Wind Power Use Capacity in Rural Areas of Complex Topography via WRF Model: a Case Study in a Mountainous Region in Rio de Janeiro State, Brazil

Capacidade de Uso da Energia Eólica em Áreas Rurais de Topografia Complexa via Modelo WRF: um Caso de Estudo em uma Região Montanhosa do Estado do Rio de Janeiro, Brasil

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Resumo

Estimulada por acordos ambientais globais, a busca por alternativas de geração de energia renovável vem aumentando em todo o mundo. Embora o Brasil tenha um grande território com diferentes recursos naturais, sua matriz energética é altamente dependente da fonte hidráulica. Este artigo avalia a capacidade de uso da energia eólica no topo de morros e montanhas, considerando o potencial eólico nesses locais e, assim, estimulando seu desenvolvimento no país. O modelo Weather Research and Forecasting (WRF) foi aplicado para identificar os recursos eólicos e definir os melhores locais para a instalação de aerogeradores na área da Cooperativa Agrícola de Vieira, localizada em Teresópolis, região montanhosa do estado do Rio de Janeiro, Brasil. Como pequenos aerogeradores operam próximos ao solo e, portanto, têm custos mais baixos do que os grandes, a produção estimada de eletricidade de um aerogerador nacional, de pequeno porte, foi comparada com o consumo real de uma lavoura de referência local. Apesar da fraça representação topográfica, os resultados mostram que a região possui recurso eólico suficiente para fornecer eletricidade aos agricultores ao longo do período estudado do ano, reduzindo seus custos de produção. Portanto, é possível melhorar o uso de energia eólica no Brasil em zonas montanhosas e, no processo, diversificar a matriz energética do país.

Palavras-chave: modelagem; regiões montanhosas; energia eólica

Abstract

Encouraged by global environmental agreements, the search for renewable energy production alternatives has been increasing around the world. Although Brazil has a large territory with different natural resources, its energy matrix is highly dependent on the hydraulic source. This paper evaluates the wind power use capacity on the top of hills and mountains, considering the wind potential in these places and so stimulating its development in the country. The Weather Research and Forecasting (WRF) model was applied to identify the wind resource and to define the best sites to install aerogenerators in the area of the Agricultural Cooperative of Vieira, located in Teresópolis, a mountainous region in Rio de Janeiro state, Brazil. As small aerogenerators operate close to the ground, and so have lower costs than large ones, the estimated electricity production of a national aerogenerator was compared with the real consumption of a local reference tillage. Despite the poor topography representation, results show that the region has sufficient wind power to provide electricity to the agriculturists throughout the studied period of the year, reducing their production costs. Therefore, it is possible to improve Brazil’s wind energy use in mountainous zones and in the process diversify the country’s energy matrix.

Keywords: modeling; mountainous regions; wind energy
1 Introduction

The relevance of wind energy potential has increased in recent years in the global scenario due to its promising advantages. It is a renewable source, reduces the fossil fuel usage and reduces the greenhouse gases and other pollutants emission into the atmosphere. The wind, considered as a renewable source, is characterized by only low levels of indirect carbon emissions, being considered an interesting alternative for fossil fuels (Fang, 2014; Aso & Cheung, 2015). In Brazil, wind energy reached 7633 Mega Watts (MW) of installed capacity in 2015, resulting in a growth of 56.2% compared to 2014. Most investments were in the country's northeast coast, where the wind is frequent and reaches high velocities. Moreover, the South of Brazil is increasing its participation in the wind power generation, being the second biggest producer in the country. The Southeast has a little contribution to the sector, while the North and the Midwest still not generating electricity from wind power (EPE, 2016).

Despite Brazil’s efforts to increase the use of wind energy in its large territory, its energy matrix is highly dependent on the hydraulic source. In 2015, it represented 64% of the total electricity generated, while wind energy represented 3.5% (EPE, 2016). The hydropower dependence reflects the great vulnerability in the Brazilian electricity sector. The bad management of water resources, of its usage’s conflicts and of the dry periods can lead to water unavailability. In spite of being renewable, hydropower can cause significant impacts in its zone of influence, such as the alteration of the river’s hydraulic characteristics and the interference in the aquatic and riverside environments. Besides that fact, in the Brazilian Northeast, the period of most intense winds are the dry months, so there is a complementation between periods of great wind power generation and great hydropower generation that can be largely explored (Dos Santos & Silva, 2013).

