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Potential for wind energy generation in Piracicaba, SP, Brazil

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alternative energy
power density of wind
Weibull distribution function

ABSTRACT
Wind power has gained space in Brazil's energy matrix, being a clean source and inexhaustible. Therefore, it becomes important to characterize the wind potential of a given location, for future applications. The main objective of the present study was to estimate the wind energy potential in Piracicaba, SP, Brazil. The wind speed data were collected by an anemometer installed at the Meteorological Station Luiz de Queiroz College of Agriculture, Piracicaba-SP. The wind speed variability was represented by the Weibull frequency distribution, a probability density function of two parameters (k and c). The parameters k and c were used to correlate the Gamma function with the annual average wind speed, the variance and power mean density. A wind profile was made to evaluate the behavior of historical average speeds at higher altitudes measured by anemometer, to estimate the gain in power density. The values of k for all heights were close to 1 which corresponds to a wind regime highly variable, and c values were also low representing a low average speed of the location. The location was characterized as being unfavorable for the application of wind turbines for power generation.

Palavras-chave:
energia alternativa
densidade de potência dos ventos
função de distribuição de Weibull

Potencial para geração de energia eólica em Piracicaba, SP, Brasil

RESUMO
A energia eólica vem ganhando espaço na matriz energética do Brasil, por ser uma energia limpa e de fonte inesgotável. Portanto, torna-se imprescindível a caracterização do potencial eólico de determinada localidade, para futuras aplicações. O objetivo principal do presente estudo foi estimar o potencial eólico em Piracicaba, SP, Brasil. Os dados de velocidade do vento foram coletados por um anemômetro instalado no Posto Meteorológico da Escola Superior de Agricultura "Luiz de Queiroz", Universidade de São Paulo, Piracicaba-SP. A variabilidade da velocidade do vento foi representada pela distribuição de frequência de Weibull, uma função de densidade de probabilidade de dois parâmetros (k e c). Utilizaram-se os parâmetros c e k para relacionar a função Gama com a velocidade média anual do vento, a variância e a densidade de potência média. Fez-se uma análise do perfil do vento para avaliar o comportamento das velocidades médias históricas em alturas superiores à da medida pelo anemômetro para avaliar o ganho de densidade de potência. Para todas as alturas os valores de k ficaram próximos de 1, o que corresponde a um regime eólico altamente variável enquanto os valores de c também foram baixos representando uma baixa velocidade média do local. A região ficou caracterizada como sendo desfavorável para a aplicação de turbinas eólicas com vista à geração de energia.

Introduction

In response to an enhanced awareness of the negative impacts of large-scale, fossil-fuel intensive energy generations, as well as the realization that the earth's resources are finite, governments, organizations and individuals are showing increasing interest in small-scale, decentralized and low-carbon energy sources (Weekes & Tomlin, 2013).

Renewable energy sources, including hydro, wind, solar, geothermal, biomass, wave and tide, and ocean thermal energy, have attracted increasing attention from all over the world due to their almost inexhaustible and nonpolluting characteristics (Li & Li, 2005). In the later part of 1990s, wind energy was the fastest growing energy technology in terms of percentage of yearly growth of installed capacity per technology source (Ackermann & Soder, 2002); additionally, among all renewable resources, wind is one of the most accessible.

Farret (2010) claims that the Brazilian Wind Power is valued at 63 million MWh year^{-1}. Through laws 10,438/2002 and 10,762/2003, a Program was launched in Brazil to encourage renewable energy sources - PROINFA, which established the purchase of 3,299.40 MW of electrical energy from renewable sources in the integrated national system, being 1,422.92 MW by 54 wind plants, with the goal to increase the electrical energy supply, due to the increasing energy demand.

Therefore, Brazil had an increase of the research investments, development and installation of the electrical generation Wind System. In addition, thanks to technological advances, its costs are continuously being reduced (4 cents kW h^{-1}), making it competitive against other energy sources (Song et al., 2003).

The year of 2011 was marked by the consolidation of the wind energy integration in the Brazilian energy matrix, and at the end of 2012 Brazil had 2.5 GW of installed wind capacity, enough to power four million households and accounting for 2% of national electricity consumption (GWEC, 2012). According to Simas & Pacca (2014) the wind energy sector has witnessed a rapid increase in the number of purchased projects in Brazil, in 2013 the installed capacity was about 5.5 GW, and until the end of 2014 the installed capacity is expected to be around 8 GW.

