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Análise da velocidade do vento com base no modelo logarítmico de cisalhamento do vento: um estudo de caso para algumas cidades brasileiras

Wind speed analysis based on the logarithmic wind shear model: a case study for some brazilian cities

Análisis de la velocidad del viento basado en el modelo logarítmico de cizalladura del viento: un estudio de caso para algunas ciudades brasileñas

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Resumo

A participação da energia eólica na geração de eletricidade tem apresentado um importante crescimento nos últimos anos. Devido a variabilidade na geração de energia eólica, dado às variações na velocidade do vento e considerando o aumento da participação eólica na matriz energética brasileira, fato que reforça a relevância da fonte, este artigo objetiva apresentar os métodos utilizados para analisar a velocidade do vento mais utilizados na literatura e analisar a velocidade do vento em várias cidade Brasileiras. O modelo logarítmico de cisalhamento do vento foi utilizado para analisar a velocidade média do vento a partir de dados históricos de doze cidade brasileiras disponíveis publicamente no banco de dados ESRL para um período de 8 anos 2010 à 2018. O estudo mostrou que localidades como, Uruguaiana/RS, Campo Grande/MS, Uberlândia/MG, São Luiz/MA e Corumba/MS são cidade que apresenta velocidade média do vento alta em todas as alturas de referência e possui um ganho de ± 2m/s de velocidade do vento com o aumento da altitude de operação. O ganho logarítmico do vento com altitude ou em baixa altitude pode ser notado, em z = 100m tivemos Wn ≈ 8 m/s em Uruguaiana/RS e Campo Grande/MS, enquanto em Manaus a velocidade média do vento é de Wn ≈ 5 m/s. Já as cidades de Porto Alegre, Florianópolis, Curitiba e Brasília, a velocidade média do vento na faixa de altitude ≥ 250 m, se torna significativa, possibilitando sua implantação caso a tecnologia seja economicamente viável.

Palavras-chave: Análise da velocidade do vento; Energia eólica; Energia eólica aerotransportada; Modelo logarítmico do vento; Matriz energética brasileira.

Abstract

The wind power' share in electricity generating capacity has increased significantly in recent years. Due to the variability in wind power generation, given the variations in wind speed and considering the increase in wind participation in the Brazilian energy matrix, a fact that reinforces the relevance of the source, this article aims to present the methods used to analyze the wind speed more used in the literature and to analyze the wind speed in several Brazilian cities. The logarithmic wind shear model was used to analyze mean wind speeds based on historical data of twelve Brazilian cities available to the public on the ESRL database for a period of eight years 2010 to 2018. The study showed that in localities such as Uruguaiana/RS, Campo Grande/MS, Uberlândia/MG, São Luiz/MA and Corumba/MS, mean wind speeds are strong in all altitudes of reference, with a gain of ± 2m/s of wind speed as the operational altitude increases. The logarithmic wind gain in high altitudes or low altitudes can be seen in z = 100 meters, where the mean wind speed found was Wn ≈ 8 m/s in Uruguaiana/RS and Campo Grande/MS, whereas in Manaus it was Wn ≈ 5 m/s. In Porto Alegre (RS), Florianópolis (SC), Curitiba/PR and Brasília/DF, the mean wind speed in altitudes ≥ 250 m becomes significant, allowing the implementation of wind farms if the technology proves to be economically feasible.

Keywords: Wind speed analysis; Wind energy; Airborne wind energy; Logarithmic wind model; Brazilian energy matrix.

Resumen

La participación de la energía eólica en la generación de electricidad ha crecido significativamente en los últimos años. Debido a la variabilidad en la generación de energía eólica, dadas las variaciones en la velocidad del viento y considerando el aumento en la participación del viento en la matriz energética brasileña, un hecho que refuerza la relevancia

de la fuente, este artículo tiene como objetivo presentar los métodos utilizados para analizar la velocidad del viento más utilizado en la literatura y para analizar la velocidad del viento en varias ciudades brasileñas. El modelo logarítmico de cizalladura del viento se utilizó para analizar la velocidad media del viento a partir de datos históricos de doce ciudades brasileñas disponibles públicamente en la base de datos ESRL durante un período de 8 años entre 2010 y 2018. El estudio mostró que localidades como Uruguaiana / RS, Campo Grande / MS, Uberlândia / MG, São Luiz / MA y Corumba / MS son ciudades que presentan una velocidad del viento promedio alta en todas las alturas de referencia y tienen una ganancia de ± 2m / s de velocidad del viento con el mayor altitud de operación. La ganancia de viento logarítmica con altitud o baja altitud se puede notar, a z = 100m tuvimos Wn ≈ 8 m / s en Uruguaiana / RS y Campo Grande / MS, mientras que en Manaus la velocidad promedio del viento es Wn ≈ 5 m / s. Por otro lado, las ciudades de Porto Alegre, Florianópolis, Curitiba y Brasilia, la velocidad media del viento en el rango de altitud ≥ 250 m, se vuelve significativa, lo que permite su implementación si la tecnología es económicamente viable.
Palabras clave: Análisis de la velocidad del viento; energía eólica; energía eólica en el aire modelo de viento logarítmico; matriz energética brasileña.

1. Introduction

The efforts to reduce the environmental impacts of energy resources and the increasing demand for energy make that renewable resources become the subject of many research studies. The most accepted and promising source of renewable energy is wind power, which by nature is a clean, inexhaustible and cost-effective source (Rasham, 2016; Souloukngа, Doka, Revanna, Djongyang, & Kofane, 2018). Wind power is the most growing renewable source of energy in developed and developing countries such as PR China, USA, Germany, Brazil, India, Canada, Poland, France, United Kingdom, and Turkey (GWEC, 2014).

The global cumulative installed capacity of wind power rose from 17,400 MW in 2010 to 432,883 MW in 2015 (GWEC, 2014). In South America, Brazil was the country that invested most on clean energy in 2017, with total investments of 6.2 billion dollars, a 10% increase from the previous year. Such growth is due in part to the resumption of auctions in the electrical power sector, where new projects of wind and solar power have been contracted (Bloomberg, 2018).

Wind power is an important source of renewable energy. However, wind systems using classic wind turbines (towers and blades) have physical and economic constraints.

Therefore, a new concept in wind power, named Airborne Wind Energy (AWE) has been explored.