The airflow over hills increases speed at upstream and reaches its apex at the top (Stangroom, 2004). Therefore, the wind power in these regions has a promising potential for its energy use, but it is not commonly explored in Brazil. Considering the country’s extension, its wind potential and its expressive dependence on the hydraulic source, viability studies in mountainous regions for wind turbines implementation are relevant ways to develop this kind of activity in the country (Da Silva et al., 2013; ABEEÓLICA, 2019).

The atmospheric modeling assists to determine the wind speed and direction in places where there are not any observed data to verify if these spots are able to produce wind energy. Furthermore, weather stations may possibly present some restraints, such as coarse resolution, data accuracy and also completeness and financial costs, as pointed by Al-Yahyai et al. (2010).

Modeling application examples are provided by Mattar & Borvarán (2016), who used the mesoscale atmospheric model Weather Research and Forecasting (WRF) to estimate the offshore wind potential in the central coast of Chile and concluded that wind power over the sea ranges between 745 and 1240 W m⁻²; Carvalho et al. (2012; 2014), who used WRF to simulate wind over Portugal, showing the impact of boundary layer parameterization and initial and boundary conditions choice in terms of wind energy production estimates; Giannaros et al. (2017) who also used WRF for simulating wind field over Greece for assessing wind resources and found a satisfactory model performance; and Lazić et al. (2014), who used the mesoscale model ETA with a new proposed MOS (Model Output Statistics) method to make wind forecast in Scandinavia and demonstrated its usefulness for wind energy applications.

Therefore, this paper aims to evaluate, via numerical modeling, the wind energy capacity in different altitudes, in the region near the Agricultural Cooperative of Vieira (CoopVieira), located in Teresópolis, Rio de Janeiro state, Brazil. There are family agriculture initiatives in this area, together with subsidized agriculture, which demands an expressive energy amount, mainly for irrigation services. Additionally, to value and stimulate the development of the wind energy industry in Brazil, the aerogenerator Verne 555, designed by the national company Enersud, was considered to estimate the electrical production over the area.
The use of sustainable technologies, such as wind energy applications in rural communities, reflects the possibility of reducing production costs related to energy consumption. The methodology developed in this study can also be used in other places in Brazil and the world that have these same complex topography and small-scale farming characteristics.

2 Material and Methods

2.1 Study Area Description

The city of Teresópolis has 770.601 km² and is in the Mountainous Region of Rio de Janeiro state, at an altitude of 871 m above sea level. The local climate is classified as tropical altitude and it is propitious for the agricultural production (IBGE, 2016). In fact, the city’s farming contribution in the Gross Domestic Product (GDP) of the state in 2013 corresponded to 18% in this sector (IBGE, 2016). In the rural area of Teresópolis, the small landholdings managed by family agriculturists dominate.

The Agricultural Cooperative of Vieira (Co-opVieira) is situated in Teresópolis between the km 33 and 45 of RJ-130 road. The Cooperative is composed of forty-one familiar agriculturists and twelve non-agriculturists, totaling fifty-three partners. The crop is predominantly of lettuce, chive, kale and watercress. The production is of industrial scale with a huge electricity consumption all over the year.

2.2 Aerogenerator Selection

To appraise and incite the development of the Brazilian wind turbine industry, as well as to provide an economically feasible solution, the aerogenerator Verne 555, designed by the national company Enersud, was selected for the study. It is Enersud’s most powerful model with 6 kW of rated output power reached by 12.00 m.s⁻¹ of rated output speed. Verne 555’s cut-in speed is equivalent to 2.20 m.s⁻¹. It is constituted of a horizontal axis wind turbine in an upwind configuration (Enersud, 2016). To optimize the wind use capacity, the analyses were made considering the tallest tower fabricated by Enersud, measuring 18 m in height.

