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Wind Power Evaluation of 17 Stations of the Rio de Janeiro State, Brazil, a Case Study from 2020-2021

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Abstract

This paper presents the results of research that evaluated the wind potential based on the growing trend of the search for green energy and prospects for the exploitation of this type of energy source in different municipalities in Rio de Janeiro state, Brazil. Average wind speed data were collected daily from 17 automatic stations provided by the Instituto Nacional de Meteorologia (INMET) for one year, from September 22, 2020 to September 22, 2021; it calculated, in sequence, the seasonal averages of the seasons and extrapolation of data to 80 meters. As per the cut-in (minimum speed) necessary for the operation of large wind turbines, a competence filter of 3 meters per second was applied to the database created, pointing out the 6 municipalities in the Rio de Janeiro state with available wind resources above the pre-required value for the presentation of the efficiency floor. It was then proved, among the stations studied, the notorious potential of Arraial do Cabo in the availability of wind resources. In this way, the present research contributes to the planning and implementation of new ways of taking advantage of the Rio de Janeiro winds, as well as for the dissemination of information through graphics and maps generated and made available in this scientific paper.

Subject Areas

Environmental Sciences, Engineering, Geophysics

Keywords

Wind Power, Wind Seasonality, Rio de Janeiro

1. Introduction

As historically stated by Malinowski (1941) [1], it is reasonable to affirm that the development of tools capable of assisting the execution of human actions and providing what is needed for their development is a practice that precedes the ascendancy of genealogy, making it one of the first practices of cultural production on record of hominids. According to the context presented, it is essential to foment studies to promote the tangential areas to the detection and exploitation of wind energy potential carried out in different Brazilian ecosystems. Then, it is inferred that in Ancient Persia, at the time of the late Parthian Empire, the weathervanes proved to be promising equipment capable of replacing the mechanics of manual labor. It follows the historical chronology; windmills were implemented in Europe after the end of the High Middle Ages and represented one of the matrix foundations of the agriculture period, which was considered the main economic activity of the time. Thus, according to Dutra (2021) [2], it appears that wind energy was used in different ways throughout antiquity, assuming the role of replacing the human driving force as a common factor among all applications.

In the 21st century, studies on wind farms seek to infer the main points for taking advantage of the circulation of winds in a given region, a resource that has a high added value for the generation of electricity. The use of this potential occurs through the implementation of wind turbines - a popular piece of equipment in the green energy segment as it is a renewable and non-polluting source. It is noteworthy, however, that recent investments in the sector have been dedicated to offshore wind farms, infrastructures which promote electricity through the movement of winds located in non-continental areas over the ocean. Comparatively, onshore wind farms have obstacles that are not present on the seabed; worth mentioning the roughness of the terrain and urban barriers, resulting in the offshore modality as the main option to be considered for energy generation. It is notable, on the other hand, how the use of these turbines has a visual impact on the region where it was implemented, modifying the landscape [3].

Based on the aforementioned factors, it is necessary to discuss the coefficients capable of influencing the wind regime. Therefore, it is known that the wind presents different behaviors during the same day, a natural unfolding of sudden changes in temperature and continental and maritime pressure zones, altering the module and direction of the current vectors. In addition, the surface roughness classes and topographic obstacles strongly influence the variation of airflow acceleration and, added to the height variant, play a crucial role in the analysis of the available wind resource [2]. Within this space-time perspective, it is evident that the wind demonstrates oscillations arising from the Coriolis force, referring to the latitudes in which it is located, classifying them in groups such as the Trade Winds and Counter Trades. Finally, it is observed that the albedo of the scenario directly impacts the diffuse reflectivity of the surface and, taking into account the amount of absorbed radiation, it partially interferes with atmospheric movements by generating thermally induced circulations.

Furthermore, within the synoptic scale, the South Atlantic Subtropical Anticyclone (SASA) high-pressure system influences the state of Rio de Janeiro by generating a semi-permanent convergence of winds with the other Subtropical Highs, and this eventuality extends itself, consequently, to the relevance and the unfolding of the variables involved in the regional perimeter. Based on what was considered, it is interpreted that SASA drives surface winds to blow from the first quadrant (0˚; −90˚) and predominantly along the East Coast. In the delimitation of Arraial do Cabo, specifically during the afternoon, the movement of the winds is guided by the intensification of the sea breeze, and it makes the zonal flow more accentuated. On the Central and West Coasts, the land-sea breeze circulation reaches vector velocity levels higher than the constant subsiding gusts of the SASA, with flow close to the continental surface and producing a wind regime perpendicular to the coast. Dissonantly, on the East and Central Coast, the prevailing winds from the South Atlantic are highly favorable to upwelling, a scenario made possible by the influence of the characterization of low sea surface temperatures, limited to the coastal zone, on the local atmospheric circulation. Therefore, it should be noted that during the passage of the frontal systems, the winds blow from the south quadrant, thus inhibiting resurgent behavior [4].

Even in the case of the South Atlantic Subtropical Anticyclone, it would be impossible not to note the influence of the high-pressure center on the location, direction and intensity of bilateral winds. There is an accentuation in these winds coming from the east and northeast sectors, an occurrence that can be caused by the seasonalitybringed by the concomitance of eventual cold fronts and, from the mesometeorological point of view, it can be said that this phenomenon is one of the main influences of the synoptic scale in atmospheric dynamics. As is popularly understood, the topographic map of the Rio de Janeiro state presents areas quite distinct from each other. The mountain region, specifically, comprises the occurrences of orographic celerity and channeling of the flow between mountains and, according to Amarante *et al.* (2013) [5], there is a diverse and complex correlation between atmospheric displacements and mountain formations in the Rio de Janeiro state and atmospheric displacement. Although the highest annual wind levels are present in the Região dos Lagos and Norte Fluminense, when it comes to mountainous locations, the wind resource is measured in the epicures, places where there is too much compression effect on the atmospheric flow [5].