Airborne wind energy is an innovative technology of renewable energy that uses aerial devices that extract the kinetic energy of wind and are sustained in the air by aerodynamic forces. Such devices, called actuated tethered airfoils, in some cases use wings similar to those of a paraglider or kitesurf or similar to a balloon or airplane wings. In literature, among the possibilities of use of wind energy with tethered airfoils, a configuration named pumping kite has stood out from others for its simplicity and low-cost investment (Mendonça, Vaz, Lezana, Anacleto, & Paladini, 2017). Airborne wind energy has the potential to overcome some of the classic technology limitations, using flying tethered wings or other devices that enable to reach higher altitudes, e.g., 600 meters high or more, where winds are stronger and more stable (Archer, Delle Monache, & Rife, 2014). Because the airborne wind energy technology does not require towers, transportation and installation costs are considerably lower (De Lellis, Mendonca, Saraiva, Trofino, & Lezana, 2016).

The focus of this research is to develop a wind model for different operational altitudes, considering the altitudes of operation of a classic wind technology and for higher altitudes, where the airborne wind energy operates.

This paper provides an overview of current methods and recent advances in wind power. The article has four sections. Section 2 presents a review of renewable energy sources explored worldwide, analyzes the Brazilian renewable energy sector, examines the main prediction methods and presents a description of the Numerical Weather Prediction, Logarithmic Wind Shear Model and Weibull Probability Distribution methods. Section 3 describes the research methodology used for wind speed analysis based on the logarithmic wind shear model. Section 4 presents the wind model and wind histogram for twelve Brazilian cities. Finally, Section 5 presents the conclusion.

2. Contextualization

Today, many countries utilize renewable energy sources for two main reasons: because of depletion of fossil fuel reserves and environmental issues. Renewable energy sources are clean, inexhaustible energy resources and had the highest growth rate of any other energy source in 2017.

The energy sector played a key role in the growth of low-carbon energy with the production of renewable electric power growing by 6.3% in 2017. Renewable energies such as photovoltaic solar energy, wind power, hydroelectricity and bioenergy account today for 25% of the world's electricity generation, which meets a quarter of the global energy demand (IEA, 2018).

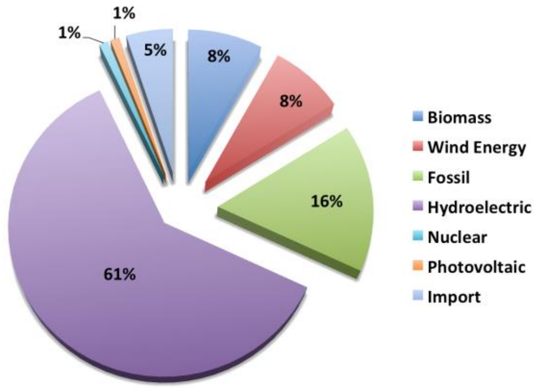
China and the United States together account for half of the increase of electricity generation from renewable sources, followed by the European Union with 8% of increase, and Japan and India with 6% each. China accounts for 40% of the combined growth of wind energy and photovoltaic solar energy (IEA, 2018). Sources that do not depend on fossil fuels for extraction or use contribute to the reduction of global warming and air pollution, and can also be used in remote, isolated communities to meet small demands (Mostafaeipour, Sedaghat, Dehghan-Niri, & Kalantar, 2011; Oyedepo, Adaramola, & Paul, 2012; Paul, Adaramola, & Oyedepo, 2015; Rasham, 2016).

Due to the stochastic nature of wind, in many locations, wind speeds are not reliable as a source of wind power (Souloukngа et al., 2018). However, the periods of strong winds often coincide with periods of lower volume of water in the reservoirs of hydroelectric plants. Therefore, to generate electricity, its use should be combined with other source such as hydroelectricity, increasing the total production of energy in the country (Silva, Zaparoli, & Fisch, 2016).

2.1. Wind power in Brazil

The Brazilian energy matrix is composed of more than 78% of energy from clean sources, and over 60% of energy comes from hydroelectric plants, as shown in Figure 1. A clean energy matrix is the aspiration of the world population and the objective of many countries. However, global climate problems, including those that hit Brazil particularly in 2013 and 2014, when the center-southern region of the country faced the most severe drought in its history, are of great concern. Because of lack of rainfalls, the water level in the reservoirs fell dramatically; making that the hydroelectric plants stopped generating power. This prompted an alert relating to the Brazilian energy matrix.

Figure 1. Brazilian electric power matrix in percentage of generated power.



Source: (ANEEL, 2018).

Through the Program of Incentives for Alternative Electricity Sources (PROINFA), the alternative sources that were still not significant had opportunities to expand. Since then, the wind energy has exhibited a considerable growth in the Brazilian electricity system. In 2018, Brazil reached a total of 13 GW of installed capacity of wind power in 542 plants, producing 13,311 GW of power, with 80% of the production chain supplied by the domestic market (ANEEL, 2018).

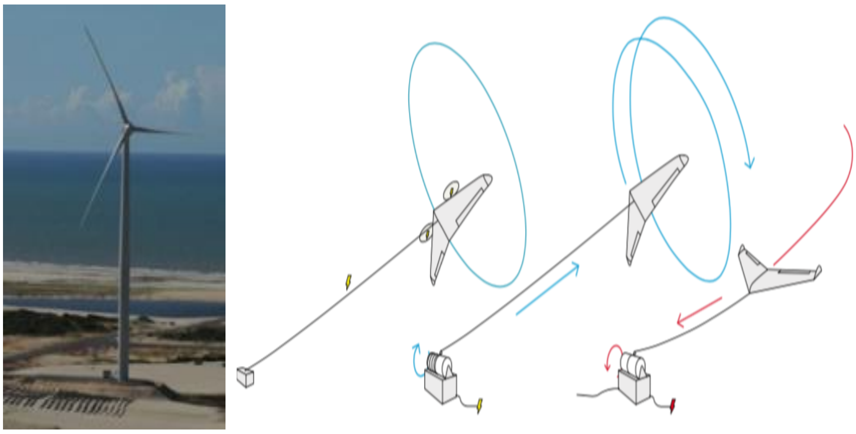
According to (Amarante, Brower, Zack, Eolica, & Solutions, 2001), the wind power capacity in Brazil is of 143 GW, according to data found in the Atlas of Brazilian Potential Wind Power. However, the data used as reference in the atlas are from 2001, which are outdated, with measurements at 50m high. According to (Witzler, 2015), estimates of the Brazilian potential would be different if measurements of wind speeds were taken at heights over 100 meters.

