-1} e^{-\left(\frac{V}{c}\right)^{k}} dV \tag{1}$$

where: c is scale factor in *m/s* and k is form factor, dimensionless.

The parameters of Weibull distribution, c and k, must be estimated in order to adjust the curve as much as possible at histogram of measured data.

There are several methods to estimate these parameters. Andrade, C. F. et al. (2014), Lima and Filho (2012) and Rocha, et al (2012) tested methods of parameter adjustment, c and k of Weibull distribution.

The method utilized this work is the adjustment of Least Squares.

1.2 Method of Logarithmic Law of vertical extrapolation of wind speed

Second Manwell et al. (2002), the Logarithmic Law is originated of study of boundary layer of fluid mechanics and of atmosphere. It is based on a combination of theoretical and empirical research. The speed V can be extrapolated by Eq.(2):

$$V(z) = V_{ref} \cdot \frac{ln(z/z_0)}{ln(z_{ref}/z_0)} \tag{2}$$

where: z_{ref} is the measurement reference height of speed, z is the height to which up want to extrapolate speeds and z_0 is the roughness length, both in *m* e V_{ref} is the speed on reference height, in *m/s* .The value z_0 is approaching average the length of roughness of terrain being studied, this data was obtained from Tab. 1.

Table 1– Values of z_0 relative to Type of terrain

TYPE OF TERRAIN	Z_0 (mm)
Very slick, ice or mud	0,01
Open sea and calm	0,2
Sea with waves	0,5
Surface with snow	3

Lawn	8
Irregular pasture	10
Careless field	30
Plantations	50
Some trees	100
Many trees, fences, few buildings	250
Forests and woodlands	500
Suburb	1500
City centers with tall buildings	3000

Source: Adapted of Manwell et al. (2002).

1.3 Method of Power Law of vertical extrapolation of wind speed

Second Manwell et al. (2002), the Power Law is a simple model to representation of vertical profile of wind speed. The speed for this method can be extrapolated by Eq. (3):

$$V_z = V_{ref} \cdot \left(\frac{z}{z_{ref}} \right)^{\alpha} \quad (3)$$

where: z_{ref} is the reference height and z is the height to which up want extrapolate the speeds, in *m*, and V_{ref} is the measured speed in *m/s*.

Studies show that the exponent α varies with altitude, day hour, seasons, type terrain, wind speed, temperature and other combinations of thermal and mechanical parameters, Justus et al (1977).

Were developed complex models to estimate this parameter, which compromise the simplicity and applicability of Power Law, in this way, the empirical models of determination of α are more utilized. Second Justus et al. (1977), α can be expressed by Eq. (4).

$$\alpha = \frac{0{,}37 - 0{,}088\, ln(V_{ref})}{1 - 0{,}088\, ln(z_{ref} / 10)} \quad (4)$$

1.4 Weibull Method of vertical extrapolation of wind speed

The Weibull Method has the advantage, compared to other methods, by directly extrapolate from a height level to another level the parameters *c* and *k* without the need extrapolate a series of speed and after the parameters *c* and *k*.

Second Justus et al. (1977), the extrapolation utilizing the Weibull Method is represented by Eq. (5) and Eq. (6) to find *c* and *k*, respectively:

$$c(z) = c_a \left(\frac{z}{z_a} \right)^{n} \quad (5)$$

$$k(z) = k_a \left(\frac{1 - 0{,}088(z_{ref} / 10)}{1 - 0{,}088(z / 10)} \right) \quad (6)$$

where: z and z_{ref} are the height which up want extrapolate the speeds and height of reference of measured speeds, respectively, in *m*, c_a and k_a are the Weibull parameters of series of measured data on the reference height, this case *25 m*. the exponent of Eq. (5) is given by Eq. (7).

$$n = \frac{0{,}37 - 0{,}088\, ln(c_a)}{1 - 0{,}088\, ln(z_a / 10)} \quad (7)$$

1.5 Root Mean Square Error (RMSE)

To know the fit of a model to the real value, up must to employ calculation techniques of error. The Root Mean Square Error (RMSE) is a of calculation techniques of error commonly used, can be expressed by Eq. (8):

$$RMSE = \sqrt{\frac{\sum_{i=1}^{n}(p_i - o_i)^2}{n}} \tag{8}$$

where: p_i is the estimated values by the employed model and o_i is the observed value.

On Eq. (8) square of differences between values ensures that all values of each comparison between points of employed model and of observed data result in positive values when added, avoiding that positive and negative error are canceled.