2.3 Model Application

The mesoscale model used is the Advanced Research Weather Research and Forecasting (WRF-
F-ARW) modeling system version 3.6.1 (Skamarock et al., 2008). The simulation was built with four grids using one-way nesting, centered between the closest weather station and the CoopVieira, in the -22.308372º latitude and -42.698486º longitude. Configured with Mercator map projection, the horizontal spatial resolutions adopted were of 27 km, 9 km, 3 km and 1 km (Figure 2). The study area consists of the last domain (d04). The dimensions of each of these domains were respectively 1620 x 1620 km², 549 x 549 km², 282 x 282 km² and 40 x 40 km². Furthermore, the time step was set to 120 s and 47 vertical levels were used.

| Physic Process | Scheme                          | Reference          |
|----------------|---------------------------------|--------------------|
| Microphysics   | Goddard                         | Tao et al., 1989   |
| Longwave       | RRTM                            | Mlawer et al., 1997|
| Shortwave      | Dudhia                          | Dudhia, 1989       |
| Radiation      | MM5 Similarity                  | Paulson, 1970;     |
|                |                                 | Dyer & Hicks, 1970;|
|                |                                 | Webb, 1970;        |
|                |                                 | Beljaars, 1994;    |
|                |                                 | Zhang & Anthes, 1982|
| Land surface   | 5-Layer Thermal Diffusion       | Dudhia, 1996       |
| PBL physics    | MRF                             | Hong & Pan, 1996   |
| Cumulus        | Kain-Fritsch                    | Kain, 2004         |

Table 1 Parameterization schemes used in this study.

The initial and boundary conditions were obtained from the Global Forecast System (GFS) model 3-hour forecast files, for 48 hours forecast horizon, and a horizontal resolution of 0.5º. The topographic data collected from the United States Geological Survey (USGS) have been set to a resolution of 10 arcminutes for grid 1; 5 arcminutes for grid 2; 2 arcminutes for grid 3 and 30 arc seconds for grid 4. The parameterizations were chosen as suggested by Dрагаул et al. (2018) and are summarized in Table 1.

In order to obtain a representative average result of the wind in the study area, this paper sought to work with weather systems that affect the airflow behavior in different modes, such as prefrontal, frontal, and low-pressure systems. Therefore, the simulations occurred in three distinct dates. On the first one, January 24th, 2014, Rio de Janeiro state was in a prefrontal synoptic condition. On the second one, November 26th, 2014, the state was in a low-pressure system and a frontal system passing through the ocean, approximately in São Paulo state’s coast. Finally, the last date, December 22nd, 2014, is characterized by presenting a cold front approaching Rio de Janeiro state and moving through it. The classification of the weather systems was made consulting satellite images and synoptic charts (INPE, 2016). In all cases, the simulations were configured to start at 0000 UTC and last 48 hours.

2.4 Wind Resource Determination

According to the model, in the d04 domain, the weather station’s closest grid point is at 1408 m of altitude and the real weather station is, actually, at 1065 m. To this particular region, the WRF’s topography had a poor reality representation in the highest resolution domain. Thus, there is a significant difference of 343 m between the real and the simulated position. Specifically, the WRF does not display that the weather station is effectively in a valley region (Figure 3). However, in the CoopVieira’s area, WRF had a better topography representation.
An interesting place to install wind turbines in the CoopVieira is, as simulated by the model, at 1155 m of altitude but it is really at 1149 m of altitude, representing 6 m of difference.

The major problem involved with the poor topography representation consists of the unrealistic atmospheric process answers provided by the model. In other words, the wind variation is highly dependent on the topographic resolution used, mainly in mountainous regions (Stull, 1988; Bilal et al., 2016). The WRF uses the USGS dataset, whose highest resolution option is equivalent to 30 arc seconds (about 1 km) (NCAR, 2016). The model was forced to 5 arc seconds topographic resolution for grid 4, but it continued to show an erroneous topography lecture. In addition, the grid spatial resolution was changed to 10.8 km, 3.6 km, 1.2 km and 0.4 km, but the problem persisted.

The 30 arc seconds USGS’s topography resolution may not be appropriate to a punctual definition of aerogenerators located in a mountainous region in Rio de Janeiro, as Teresópolis. Even so, it was feasible to estimate the average wind dynamic at altitude ranges of 100 m. Therefore, to the three simulated dates, the average wind speed vector and direction were calculated at 10 m height as well as

Figure 3 WRF contour plans superimposed on Google Earth satellite image.
the associated standard deviations. This procedure was executed considering the range of 1000 to 1100 m, 1100 to 1200 m, 1200 to 1300 m and 1300 to 1400 m.