2.2. Wind turbines

Conversion of the kinetic energy of the wind into electric power is achieved with a generator. In the classic horizontal-axis wind towers, the wind pushes and turns the blades of the turbine, causing the generator to work, resulting in mechanical energy. This mechanical energy is converted into electricity by means of an electrical generator that exists inside the nacelle.

In the airborne wind energy systems, energy can be generated in two ways: on the ground (lift mode) or on-board (drag mode). In the systems with the ground-based generator (lift mode), electric power is produced on the ground by mechanical work done by the wind traction force, which is transmitted from the aircraft to the on-ground generator through one or more connection cables. When wind pushes the aircraft, the cable traction force makes the generator to work by producing a rotational motion. In the drag mode system, using on-board generator, electricity is produced in the aircraft and transmitted to the ground via a special cable with twofold purposes: keep the aircraft at controlled height and accommodate the electric cables that transmit energy to the ground. The systems with on-board generators produce electricity continuously during the operation, except during takeoff and landing maneuvers, when energy is consumed (Cherubini, Papini, Vertechy, & Fontana, 2015). Figure 2 shows two modes of wind power generation, one via classic wind towers (WTs) and the other via tethered airfoils in pumping kite (PK) mode.

Figure 2. The basic idea of wind energy is exemplified using a classic tower and wing tied to a cable to replace the wind turbine blades, producing electricity in the drag mode (in the middle) or in the lift mode (on the right).



Source: Adapted from (Zillmann & Bechtle, 2018).

The basic concept of the airborne wind energy using tethered airfoils is to replace wind turbine towers with cables, and the blades for tethered airfoils like a kite or airplane wing (Archer et al., 2014; Cherubini et al., 2015; Fagiano & Milanese, 2012). The airfoil is connected to the ground by one or more cables whose role is to transfer energy to the ground, either mechanical, when the generator is on the ground, or electrical, when the generator is on board. The airfoils extract energy from the wind at high altitudes, where winds are stronger and more frequent and inaccessible for classic wind turbines.

2.3. Current forecasting & prediction methods

Forecasting wind power production has played a key role in tackling the challenges of balancing supply and consumption of energy in an electrical system, given the uncertainties of wind energy production. Wind speed is a key variable when the energy output capacity of a wind farm is estimated: when it is known, it reduces the project risks (uncertainties) and enables a suitable planning of the electrical system balance. However, wind prediction based on measurements is a complex problem due to the stochastic nature of wind.

Table 1 describes the articles that compose this literature review portfolio and which deal with wind speed models.

Table 1. Studies discussing wind speed models.

Title	Journal	Author
The characteristics of wind velocity that favor the fitting of a weibull distribution in wind-speed analysis	Journal of Climate and Applied Meteorology	(Tuller & Brett, 1984)
Meteorological and oceanographic surface roughness phenomena in the English Channel investigated using ERS synthetic aperture radar and an empirical model of backscatter	Journal of Geophysical Research-Oceans	(Scoon & Robinson, 2000)
Hourly wind speed analysis in Sicily	Renewable Energy	(Bivona, Burlon, & Leone, 2003)
Wind speed analysis in La Ventosa, Mexico: a bimodal probability distribution case	Renewable Energy	(Jaramillo & Borja, 2004)
Analysis of height variations of sodar-derived wind speeds in Northern Spain	Journal of Wind Engineering and Industrial Aerodynamic	(Perez, Garcia, Sanchez, & de Torre, 2004)
Effects of air-sea interaction parameters on ocean surface microwave emission at 10 and 37 GHz	IEEE Transactions on Geoscience and Remote Sensing	(Aziz et al., 2005)
Design of an offshore wind farm on Lake Michigan: Part 1	38th Annual North American Power Symposium	(Wilson, Morcos, & IEEE, 2006)
Large scale modulations of spectral aerosol optical depths by atmospheric planetary waves	Geophysical Research Letters	(Beegum, Moorthy, Babu, Reddy, & Gopal, 2009)
Wind speed analysis in the province of Alicante, Spain. Potential for small-scale wind turbines	Renewable & Sustainable Energy Reviews	(Cabello & Orza, 2010)
Mapping of Annual Extreme Wind Speed Analysis from 12 Stations in Peninsular Malaysia	Selected Topics in System Science and Simulation in Engineering	(Razali, Sapuan, Ibrahim, Zaharim, & Sopian, 2010)