1.6 Power Density

The wind potential of a location can be determined by the concept of power density, regardless of wind turbines, Castro (2009), the power density can be calculated by Eq. (9):

$$P = \frac{1}{2}\rho V^3 \tag{9}$$

where , ρ is the air density in *kg/m³* and V is the Wind speed, in *m/s*, the power density P result is expressed in *W/m²*.

It is interesting know the error involved in the methods regarding power density, because this is the end objective of all estimate of wind resource.

2. METHODOLOGY

Were analyzed three methods of vertical extrapolation of wind speed: Logarithmic Law, Power Law and Weibull Method, by calculating the probability distribution of Weibull, using data of obtained speed and direction by the SONDA of station of Petrolina, on Brazilian Northeast.

For that the data were compared under the same conditions, the speed data were grouped into 12 sectors according to the direction, each sector covers 30 degrees with reference to North direction and clockwise. Also, were performed the same processes with all data without division in sector.

The reference height is *25 m*, and the height which up want to extrapolate is *50 m*. Were calculated the speeds by Logarithmic Law by way of Eq. (2).

On calculating each sector, the parameter z_0 was determined by analysis of the terrain type through satellite imagery, taking based on a radius circumference of *10 km*, obtaining up the arithmetic mean of roughnesses in accordance with the type of terrain based on the Tab. 1. Thus the adjustment must better represent local conditions, since around the measuring point there are variations of terrain types. In Fig. 1 is possible to see the area that was evaluated and the distribution of 12 sectors.

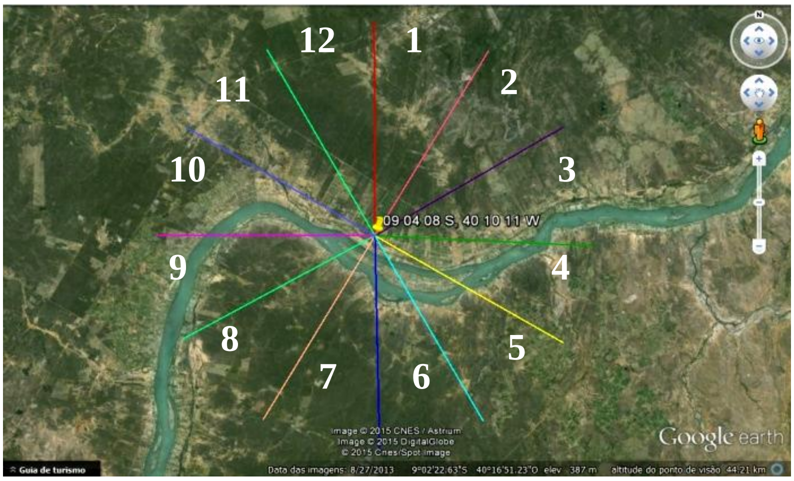

Figure 1: Google Earth measuring point image showing the division of the sectors and types of terrain.

In approach without division of speeds in sectors, the roughness was obtained by average the roughness of the 12 sectors.

By method of Power Law the speeds were calculated by Eq. (3) and Eq. (4). On Weibull Method were calculated the values of the parameters of Weibull distribution for the level of *25 m* of measured values and then were applied the Eq. (5), Eq. (6) and Eq. (7) to extrapolation of the parameters *c* and *k*.

Then were constructed the Weibull distributions with calculated data by the methods and with the measured data at *50 m*, with the Eq. (1). Were built the frequency histograms to observe the adjustment of curves to collected data for the 12 sectors and for all data without division. To adjust of Weibull distribution was used the method of Least Squares.

In sequence was calculated the error (RMSE) between the curves of extrapolation methods and the curve of the collected data by Eq. (8).

After was calculated the wind power density by Eq. (9) with the obtained data by the methods of logarithmic Law, Power Law and Weibull Method and compared with wind power density of the measured data, also was calculated the power density of Weibull distribution of the measured data, in order to observe the error of Weibull distribution in relation the measured data, both in approach with and without sectorization. Finally, was calculated the error of the power density with respect collected data. The calculated error is the difference between the measured and extrapolated values in relation at measured.

3. RESULTS AND DISCUSSION

The result of Weibull distributions obtained by approach without sectorization are presented in Fig. 2, and by approach sectored, the Weibull distributions are in Fig.3