The wind vertical profile for the three simulations and in each range was determined using the Law of the Wall, simplified solutions that calculate the wind speed in the turbulent sublayer (Cataldi, 2002). The Businger-Dyer relations (Businger et al., 1971) for a neutral boundary layer (Stull, 1988) were applied due to the lack of turbulence parameters data near the surface (Equations (1) and (2)).

Considering that the three simulation dates are typical days of each month, the monthly average values of the friction velocity were obtained by equation (1). The Wind Atlas of the State of Rio de Janeiro (Amarante et al., 2002) estimates the roughness length to be 1 m, as it is a rural zone in a mountainous terrain. The reference height was set to 10 m, the level where the model simulates the wind speed. Von Kármán constant is equal to approximately 0.4.

Equation (2) provides the wind speed data in function of the height $u(z)$. These data were calculated for the trimester of November, December and January and its average. These averages have enabled the provision of the wind vertical profile of the region. Similarly, it was used to discover the monthly standard deviations. This procedure enables the comparison between the average values summed and subtracted from one standard deviation (68.2% of a normal distribution), in order to define a normal operation range for a certain period and height of interest.

$$u_{\tau} = k\overline{u}(h_{r})/\ln(h_{r}/z_{0}) \quad (1)$$

$$u(z) = u_{\tau}/k \ln(z/z_{0}) \quad (2)$$

2.5 Energetic Production

The probability density function $f(u)$ of Weibull Distribution indicates the time fraction for which the wind has a certain velocity (equation (3)) (Mathew, 2006; Murthy & Rahi, 2016). The Wind Atlas of the State of Rio de Janeiro (Amarante et al., 2002) provided the shape factor $k$ as being equal to 2. The scale factor $c$ is represented by equation (4), which considers the gamma function $\Gamma$ (Amarante et al., 2002; Murthy & Rahi, 2016).

$$u = k/c \left( \frac{u}{c} \right)^{k-1} \exp - \left( \frac{u}{c} \right)^{k} \quad (3)$$

$$c = \frac{\overline{u}}{\Gamma(1 + 1/k)} \quad (4)$$

The energetic production $EP$ is estimated by the association of the aerogenerator power curve $P(u)$, in kW, with the probability density function (Equation (5)) (Mentis et al., 2016). This study intended to find the monthly EP, so $H$ corresponds to the number of hours in a month. The EP determination considered the normal wind speed distribution at 18 m height for each altitude range.

$$EP = H \int_{u_{l}}^{u_{r}} P(u)f(u)du = H \sum_{i=1}^{N} P(u)_{i}f(u)_{i}\Delta u_{i} \quad (5)$$

To evaluate the wind turbine performance considering the height and, consequently, the wind speed (Mathew, 2006), equation (6) defines the capacity factor $CF$ of the Verne 555 (Mentis et al., 2016; Watts et al., 2016). This factor represents the ratio between the energy generated in local circumstances and the potential energy produced in a year by the machine rated power $P_n$. The annual energetic production $AEP$ is considered using $H$ as the number of hours in a year (equation (6)). For this purpose, the scale factor was calculated as an average wind velocity of the simulated studied period.

$$CF = AEP/8760 \, P_n \quad (6)$$

3 Results and Discussion

3.1 The Local Wind Dynamic

Visualization of the wind dynamic over the study area is relevant to comprehend how the air flows in this local situation. Figures 4, 5 and 6 show the wind behavior in the study area according to the model, despite the inadequate topography representation. They exhibit the contour plans and the streamlines at 10 m height in d04 at 1400 UTC for January 24th 2014, November 26th 2014 and December 22nd 2014, respectively. In the November simulation, wind has the highest velocities, mainly between -22.36 and -22.41 latitude and -42.85 and -42.55 longitude. This region is where WRF sees the steepest slopes. The other simulations present, with less impact, a similar behavior. Furthermore, in all
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Simulations, at downwind (South of the peaks), recirculation zones and more turbulent wind patterns are observed, induced by the region’s uneven topography. This type of analysis is important because it delimits, in function of the topographic distribution, the places with greater (upwind) and smaller (downwind) wind power generation potential in the area.