Analyzing potential evapotranspiration and climate drivers in China	Chinese Journal of Geophysics - Chinese Edition	(Xu & Levy, 2011)
Weibull Parameters Estimation Using Four Different Methods And Most Energy-Carrying Wind Speed Analysis	International Journal of Green Energy	(Bagiorgas, Giouli, Rehman, & Al-Hadhrami, 2011)
An Overview: the Development of Prediction Technology of Wind and Photovoltaic Power Generation	Proceedings of International Conference on Smart Grid and Clean Energy Technologies -ICSGCE	(Zheng, Chen, Huo, & Zhao, 2011)
Current methods and advances in forecasting of wind power generation	Renewable Energy	(Foley, Leahy, Marvuglia, & McKeogh, 2012)
Optimization of airborne wind energy generators	International Journal of Robust and Nonlinear Control	(Fagiano, Milanese, & Piga, 2012)
Orbit Control for a Power Generating Airfoil Based on Nonlinear MPC	American Control Conference	(Gros, Zanon, Diehl, & IEEE, 2012)
Rotational Start-up of Tethered Air- planes Based on Nonlinear MPC and MHE	European Control Conference (Dedecca, Hakvoort, & Ortt)	(Zanon, Gros, Diehl, & IEEE, 2013)
On Real-Time Optimization of Airborne Wind Energy Generators	IEEE 52nd Annual Conference on Decision and Control	(Zgraggen, Fagiano, Morari, & IEEE, 2013)
Direct feedback control design for nonlinear systems	Automatica	(Novara, Fagiano, & Milanese, 2013)
Long-Term Wind Speed Analysis and Detection of its Trends Using Mann-Kendall Test and Linear Regression Method	Arabian Journal for Science and Engineering	(Rehman, 2013)
Guishan Off-Shore Wind Power Farm Interconnection: A Real Project Study	IEEE Pes Asia - Pacific Power and Energy Engineering Conference	(Li, Chen, Yang, Guan, & IEEE, 2013)
Simplified method to derive the Kalman Filter covariance matrices to predict wind speeds from a NWP model	6th International Conference on Sustainability in Energy and Buildings	(Lynch, Omahony, & Scully, 2014)
A spatio-temporal dynamic regression model for extreme wind speeds	Extremes	(Mahmoudian & Mohammadzadeh, 2014)
Airborne wind energy: Optimal locations and variability	Renewable Energy	(Archer et al., 2014)
Airborne Wind Energy: Airfoil - Airmass Interaction	The International Federation of Automatic Control (IFAC)	(Zanon, Gros, Meyers, & Diehl, 2014)
Real-Time Optimization and Adaptation of the Crosswind Flight of Tethered Wings for Airborne Wind Energy	IEEE Transactions on Control Systems Technology	(Zgraggen, Fagiano, & Morari, 2015)
Wind speed and power density analysis based on Weibull and Rayleigh distributions (a case study: Firouzkooh county of Iran)	Renewable & Sustainable Energy Reviews	(S. H. Pishgar-Komleh, Keyhani, & Sefeedpari, 2015)
Regionalization Of Wind-Speed Data To Analyse Tree-Line Wind Conditions In The Eastern Andes of Southern Ecuador	Journal Erdkunde	(Wagemann, Ties, Rollenbeck, Peters, & Bendix, 2015)
Application of brushless excitation system in Wind power generation	4th International Conference on Renewable Energy Research and Applications	(Mishra, Kumar, & IEEE, 2015)
Dynamic model of a pumping kite power system	Renewable Energy	(Fechner, van der Vlugt, Schreuder, & Schmehl, 2015)

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Electric power generation in wind farms with pumping kites - An economical analysis	Renewable Energy	(De Lellis et al., 2016)
Wind speed analysis and energy calculation based on mixture distributions in Narakkalliya, Sri Lanka	Journal of the National Science Foundation of Sri Lanka	(Rajapaksha & Perera, 2016)
On the Autonomous Take-Off and Landing of Tethered Wings for Airborne Wind Energy	American Control Conference (ACC)	(Van, Fagiano, Schnez, & IEEE, 2016)
Effectiveness of Using Multisatellite Wind Speed Estimates to Construct Hourly Wind Speed Datasets with Diurnal Variations	Journal of Atmospheric and Oceanic Technology	(Kako, Okuro, & Kubota, 2017)
Evaluation of wind energy potential for different turbine models based on the wind speed data of Zabol region, Iran	Sustainable Energy Technologies and Assessments	(S. Pishgar-Komleh & Akram, 2017)
Wind speed analysis using the Extended Generalized Lindley Distribution	Renewable Energy	(Kantar, Usta, Arik, & Yenilmez, 2017, 2018)

Source: Authors.

The models for wind energy generation prediction most used in the literature can be grouped into three groups. The first group is based on the analysis of time series wind speed data; the second is based on a probability distribution; and the third group uses predicted values from a numerical weather prediction (NWP) model as an input variable, as shown in Table 2.

Table 2. Prediction models and wind speed prediction.

Methods	Author
Logarithmic wind shear model	(Archer et al., 2014; De Lellis et al., 2016; Cabello e Orza, 2010; Fagiano et al., 2012; Gros et al., 2012; Zanon et al., 2013; Zgraggen et al., 2013; Novara et al., 2013; Rehman, 2013; Zanon et al., 2014; Zgraggen et al., 2015; Mishra et al., 2015; Fechner et al., 2015; Archer et al., 2014; Cabello & Orza, 2010; De Lellis et al., 2016; Fagiano, Milanese, & Piga, 2012; Fechner, van der Vlugt, Schreuder, & Schmehl, 2015; Gros, Zanon, Diehl, & IEEE, 2012; Mishra, Kumar, & IEEE, 2015; Novara, Fagiano, & Milanese, 2013; Rehman, 2013; Zanon, Gros, Diehl, & IEEE, 2013; Zanon, Gros, Meyers, & Diehl, 2014; Zgraggen, Fagiano, & Morari, 2015; Zgraggen, Fagiano, Morari, & IEEE, 2013)
Weibull Probability Distribution	(Tuller e Brett, 1984; Bivona et al., 2003; Jaramillo e Borja, 2004; Perez et al., 2004; Wilson 200 et al., 2006; Razali et al., 2010; Bagiorgas et al., 2011; Pishgar-Komleh et al., 2015; Wage- mann et al., 2015; Rajapaksha e Perera, 2016; Pishgar-Komleh e Akram, 2017; Bagiorgas, Giouli, Rehman, & Al-Hadhrami, 2011; Bivona, Burlon, & Leone, 2003; Jaramillo & Borja, 2004; Perez, Garcia, Sanchez, & de Torre, 2004; S. Pishgar-Komleh & Akram, 2017; S. H. Pishgar-Komleh, Keyhani, & Sefeedpari, 2015; Rajapaksha & Perera, 2016; Razali, Sapuan, Ibrahim, Zaharim, & Sopian, 2010; Tuller & Brett, 1984; Wagemann, Ties, Rollenbeck, Peters, & Bendix, 2015; Wilson, Morcos, & IEEE, 2006)
Numerical Weather Prediction (NWP)	(Foley et al., 2012; Lynch et al., 2014; Foley, Leahy, Marvuglia, & McKeogh, 2012; Lynch, Omahony, & Scully, 2014)

Source: Authors.

In the logarithmic wind shear model, the Logarithmic Law and Power Law models are used to estimate variation of wind speed with altitude (Manwell, McGowan, & Rogers, 2009). Time series of wind speeds are usually unavailable at different altitudes of the site concerned, so a wind logarithmic profile can be used to obtain the estimated output power. A logarithmic profile is often used to estimate the wind speed at the operational altitude wn(z) based on a base wind speed at some altitude w(zR), using a terrain roughness parameter z0. This method enables calculating the horizontal wind speed through a consistent and reliable extrapolation of the wind speed from one altitude to another.