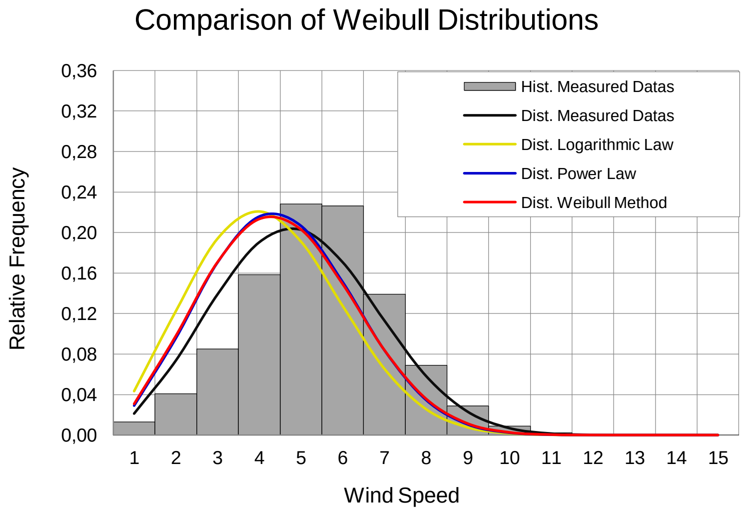

Figure 2: Comparison Chart of Weibull distributions of methods of distribution of measured data of the frequency histogram of all data measured with no sectorization.

On Tab. 2 , are the errors (RMSE) regarding the approach without sectorization. And in Tab. 3 are exposed the error (RMSE) by sectors.

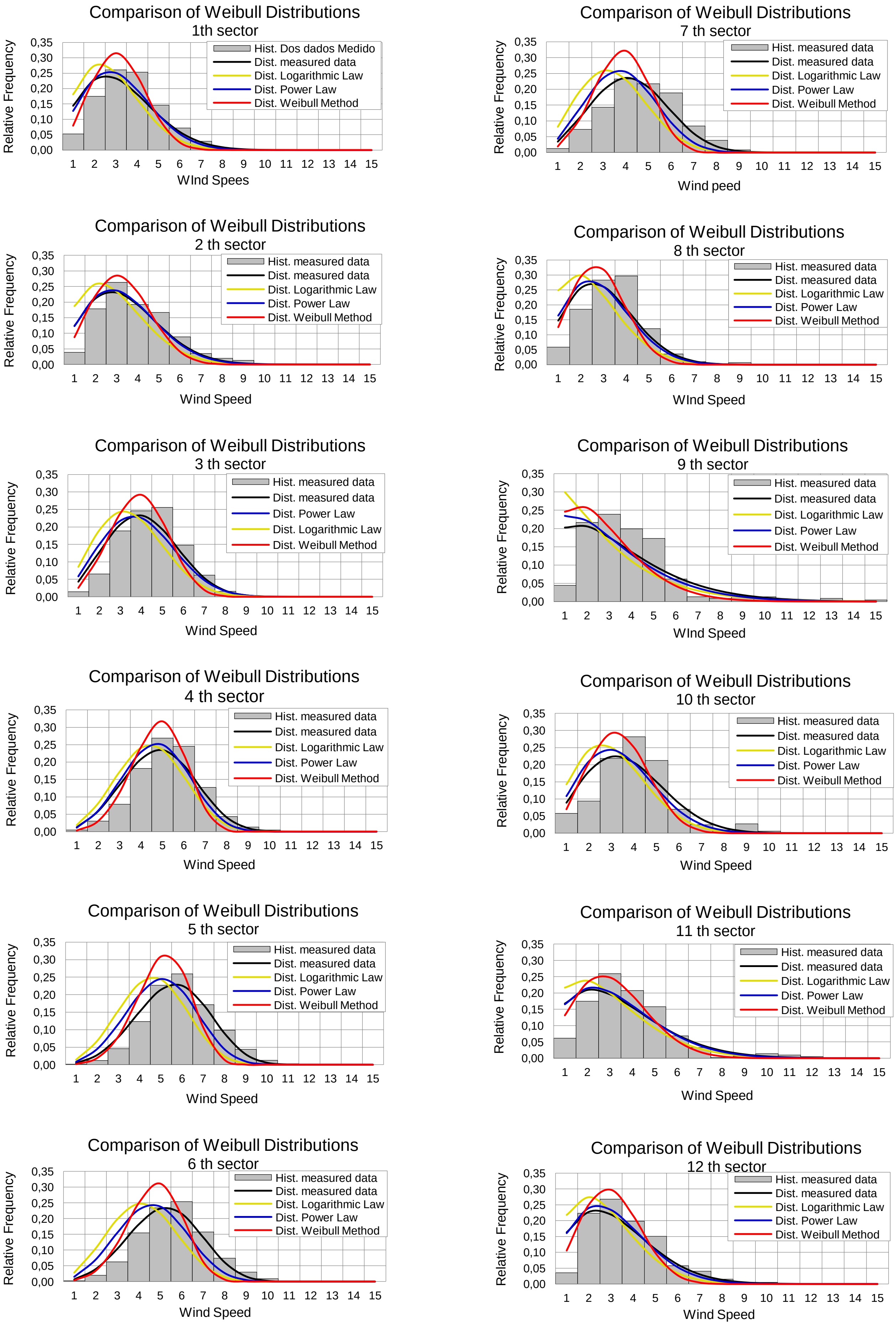

Figure 3: Graphs of the Weibull distribution and frequency histogram of the sectors 12