Wind, as an energy source, is extremely variable; hence, when choosing the place for installation of wind turbines, it is necessary to take into account some criteria, like mean wind speed, daily and seasonal variations, turbulence levels and extreme winds. For this reason, statistical studies are important to know the probability of occurrence of these events (Salami et al., 2013), to ensure that turbines are installed in locations which maximize the financial and environmental benefit (Weekes & Tomlin, 2013).

Over the last two decades, many researchers have devoted to develop an adequate statistical model to describe wind speed frequency distribution (Li & Li, 2005). In recent years, most attention has been focused on Weibull method for wind energy applications, not only due to its greater flexibility and simplicity but also because it can provide a good agreement with experimental data (Lun & Lam, 2000). In the energy field, the wind speed distribution is ultimately used to estimate the wind energy output. Wind power density (WPD) is an important parameter in the study of viability of wind energy expressed in W m^{-2} and it takes into account the frequency distribution of the wind speed and the dependence of wind power on air density and the cube of the wind speed (Al-Nassar et al., 2005);

Wind measurements are generally performed below Wind Turbines (WT) hub heights owing to the economic unfeasibility of using various anemometric towers to map each space and height of the spot (Atlas, 2012). Therefore, a wind shear model proves to be necessary to extrapolate the observed wind resource from the available lower heights to the WT hub height (Gualtieri & Secci, 2014). Many recent studies make use of data from a single anemometer tower to characterize a particular region (Al-Nassar et al., 2005; Shata & Hanitsch, 2006; Ben Amar et al., 2008; Mostafaeipour et al., 2013). Given the above, the application of wind energy can be promising for the generation of the power required in the operation of pumps of which the water pumping for irrigation systems is not grid-connected. For the application of this technology, it is important research focused on this area, and therefore the local characterization of wind potential is essential. It is believed that future studies applied to water pumping for wind-powered irrigation may be developed in the Piracicaba region through research centers.

Thus the main purpose of this article is to estimate the wind energy potential in Piracicaba-SP, Brazil, through: a) identification of the meteorological parameters of Piracicaba site (statistical characteristic of wind speeds); b) Weibull shape factor, investigated by examining the effect of the assumed shape of the wind speed probability distribution on the predicted wind resource; and c) calculating the wind power density and assess whether Piracicaba is a good place to install a small wind turbine.

Material and Methods

The wind data were obtained from the Weather Station of the Department of Biosystems Engineering, located at Luiz de Queiroz College of Agriculture (ESALQ-USP), in Piracicaba-SP, Brazil, (22° 42' 30" S; 47° 38' 00" W; 546 m). As the average altitude of Piracicaba is approximately 547 m, it was considered that the wind speed measurements of the tower installed at 546 m altitude represents the wind conditions of the region, which according to Wind Atlas of the State of São Paulo has altitudes between 400 and 800 m.

The instantaneous wind speed was measured with an anemometer (RM Young Wind Monitor) connected to a CR510 data logger (Campbell Scientific), installed in a 10-meter-high tower . Wind speed records from 2012 were used for the analyses, with 366 days in total. For the simulations, hourly means were used, thus each mean was composed of four samples. According to Mostafaeipour et al. (2013) one year of wind speed data is sufficient to represent the long-term variations in the wind profile within an accuracy level of 10 percent.

In order to characterize the regime of wind speed, the values were set in a decreasing order and divided into classes of 1 m s^{-1}, being the minimum interval equal to 0-1 m s^{-1} and the maximum to 8-9 m s^{-1}. According to the methodology proposed by Gabriel Filho et al. (2011), a wind speed vertical profile was made from the wind speed data for the height of 10 m, composing a speed profile with 6 heights: 15, 20, 25, 30, 40 and 50 m; due to the common heights of wind turbines from 30 to 50 m above the ground level (Shata & Hanitsch, 2006).