The Weibull distribution method was first proposed in the 1930s to interpret materials fatigue but it has also been used in several studies with an aim to analyze the wind speed frequency and its probability density function. The Weibull distribution function is widely used in numerous investigations on wind energy (Chang, 2011; Diaf & Notton, 2013; Lima & Bezerra, 2012). To determine the Weibull probability density function, two parameters must be known: ‘k’, a shape factor, and ‘c’ a scale factor. Both factors are a function of the mean wind speed and standard deviation. The Weibull probability density function is given by:

$$p\,(V) = (k/c)^{k-1}\ \exp[-(V/c)^{k}] \qquad (1)$$

Analytical and empirical methods for determination of k and c can be found in (Manwell et al., 2009). There are other methods to estimate Weibull parameters, such as the graph method, standard deviation and the maximum likelihood method.

The Numerical Weather Prediction model (NWP) is defined as the production of weather forecasts through the integration of a series of mathematical equations that describe all dynamic and physical processes in the atmosphere using numerical methods (Cassola & Burlando, 2012; Schulze, 2007). Schulze described weather forecasting as the conversion of observational data into predictions through a model consisting of three basic steps. The first step consists of collecting and analyzing meteorological data to define the initial conditions of the model using data assimilation techniques. The second step utilizes deterministic models of numerical prediction to project the initial conditions of the system into future states. The third step consists of the process of converting the numerical models output into valuable practical information for users.

3. Methodology

To simulate energy production in a wind farm it is necessary to know the average wind speed at the operational altitude. It should be noted that the operational altitude of a WT is determined by the tower height, but for a PK system, the airfoil height changes constantly throughout the energy generation phase. To overcome this difficulty, the wind measurements taken at a certain altitude at the site should be extrapolated to any other altitude using the logarithmic wind profile as long as its parameters have been identified.

Assuming that a WT is fixed by the tower height and PKs will operate within the limit of the atmosphere layer, which, according to (Archer, 2014), extends up to 600m above the ground, we therefore can use the logarithmic wind shear model, Equation 1:

$$W_n(z) = W_R \frac{\ln\left(\frac{z}{z_0}\right)}{\ln\left(\frac{z_R}{z_0}\right)}, \qquad (1)$$

where $W_n(z)$ represents the wind speed at height z; the parameters z_R and W_R are the reference altitude and the corresponding wind speed, respectively, which are generally available by measurement. The parameter z_0 is the surface roughness. The surface roughness represents the wind gain with the operational altitude due to friction, actions that dissipate the wind flow in irregular terrains.

To create the simulations in this research, twelve Brazilian cities were chosen as case study, as shown in Table 3.

Table 3. Geographic location of the Brazilian cities.

Locality	Latitude	Longitude
Uruguaiana/RS	29.78°S	57.03°W
Uberlândia/MG	18.87°S	48.22°W
São Luiz/MA	2.69°S	44.23°W
Corumba/MS	19.00°S	57.67°W
Porto Alegre/RS	30.00°S	51.18°W
Fortaleza/CE	3.73°S	38.55°W
Florianópolis/SC	27.67°S	48.55°W
Curitiba/PR	25.52°S	49.17°W
Campo Grande/MS	20.47°S	54.67°W
Brasília/DF	15.87°S	47.93°W
Boa Vista/RR	02.83°S	60.70°W
Manaus/AM	3.15°S	59.98°W

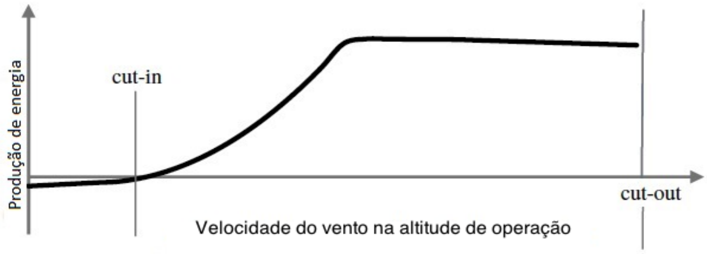
Source: Authors.

Subsequently, sites which data were available on the database of the Earth System Research Laboratory - ESRL of the National Oceanic and Atmospheric Administration –

NOAA, in the USA (NOAA/ESRL, 2018), were selected, and wind data were obtained for a period of eight years, from 2010 to 2018. Data consist of at least one survey per day, with wind measurements at different altitudes. An altitude grid was defined at a resolution of 10 meters, and the average was obtained for each grid slot. Then, with the resulting dataset, the roughness parameter of the wind model was identified using the method of least squares.

An important property of the energy generation system to be analyzed is the power curve because it indicates the relation between the electrical power generated as a function of the nominal wind speed1. A wind turbine (WT), as well as a pumping kite (PK), has a power curve that characterizes the energy generation efficiency, as shown in Figure 3.

Figure 3. Generic power curve applicable either to a WT or a PK.



Source: Heilmann and Houle (2014, p.274).

To obtain how much energy is produced by a WT and a PK system for a certain wind intensity at the operational altitude, it is necessary to obtain its respective power curves. For the WTs, the methodology developed by (Manwell et al., 2009) was used, which consists of determining the angle of attack of the blades and the turbine rotation speed to maximize the generated power. In WTs, the output power is proportional to the product of the blades' rotation speed by the torque on the generator shaft. This procedure is detailed in (Manwell et al., 2009) and also in (De Lellis et al., 2016).

The PK power curve can be obtained by optimizing its operation point as a function of the wind speed. To optimize the PK system, (Luchsinger, 2014) considered as ideal the crosswind operation, disregarding tethers drag and the need for a significant height angle to reach higher-altitudes winds, where they are stronger. To overcome this difficulty, we considered the mass-point equations of the tethered airfoil, as proposed by Fagiano (2009), which showed that mechanical energy is nearly proportional to the product of the velocity of the cables unwinding by the cable traction force.

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[1] Nominal wind should be understood as the mean wind (not considering turbulence) at a certain height.

4. Result

Table 4 presents the interpolated parameters of the logarithmic wind shear model for twelve Brazilian cities: Uruguaiana, Uberlândia, Salvador, Boa Vista, São Luiz, Porto Alegre, Fortaleza, Florianópolis, Curitiba, Campo Grande, Brasília, and Manaus for the period from January 2010 to January 2018.