Table 2: Mean Square Error of the methods without sectorization

Logarithmic Law	Power Law	Weibull Method
0,0249	0,0144	0,0145

Table 3: Mean Square Error of the methods by sector

Sector	Logarithmic Law	Power Law	Weibull Method
1	0,0202	0,0079	0,0330
2	0,0246	0,0027	0,0223
3	0,0282	0,0097	0,0225
4	0,0201	0,0098	0,0300
5	0,0450	0,0262	0,0402
6	0,0482	0,0280	0,0372
7	0,0392	0,0190	0,0346
8	0,0342	0,0073	0,0223
9	0,0287	0,0104	0,0224
10	0,0282	0,0137	0,0277
11	0,0169	0,0030	0,0218
12	0,0231	0,0063	0,0308

In Fig. 2 can up see that the Power Law and Weibull Method presented similar behavior and showed better adjustment the curve of measured data, however the Power Law showed lower RMSE, according to Tab. 2.

In Fig. 3 can up see that the curves relating to methods vary in each sector and that the Power Law fits better in all sectors, in agreement with the Tab. 3, where it is possible to note that the method of Power Law has less error in all sectors. The Logarithmic Law and the Weibull Method showed similar error values, however the Logarithmic Law distanced more of the measured values with the biggest error in the sixth sector.

According to Tab. 2 and 3, and the graphs of Fig. 2 and 3, it can be stated that between tested method the more efficient to extrapolating of profiles of wind speed is the Power Law, since in all the results this method showed a lower error.

By Tab. 3 is observed that on the sectors 5, 6 and 7 occur the biggest errors in all methods. Analyzing Fig. 1 can be see that in the sectors mentioned passes a water body, near the anemometer tower, causing sudden changes in terrain type, which can change the wind speed profile causing the real winds are different from extrapolated data.

The uncertainties of calculation of power density are shown in Tab. 4 to the approach without sectorization and on Tab.5 for sectored approach.

Table 4: Error power density of methods and Weibull distribution with the data measured without sectorization.

Logarithmic Law	Power Law	Weibull Method	Weibull Distribution
0,4661	0,3682	0,3629	0,1684

Table 5: Error power density of the methods and distribution of Weibull on measured data, with sectorization.

Logarithmic Law	Power Law	Weibull Method	Weibull Distribution
0,4737	0,3334	0,4593	0,1727

The fourth column of Tab. 4 and Tab. 5 shows the error of power density of distribution of Weibull measured data with respect the power density of the measured data, to observe if the distribution of Weibull adjusts well in the calculation of power density from the Weibull frequency.

In Tab. 4 and tab. 5 is noted that the error of power density by the two approaches are similar. According to the tables mentioned the method most effective to predict wind power density is the Power Law, since this method showed less uncertainty on results, and the effective least is the Logarithmic Law.

Regarding the Weibull distribution, it is can be pointed out that the curve of the measured data presented good adjustment at the frequency histogram, however when the power density was calculated from the Weibull distribution, the error in relation to the measured data was around 17 % of the actual value, a considerable error in the two approaches developed in this work.

The high error of methods with respect to power density may be a consequence of the discrepancy between the Weibull distribution and the measured data, it is possible that the high error of methods tested be due to probability distribution that was used.

4. CONCLUSION

This work aimed to analyze the methods of vertical extrapolation of wind speed of the Logarithmic Law , Power Law and Weibull Method in order to determine the method that shows less error (RMSE), the end of this work it concluded up that the Power law provides greater accuracy of results and the Logarithmic Law shows higher errors, therefore the method unless indicated for wind resource analysis is the Logarithmic Law.

Also it was noted that the sector approach enables to view errors in wind resource analysis, as noted in the previous section about the sectors 5,6 and 7.

Another objective of this study was the analysis of power density, which was performed, through which it can be noted that the sector approach and without division approach provided similar results. Again the Power Law showed the best adjustment at the measured data, therefore the tested method this work most suitable for wind resource analysis is the Power Law.

Through the power density analysis also observed up that the Weibull distribution, although it has adjusted well to the histogram of the measured data, it did not show the same effectiveness when analyzing the power density.

Finally, concluded up that the most suitable method to extrapolation of wind speed is the Power Law, but should be careful when there is sudden changes of terrain near the analyzed site , since this method does not detect this type of variation.

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