In the turbulent regime, at higher altitudes the mean speed tends to increase, as nearest the ground there is a tangential force against the displacement of the air parcel delaying the movement. For projects involving wind conversion system, it is required to estimate Wind speeds at various elevation (Safari & Gasore, 2010). For this, it uses the Logarithmic Law, which is the simplest way to estimate the wind speed at an elevation from measurements on a reference level. A practical simplification showed by Castro (2004) and Farret (2010) was used.

$$\frac{u_1}{u_2}=\frac{\ln\left(\frac{h_1}{h_0}\right)}{\ln\left(\frac{h_2}{h_0}\right)} \quad (1)$$

in which:

u_1 - wind speed at height h_1
u_2 - wind speed at height h_2
h_0 - characteristic length of soil roughness

The h_0 values were defined according to Hassan & Sykes (1990), who adopted the minimum value to the classification "low grass/steppes", with h_0 equal 0.01; and in accordance with the local vegetation.

The Weibull distribution with two parameters, Eq. 2, was used to describe the wind behavior.

$$f(v)=\frac{k}{c}\left(\frac{v}{c}\right)^{k-1}\exp\left[-\left(\frac{v}{c}\right)^{k}\right] \tag{2}$$

where k is the shape parameter (dimensionless) and c (m s^{-1}) is the scale parameter having the dimension of speed. For each location the distribution parameters k and c will take on different values, and can be determined by several different methods.

In order to quantify the wind power to energy generation, it was determined the average wind power density in terms of wind speed as follows:

$$WPD=\frac{\sum_{i=1}^{N}\frac{1}{2}\rho v_i^{3}}{N} \tag{3}$$

where i is the measured hourly wind speed and N is the total sampled data used for 1 year.

For the calculation of scale parameter "c" and shape "k", it was applied the regression method, which consists in linearization of Weibull Cumulative Distribution Function, Eq. 4, given by the expression:

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

The result of linearization is hereinafter:

$$Y=kX-k\ln c \tag{5}$$

Where Y and X are described by the expression:

$$Y=\ln\left\{-\ln\left[1-F(v)\right]\right\} \tag{6}$$

$$X=\ln v \tag{7}$$

Plotting different values of Y versus X, a straight line with slope a = k and linear coefficient b = - k ln c, is obtained. Isolating the parameter "c" it has the expression:

$$c=\exp\left(\frac{-b}{a}\right) \tag{8}$$

The determination of the Weibull Cumulative Probability Function was performed using numerical methods applied to discrete frequency distribution of velocities, when v_0 was the maximum speed in this distribution. It was calculated

$$F(v)=\int_0^u f(t)\,dt$$

by trapezoidal integration method (Gabriel Filho et al., 2011), as follows:

$$F(v_0)=\frac{f(v_0)}{2} \tag{9}$$

$$F(u_i-\Delta u)+\Delta u\frac{(u_i-\Delta u)+f(u_i)}{2}\quad i=1,\ldots,n \tag{10}$$

where it was considered the partition {0, u_0, ..., one} with consecutive points distant from each other Δu.

The degree of adjustment of series observed in the Weibull model was verified by the residual error calculated by:

$$E^2=\sum_{i=1}^{N}\left[F_{obs}(u_i)-F_{calc}(u_i)\right]^2 \tag{11}$$

where:

F_{obs} - cumulative probability observed

F_{calc} - cumulative probability calculated by Weibull model

The F_{obs} value was achieved by the trapezoidal integration method, Eq. 10, whereas F_{calc} was achieved by the Weibull Cumulative Probability Function F(v).

After determining the parameter k, it is necessary to calculate the Gamma Function value (Celik, 2004) that can be used in the probability density distribution equation. The function is calculated as follows:

$$\Gamma(x)=\int_0^{+\infty} t^{x-1}\exp(-t)\,dt \tag{12}$$

$$\Gamma(1+x)=x\Gamma(x) \tag{13}$$

Gamma Function is complex but it is necessary to know their values only over a fairly narrow range of values, corresponding to the standard deviation of the wind, respectively at 20 and 100% of average speed. The characterization of the site according to the wind regime correlated to the Gamma function with annual average wind speed, the variance and mean power density, was performed as follows:

- Annual average wind speed:

$$u_{aa}=c\Gamma\left(1+\frac{1}{k}\right) \tag{14}$$

- Variance of the wind speed frequency:

$$\sigma^2=c^2\left[\Gamma\left(1+\frac{2}{k}\right)-\left(\Gamma\left(1+\frac{1}{k}\right)\right)^2\right] \tag{15}$$

- Mean power density of the wind:

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

To calculate the average power density P_m, the air density equal to 1.12 kg m^{-3}, for an altitude of 546 m and an annual average temperature of 22.4 °C was used.