Table 4. Interpolation of the parameters of the logarithmic wind shear model for several Brazilian cities from January 2010 to January 2018.

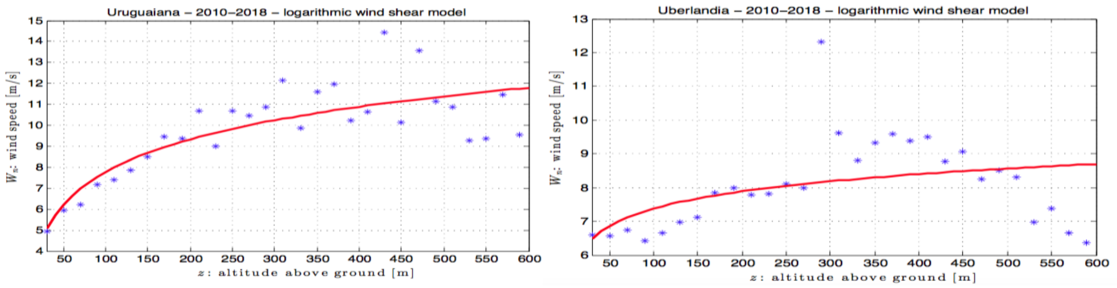
Locality	Z_{ref} (m)	W_r (m/s)	Z_0 (m)
Uruguaiana/RS	30	5.08	3.0963
Uberlândia/MG	30	6.48	0.0047
São Luiz/MA	30	5.23	0.7004
Corumba/MS	30	5.53	0.1547
Porto Alegre/RS	30	3.69	3.7649
Fortaleza/CE	30	6.34	0.0223
Florianópolis/SC	30	4.19	1.3777
Curitiba/PR	30	4.45	1.0614
Campo Grande/MS	30	7.29	7.3962
Brasília/DF	30	5.00	0.3150
Boa Vista/RR	30	4.70	1.9359
Manaus/AM	30	3.22	2.9098

Source: Authors.

The parameters presented in Table 4 provided the power curves shown in Figure 4. It should be noted that Uruguaiana/RS is a city where mean fast winds occur in all altitudes of reference. At 100 meters high, wind speed is approximately 8 m/s, and at 400 meters, mean wind speeds reach 11 m/s. Also worth noting is that in Campo Grande/MS, Uberlândia/MG, São Luiz/MA and Corumba/MS there is optimal wind potential with mean speed exceeding 7m/s at 100 meters high, and at 400 meters above the ground, mean wind speeds are over 8.5 m/s. Other cities such as Porto Alegre/RS, Curitiba/PR, Brasília/DF and Boa Vista/RR have mean wind speeds exceeding 6 m/s at 100 meters high and at 400 meters high mean wind speeds exceed 8 m/s. It can be seen that Boa Vista/RR is a location where mean wind speeds are found in all altitudes, reaching approximately 9.2 m/s at 400 meters high. In turn, Florianópolis/SC has low average wind speeds, around 5.7 m/s at 100 meters above the ground, and at 400 meters high, average wind speeds are approximately 7.8 m/s. Near the ground surface, the only city with strong winds is Campo Grande/MS, where at low altitudes wind speeds are approximately 7.4 m/s.

To generate wind power using conventional technology, i.e. towered horizontal turbines, Porto Alegre, Florianópolis, Curitiba and Brasília present a very low wind potential compared to other cities. It can be seen that wind gains increase significantly at higher altitudes in all cities studied, varying around 2 m/s for the amplitude of 100 to 400 meters high. It should also be noted that Uruguaiana, Uberlândia, Salvador, Boa Vista, São Luiz, Fortaleza and Campo Grande can be considered a prime location for wind power farms operating at altitudes 100 meters above the ground in Brazil. In Porto Alegre, Florianópolis, Curitiba and Brasília, mean wind speeds at altitudes of $\geq$ 250 m become significant, enabling its implementation if the technology is economically viable. Figure 4 shows the power curves obtained with the interpolated wind shear model for different Brazilian cities, developed in the matlab software version 8.3.0.532 (R14).

Figure 4. Wind models for some Brazilian cities in a period of eight years - from 2010 to 2018.