3.2 Wind Speed and Direction Variability by Altitude Ranges

The mountains have an important role in airflow behavior. Spots without obstacles have stronger wind velocities and fewer turbulence impacts (Stull, 1988). In mountainous regions, the higher hills are above the surface barriers. Figure 7 compares the monthly wind speed variability in the study area at 10 m height in different altitude ranges. Each column symbolizes the average wind velocity and the error bars are the respective standard deviations. For the three dates simulated, wind increases its average speed between 1000 and 1400 m. The average speeds in all situations are higher than the aerogenerator Verne 555’s cut-in speed, showing the local wind resource capacity to generate energy during the analyzed period.

Figure 8 shows average wind speed at 10 m height measured by the closest weather station (-22.334839º latitude and -42.676932º longitude). In the same period of WRF simulation. The weather station is located at 1065 m height, represented in Figure 7 by the first class of altitude range (1000 – 1100 m). For the January 24th simulation, the difference between the average speeds of simulated and observed data in this range is about 1.02 m.s⁻¹. For the November 26th simulation, this difference is about...
2.11 m.s\(^{-1}\). Finally, for the December 22\textsuperscript{nd} simulation, the difference is about 1.13 m.s\(^{-1}\). In all cases, WRF overestimates the values. This considerable difference between observed data and the model’s results confirms the influence of topography representation in atmospheric modeling calculation.

Wind direction is an important parameter to determine the wind turbine location on a wind farm. The machine’s installation should be placed where there is a minimum number of obstacles in the prevailing wind direction (Stull, 1988). Table 2 shows the average and the standard deviation wind direction by altitude range and date simulated. In the study area, in all cases at 10 m height, the wind is predominantly from northwest, with variations between southwest and northeast. Table 3 represents the average and the standard deviation wind direction measured by the closest weather station, at 10 m height. January 24\textsuperscript{th}-25\textsuperscript{th} and December 22\textsuperscript{nd}-23\textsuperscript{rd} have average wind direction from northwest, similarly to WRF’s results. However, in November 26\textsuperscript{th}-27\textsuperscript{th} wind is predominantly from north, differing from the model’s simulation.

Different airflow behaviors, in terms of average wind vertical profile for each altitude range studied, were found (Figure 9). The x-axis reproduces the average wind velocity and the y-axis symbolizes the height above the surface. From left to right, each line corresponds to a different altitude class: 1000 to 1100 m; 1100 to 1200 m; 1200 to 1300 m; 1300 to 1400 m. Thus, not only wind increases its intensity with the height above the ground, but also with altitude above sea level. Between 1300 to 1400 m, the wind has a significantly larger value, being more interesting for wind energy use in the area.

| Altitude (m) | Wind Direction |
|--------------|----------------|
|              | 01/24/2014     | 11/26/2014 | 12/22/2014 |
| 1000 - 1100  | 147.25         | 111.56     | 132.40     | 72.60 |
| 1100 - 1200  | 132.82         | 109.51     | 126.05     | 60.35 |
| 1200 - 1300  | 135.32         | 112.11     | 128.72     | 52.47 |
| 1300 - 1400  | 127.29         | 108.63     | 128.23     | 54.42 |

Table 2 Wind direction by altitude range and simulated date.
3.3 Wind Power Production

Estimating wind power production in a given place by a certain aerogenerator model provides an effective result of the local wind energy capacity use. Comparison with the agriculturists’ energy consumption helps to evaluate the efficiency of a given wind power capacity to meet specific production needs. Therefore, Figure 10 displays the electricity furnished by Verne 555 at 18 m height in a normal range operation in the four studied altitude ranges. This energy production does not include the energetic system’s loss.

The electricity production considering the average speed plus the standard deviation in the four altitude classes is capable of supplying the crop consumption. The analysis of the average speed for power generation indicates that it is partially capable to attend the agricultural demand in most cases: 1000 to 1100 m, 1100 to 1200 m and 1200 to 1300 m. In contrast, average speeds less standard deviations produce sufficient energy just in a short period at 1300 to 1400 m.