Results and Discussion

The data totalized 8,784 h of recordings, being established classes of 0-1, 1-2, 2-3, 3-4, 4-5, 5-6, 7-8 m s^{-1}. It is represented in Figure 1 the data of hourly wind speeds observed in Piracicaba in the form of a histogram, at the height of 10 m.

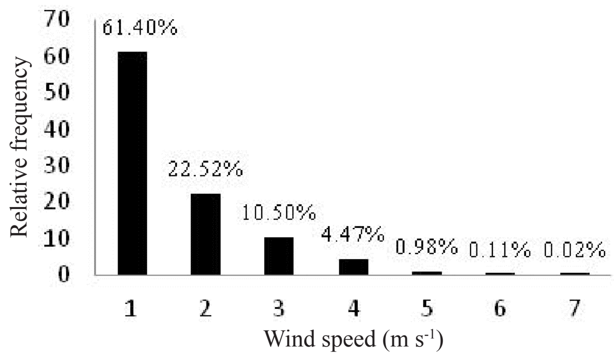

Figure 1. Relative frequency of occurrence of wind speed at the height of 10 m from the ground

The analysis of this histogram clearly reveals that wind speeds around 0-1 m per second, are important (61.40%). According to Halacy (1977) there is a scale for range of winds called "Beaufort scale", and it classified winds between 0-1 m per second (or 0-3 miles an hour) as calm and light air. Furthermore the best range for wind speed is between 3 to about 10 m s^{-1} (or 7 to 24 mph); this is the dominant wind range to engineer applications. Goswami (1986) claims that only sites that have an annual average wind speed in excess of 5 m s^{-1} at a 10-m height should be considered for wind power.

Because the average speed at the 10-m height of the hub turbine was below the indicated value for electrical energy generation, the speed was extrapolated to greater heights, in order to achieve speed ranges within the acceptable. The statistical parameters to the other heights can be seen in Table 1.

Table 1. Statistical Parameters of wind speed for different heights

	Height (m)						
	10	15	20	25	30	40	50
Average	1.039	1.100	1.143	1.177	1.204	1.247	1.281
SD*	0.793	0.837	0.854	0.875	0.900	0.962	0.986
Variance	0.629	0.701	0.729	0.766	0.810	0.926	0.972

* Standard Deviation

According to Weekes & Tomlin (2013), the distribution is defined by a mean wind speed and a shape factor (k), which describes the spread of wind speeds about the mean. Due to the non-linear relationship between wind speed and wind power, the value of k will impact on the predicted power in the wind. Table 2 shows the calculated values of the k and c parameters by regression method for all heights.

Table 2. Values of the two parameters of the Weibull distribution to the heights of 10, 15, 20, 25, 30, 40 and 50 m hub turbines

	Height (m)						
	10	15	20	25	30	40	50
k	1.239	1.232	1.237	1.234	1.228	1.204	1.203
c	1.197	1.248	1.283	1.308	1.333	1.370	1.400

Gabriel Filho et al. (2011) calculated the parameters k = 2.053 and c = 3.132 for a town 115 km (Botucatu, SP) away from Piracicaba. Botucatu located in the Western Plateau of São Paulo has higher altitudes than Piracicaba, reaching close to 900 m (Atlas, 2012). Comparing those values (measured at the 14 m height) with this paper (at the 15 m height), it can be noted that the value of the "available wind" measured in Piracicaba, represented by c, is less than half of it, and the k value was also lower.

The shape parameter k shows the skewness rate of the Weibull curve. Higher k values (between 2 and 3) mean the curve is more skewed toward higher wind velocities, and k lower values (between 1 and 2) mean the curve is more skewed toward lower wind velocities, thus indicating that lower wind velocities are more probable to happen. The scale parameter c shows the peak value of the Weibull curve. In fact, higher values for c mean the distribution is spread over a wider range (Mostafaeipour et al., 2011b).

Analyzing k and c values for Piracicaba, it can be realized that shape parameter values were near 1, for all heights, showing that the low speed wind is prevailing, which can be confirmed in Table 1 by the average speed of wind. Observing the values of scale parameter that is also related to the "available wind" in the region, it can be noted that it was also low and near 1, which means that speed values are more concentrated in one speed range (Figure 2).