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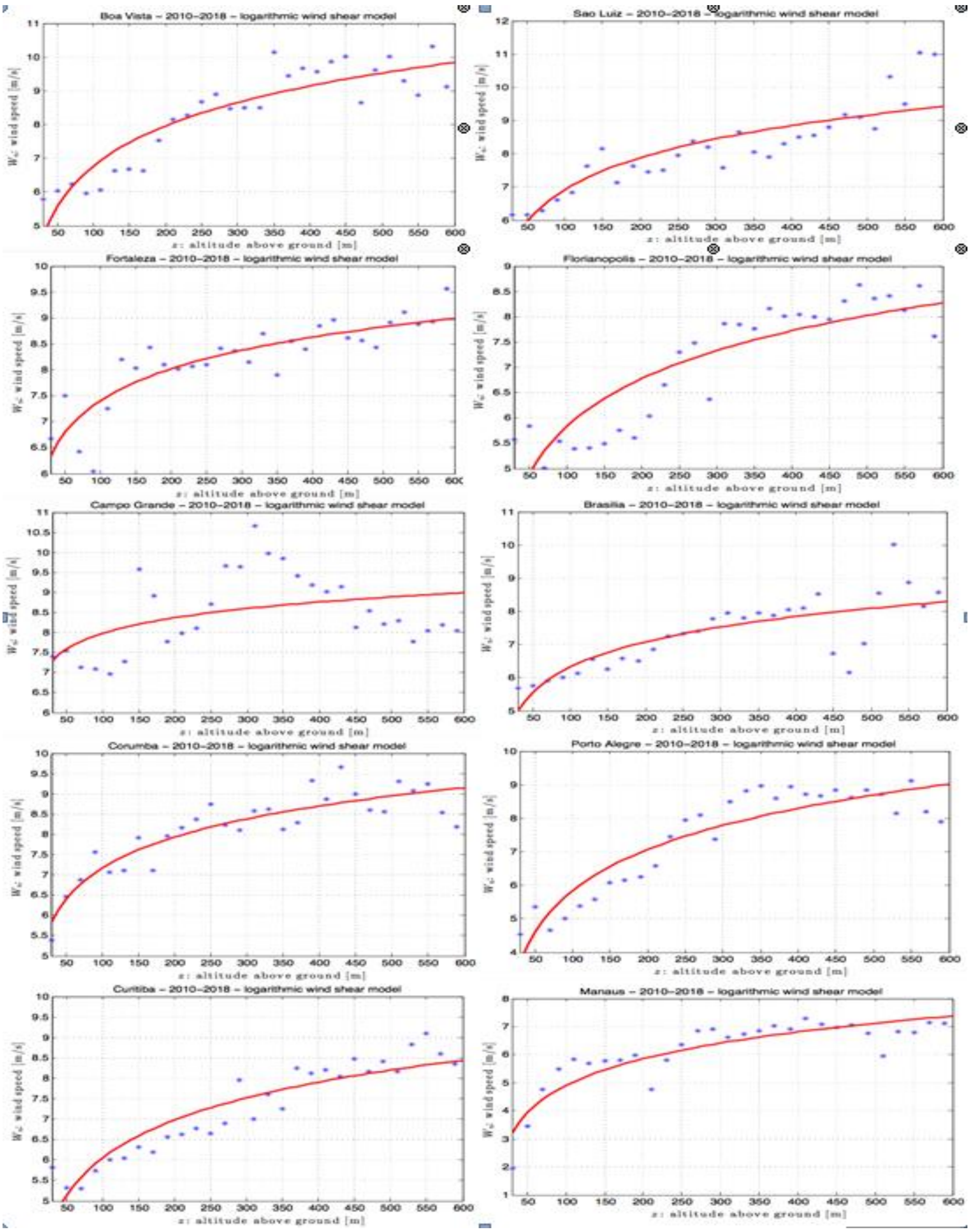
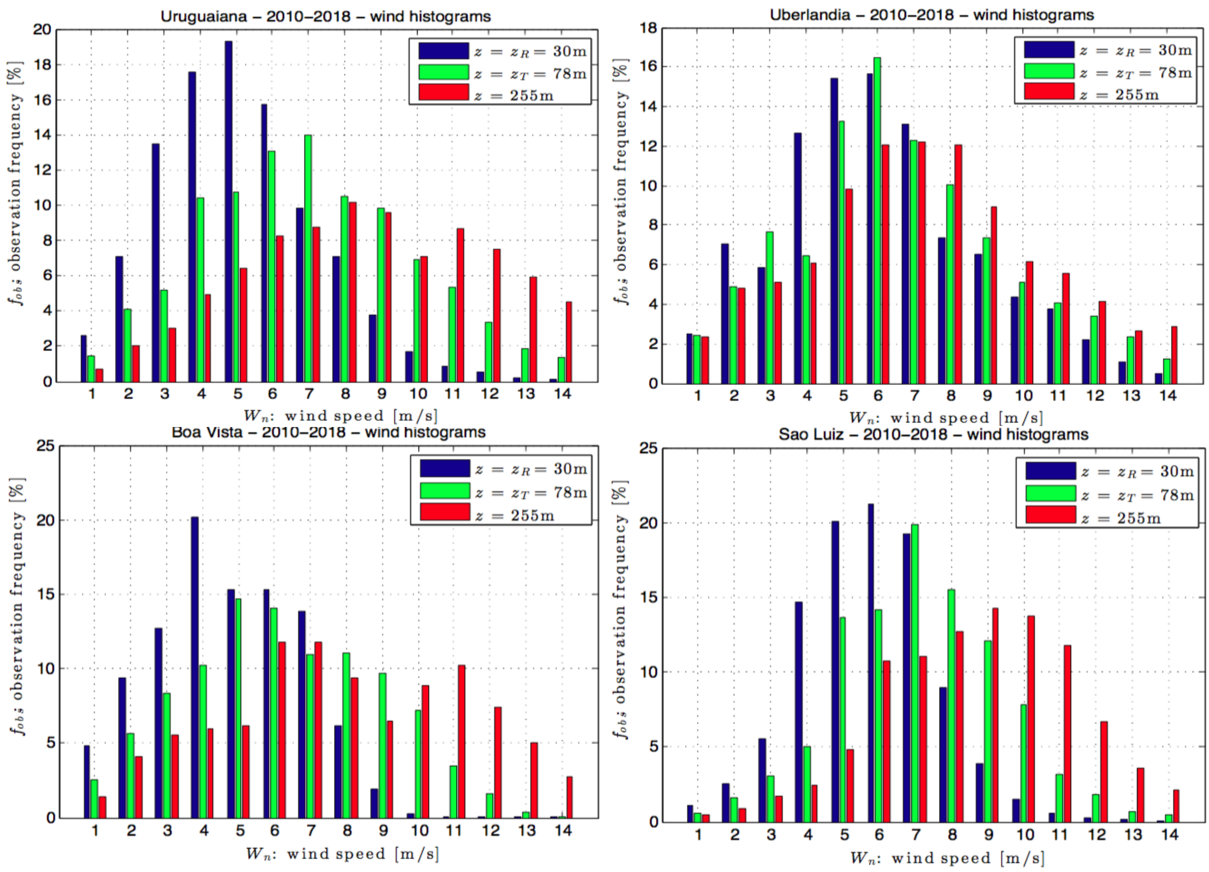