Results show that power increases with altitude, evidencing that between 1300 and 1400 m above sea level are the best sites to install wind turbines in the study area. At these altitudes, one wind turbine can provide energy, on average, for two properties like the analyzed one. In the best scenario, considering the average speeds plus the standard deviations, 7.32% of CoopVieira’s forty-one agriculturists could be supplied by one single turbine with 6 kW of rated output power at 18 m above the surface. In other words, at least fourteen aerogenerators Verne 555 are required to compose a wind farm that completely serves the Cooperative. As each wind turbine Verne 555 costs around BRL 57,450.00, without the electrical equipment, the power inverter, installation services, assembly and freight, the implementation price of this wind farm would be of BRL 804,300.00. Considering the average consumption of 505 kWh and that the tariff costs BRL 0.56649 per kWh, the fifty-three CoopVieira’s partners can recover the initial investment in approximately four years and four months. Besides that, searching for a more complete sustainable cycle in agriculturists’ production, the crop’s practices optimization can also rise the local wind energy performance (De Guimarães et al., 2017). Another possibility to improve the wind power use in the area would be the implementation of an aerogenerator that works in higher heights, where the wind tends to be more intense and, consequently, more kinetic energy could be converted in electricity.

Regarding the Verne 555’s capacity factor, Table 4 evidences its possible values in different altitudes for the average wind speed, the average wind speed plus the standard deviation and the average wind speed less the standard deviation. Once again, between 1300 and 1400 m, where the wind has the highest velocities, the capacity factor shows the best performance. Even between 1000 and 1100 m, where there is less wind power capacity, the capacity factor for the average wind velocity is expressive for a small wind turbine (Wiser et al., 2012). In other words, Verne 555 represents an interesting machine in its category of small aerogenerators in the Brazilian market. However, it is still insufficient in terms of supply. Regardless of the quantity and the capacity of the wind turbines operating, the distributed generation is an interesting alternative to CoopVieira. The not consumed active power goes to the grid and can be transformed in power credits (kWh), representing reduction costs in the tillage productions (Brasil, 2012; Brasil 2015).

| Wind Direction | 01/24/2014 | 11/26/2014 | 12/22/2014 |
|----------------|------------|------------|------------|
| average (degrees) | σ (degrees) | average (degrees) | σ (degrees) | average (degrees) | σ (degrees) |
| 143 | 115 | 90 | 52 | 143 | 99 |

Table 3 Wind direction measured by the closest weather station in simulation dates.

4 Conclusions

Results evidence that, between 1000 and 1400 m of altitude, the wind in the study area reaches enough speed to start and maintain wind power generation throughout the studied period. The altitude range from 1300 to 1400 m highlights the best sites for wind energy improvement. This finding allows the local agriculturists to have a second energy sour-
The accurate selection of the best locations to install wind turbines by atmospheric modeling was unfeasible due to the low topography resolution in WRF and in GFS’s initial and boundary conditions for wind power purposes. Teresópolis has a very irregular relief, with valleys and mountain peaks distributed in distances of less than 1 km, which would require a higher topography resolution than the one used in this study. This problem is relevant not only for wind project evaluations but also to extreme events forecasts, thus preventing disasters. In this context, to elaborate studies in regions with these characteristics, it is required to use WRF’s newer versions and to employ a greater topographic resolution. The use of a subroutine to replace the current base topography in the model is also considered a solution, such as the Shuttle Radar Topography Mission (SRTM) application (Lupascu et al., 2015). Besides that, to correctly run the model, it is necessary to apply a land use data file with compatible resolution.

The numerical simulation is a considerable resource for wind atlas elaboration in places with
precarious observed data stations, like Brazil, for example. However, to prepare this kind of research, as shown in this paper, it is necessary to use a very refined atmospheric modeling strategy, investigating not only the model’s physics parameterizations but also the topography resolution. Without these methodological cares, a wind atlas may erroneously indicate areas with wind power potential use, especially in uneven topographies or very urbanized sites.

Given the region’s lack of observed data and the poor topography representation in the WRF, this work served to have an order of magnitude of wind variation with altitude in the study area. It is possible to use wind energy in Brazilian mountainous regions when there are suitable support resources. This fact contributes to diversify the country’s energetic matrix, using one of the most attractive renewable energy sources. Therefore, the investment in this technology expansion is totally worth, contributing to wind energy development in Brazil.

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