Confronting the values obtained at all heights in Piracicaba with the values of Wind Atlas of the State of São Paulo (at 100 m height), it notes that the region in fact is located where there are low values of k, characterizing the region as having low wind potential.

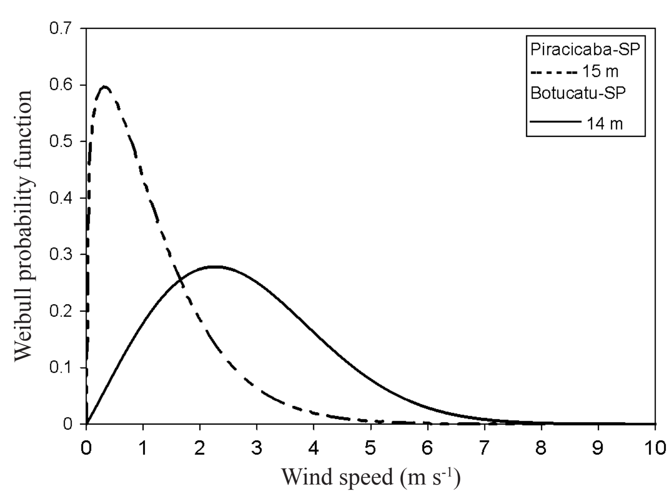

Figure 2. Comparison between scale and shape parameter values for Piracicaba and Botucatu, SP

While it is working with wind speed data in time-series format usually the data is arranged in the frequency distribution since it is more convenient for statistical analysis (Celik, 2004). This process is illustrated as an example in Table 3. The wind speed is grouped into classes (bins) as given in the second column of Table 3.

Table 3. Arrangement of the estimated hourly time-series data in frequency distribution format for 50 m and the probability distribution calculated from the Weibull function (fw(u_j))

j	u_j	u_{mj}	f_j	f(u_j)	fw(u_j)	E_r*
1	(0-1)	0.5	4851	0.5523	0.59881	0.00013
2	(1-2)	1.5	1960	0.2231	0.29112	0.00489
3	(2-3)	2.5	1022	0.1163	0.10220	0.00701
4	(3-4)	3.5	606	0.0690	0.03050	0.00260
5	(4-5)	4.5	252	0.0287	0.00813	0.00037
6	(5-6)	5.5	74	0.0084	0.00199	2.55E-05
7	(6-7)	6.5	16	0.0018	0.00045	9.26E-07
8	(7-8)	7.5	2	0.0002	0.00010	2.82E-08
9	(8-9)	8.5	1	0.0001	0.00002	2.05E-09
						0.01503

*Residual error

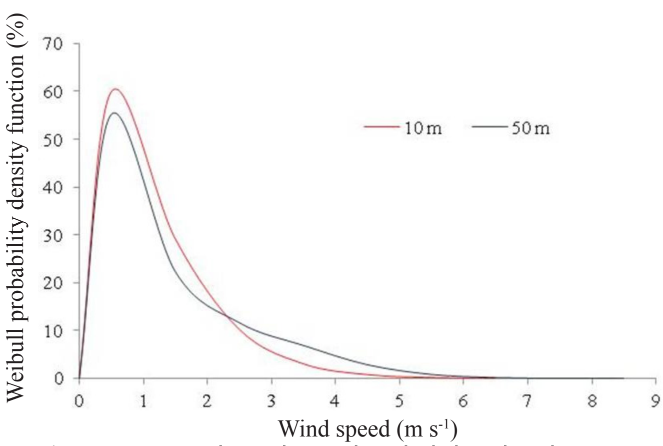

Figure 3. Annual wind speed probability distributions calculated from the Weibull function, for 10 and 50 m heights

The mean wind speeds are calculated for each speed class interval (the third column). The fourth column gives the frequency of occurrence of each speed class. The probability density distribution is presented in the fifth column (Table 3). The annual probability density derived from the time-series data of Piracicaba is presented in Figure 3.

The degree of fit of the observed series in the Weibull model was verified by residual error; it was equal to 0.12, 0.278, 0.486, 0.67, 0.866, 1.185 and 1.503% for the simulated heights of 10, 15, 20, 25, 30, 40 and 50 m, respectively.