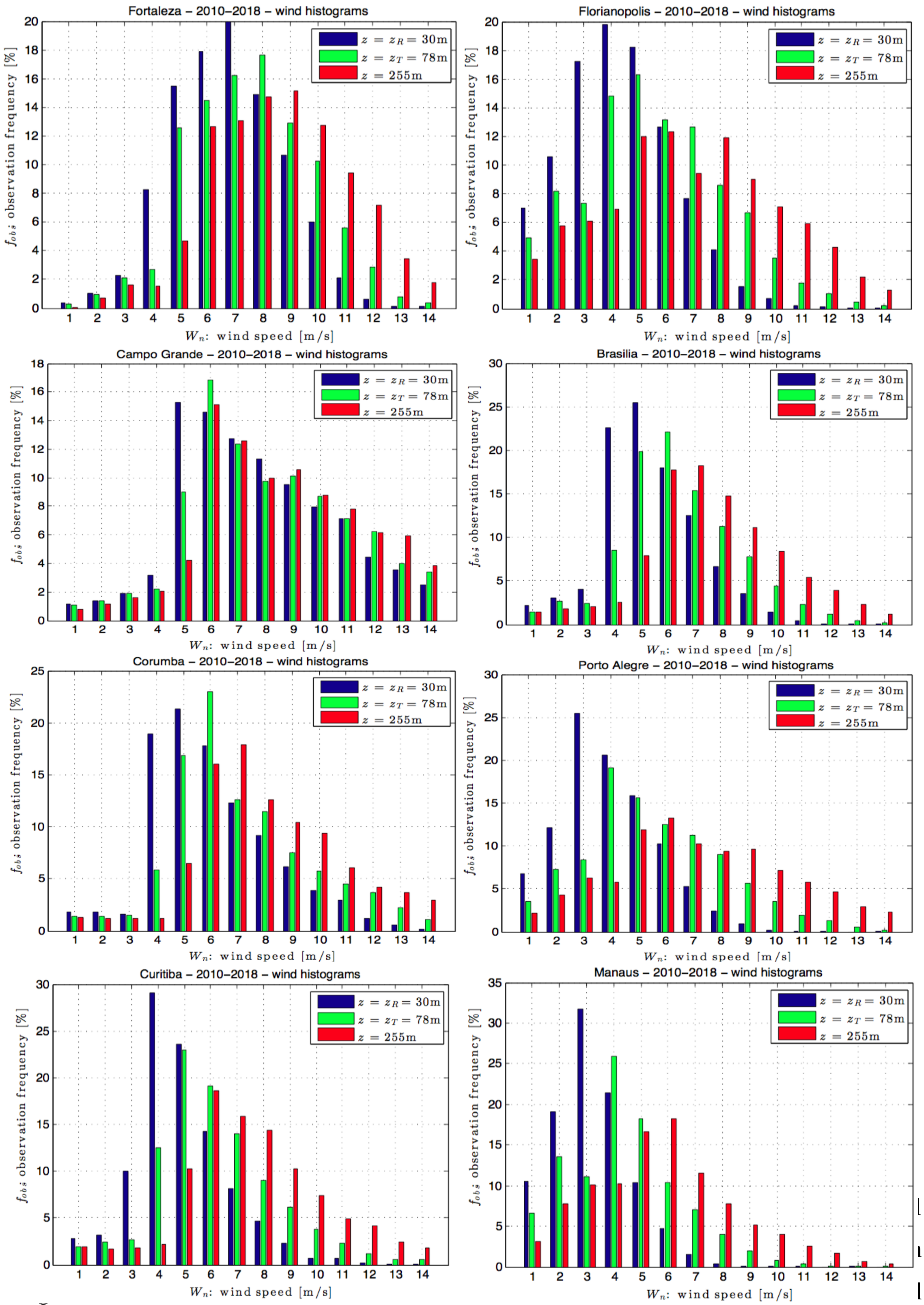
Source: Authors.

Other requisite to calculate average energy output over a certain period of time consists of its respective wind histograms at the operational altitude. Histograms of wind speeds are used to represent the frequency of occurrence of wind speeds in a given period of time. Knowing that the axis height of a WT is zT = 78 m, therefore we will need a histogram at this operational altitude. Taking into account the PK operational altitude variation and the limited number of samples, the resulting histogram would not be representative. To solve this problem, the proposed procedure makes an extrapolation of the measurements taken at the site at a certain altitude to any other altitude using the logarithmic wind profile.

Figure 5 presents the histograms for the cities of Uruguaiana, Uberlândia, Salvador, Boa Vista, São Luiz, Porto Alegre, Fortaleza, Florianópolis, Curitiba, Campo Grande, Brasília and Manaus in z = zT and in z = 255m. It can be seen that as the altitude increases, stronger winds occur at higher observation frequencies, which corroborates the motivation for the production of energy at higher altitudes.

Figure 5. Wind histograms for some Brazilian cities in a period of eight years, from 2010 to 2018.





according to Figure 4, we have w(z) ≈ 7.4m/s. However, if we change to ± 2m/s around this mean value, we can see in the histogram that in approximately 70% of the time, wind speeds are in the interval between 5.4 and 9.4 m/s. In another view, in Manaus we find a lower mean wind speed value, where $w(z) \approx 4.5$m/s, and considering the same variation of $\pm$ 2m/s in this mean value, we can see that in 50% of the time, we have winds in the range between 2.5 and 6.5m/s. This shows that in some Brazilian localities, e.g., Uruguaiana, mean wind speeds that were found in approximately 70% of the time are in the in the range of 5.4 to 9.4 m/s, which can generate a large quantity of energy. It should also be noted that the wind profile in Manaus exhibits slower speeds in all altitudes, when compared to Uruguaiana. This difference has a strong impact on power generation and on the profitability of the wind farm.

5. Conclusions

The technological development of wind power is a promising alternative to overcome the problems that arise with the use of fossil fuels, considering the growing demand for energy that must be satisfied. Another concern is related to the environmental problems caused by the use of fossil fuels. Thus, the use of renewable energy sources such as wind energy would be an alternative to tackle these issues.

In this study, wind speeds and wind power potential in twelve Brazilian cities were investigated. The logarithmic wind shear model was used to analyze the mean wind speed in a period of eight years. This model is often considered in the literature to represent how mean wind speed increases in altitudes up to 600 meters above the ground,

Based on data available for the public on the ESRL database, the wind model was interpolated for the Brazilian cities of Uruguaiana, Uberlândia, Salvador, Boa Vista, São Luiz, Porto Alegre, Fortaleza, Florianópolis, Curitiba, Campo Grande, Brasília and Manaus.

First, the wind model in the studied localities was found based on wind measurements available for these cities. Then, the curve of power was plotted considering the machine characteristics. The respective wind histograms were also presented, representing the observation frequency of different intervals of wind speeds at each specific site.

The study showed that the localities Uruguaiana/RS, Campo Grande/MS, Uberlândia/MG, São Luiz/MA and Corumba/MS are cities that have strong winds on average in all altitudes of reference with gains in wind speed as the operational heights increase.

The study also revealed that in other localities, e.g., Porto Alegre, Florianópolis, Curitiba and Brasília, winds at low altitudes are not significant for the installation of a classic wind farm, but may have faster winds at higher altitudes, which might justify the implementation of a wind farm if the technology proves to be economically feasible.

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