The wind speed distribution predominantly determines the performance of wind power systems. Once the wind speed distribution is known, the wind power potential and, hence, the economic viability could be easily obtained (Zhou et al., 2006). Wind power density is generally considered a better indicator of the Wind resource than Wind speed (Al-Nassar et al., 2005). The calculated values of power density (Eq. 12) can be viewed in Figure 4.

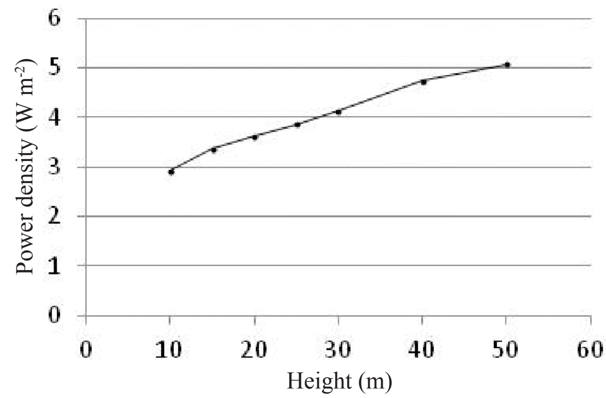

Figure 4. Calculated values of power density for all hub turbine heights

As the yearly average wind power density values are between 2.92 and 5.07 W m^{-2}, it indicates that this particular site corresponds to the wind power class of 1, since the density value is less than 100 W m^{-2}. It is observed that the gain of power density, at the height of 50 m, was of 42.4% when compared to the 10 m height; however, for this height this power density is very small and not worth the investment in a wind turbine. This pattern is confirmed in the Wind Atlas of the State of São Paulo, which shows that for the region of Piracicaba the power density does not exceed 100 W m^{-2} at 100 m height. Therefore, this site is not ideal for grid-connected applications. This level of power density may be adequate for non-connected electrical and mechanical applications, such as battery charging and water pumping (Celik, 2004).

When comparing the values of mean wind speed at 30 m height, of this paper, with the table of the Al-Nassar et al. (2005), where the wind power density is smaller than 100 W m^{-2}, and this way classified as a fair wind for energy generation, the power density in Piracicaba, for all heights, is classified as a poor density because it is less than 100 W m^{-2} (Mirhosseini et al., 2011a). A classification made by the European Wind Energy Association (EWEA) starts the classes with a speed over 6.5 m s^{-1} and for this speed the wind is considered fairly good (Garrad, 1991); it means that the location of our studies does not fall into any classification, according to that study. It should be noted that this classification takes into account the capacity of power generation from the current technologies. It is expected that over the years it is possible to produce more power with a lower density wind.

Applying the current technology for small turbines, according to Urtasun et al. (2013) for small wind generation (less than 100 kW), a Permanent Magnet Synchronous Generator (PMSG) is preferred because of its reliability, high efficiency and low cost. As described by Whale et al. (2013), small wind turbines (SWTs) have a swept area less than 200 m^2, and the power capacity of such a machine is typically less than 50 kW.

Considering the simulated speed for a 20 m height, the power generated was calculated for a easily accessible commercial turbine in Brazil, the Verne 555 with 5.55 m of diameter of the rotor and 24.2 m^2 of swept area. The speed data higher than 3 m s^{-1} correspond to 610 h, out of 8,784 measured hours; it represents 6.9% of the total hours, or approximately 25 days a year. When the generated power is calculated during effective hours (> 3 m s^{-1}) by Eq. 2, with total of the 610 h, the wind turbine power is equal to 0.82 kWh year^{-1}. This potential for wind power generation is far below that found in favorable regions to that purpose (Ben Amar et al., 2008; Atlas, 2012). Furthermore, only the places where the turbines produce energy at least in 50% of the time are suitable for electric power generation (Goswami, 1986).

Conclusions

1. Weibull model was adequate for the distributions obtained, showing small residual errors for measurement and simulated heights. Systematic methods, such as the trapezoidal integration and linear regression, to determine the values of k and c could characterize the wind regime of Piracicaba.

2. Analyzing the values found for wind power density, it can be noted that the chosen place is not technically feasible for the installation of small wind turbines.

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