In summary, the current energy production market is on the verge of searching for new places to explore renewable resources and, then, mitigate part of the intrinsic environmental impacts of the process. It is essential to understand and study the Brazilian wind potential, especially in Rio de Janeiro—an extensive energy consumer center, as the country, is rich in the presence of ecosystems capable of generating green energy. In view of the above, the potential availability of the wind resource in Rio de Janeiro was evaluated through wind data provided by the meteorological centers of the National Institute of Meteorology (INMET), stations distributed in the municipalities of the state. After that, wind maps were built based from September 22, 2020 to September 22, 2021, it recognizing the regions with greater availability of wind and the months in which the flow is stronger. This diagnosis made it possible to suggest suitable areas for a possible installation of a wind farm or implementation of small wind turbines. In the end, the research contributed to the planning and feasibility of using wind resource as an alternative to generate electric power and preserve the environment.

On that account, with the objective of investigating the seasonality of the winds and the wind potential, as well as the most prominent areas of the Rio de Janeiro state, Brazil, this paper will describe in chapter 02 the methodology used and, alongside the Chapter 03, the main results in the form of graphs and wind maps, concluding in chapter 04 gathering the final considerations of the work.

2. Methodology

The current research used daily average data of wind speed that were provided by INMET. Altogether, there were 17 automatic weather stations located in different municipalities in Rio de Janeiro state. The sensors have a high-level accuracy and are arranged at the height of 10 meters. According to Wang and Zhao (2013) [6], the wind has characteristics such as intermittency, randomness and volatility, which impact the security and stability of associated electrical energy systems. Therefore, it is very important to know the seasonality of the winds in the candidate regions to host wind farms.

The analysis period is delimited between September 22, 2020, and September 22, 2021, it starting on the first day of spring and ending on the last day of winter. **Table 1** presents the geographic coordinates of the studied stations.

To begin with, the averages of wind speeds were calculated for the four seasons of the analyzed period, namely: spring, summer, autumn and winter. As a result, the values obtained served as a theoretical framework for the visual arrangement of the data displayed in the elaborated graphs. These images were emitted with the aid of Excel software and demonstrate in an uncomplicated way the comparative result between the wind speeds corresponding to the regions included in the study. It is also worth mentioning the use of the Geosoft program, Oasis Montaj, a tool responsible for rendering the interpolated two-dimensional maps.

Furthermore, the roughness of the surrounding terrain around the stations previously mentioned was evaluated. This process used the inference method based on what can be observed in the images from Google Maps, as shown in **Figure 1**.

Table 1. Geographic coordinates of the automatic weather stations used in the research.

Station	Longitude (degree)	Latitude (degree)
Arraial do Cabo	−42.0214	−22.9753
Campos dos Goytacazes	−41.0517	−22.0417
Carmo	−42.6009	−21.9387
Duque de Caxias - Xerém	−43.2822	−22.5897
Itatiaia	−44.7031	−22.3739
Jacarepaguá	−43.4028	−22.9400
Macaé	−41.8119	−22.3761
Pico do Couto	−43.2914	−22.4647
Resende	−44.4450	−22.4514
Rio Claro	−44.0409	−22.6536
Rio de Janeiro - Copacabana	−43.1906	−22.9883
Rio de Jeneiro - Vila Militar	−43.4114	−22.8614
Saquarema Sampaio Correia	−42.6089	−22.8711
Seropédica	−43.6847	−22.7578
Teresópolis - Parque Nacional	−42.9869	−22.4486
Três Rios	−43.2083	−22.0983
Valença	−43.6956	−22.3581

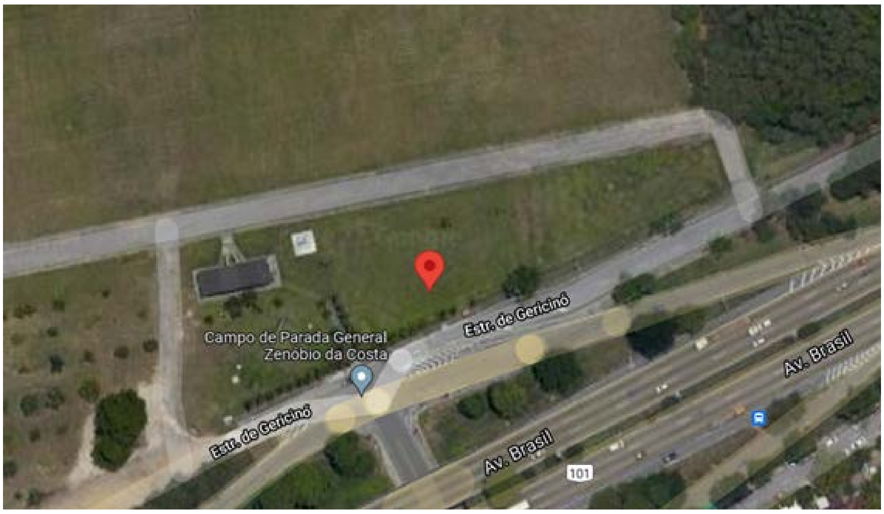

Figure 1. Satellite image of Vila Militar meteorological station [7].

It is possible to notice that the roughness estimate (Z_0) was interpreted by correlating the satellite images with the type of decked terrain in the respective place, as can be seen in Table 2.

Table 2. Roughness intervals [3].

Land type	Zo (m) Min.	Zo (m) Max.
Mud/ice	0.00001	0.00003
Calm sea	0.0002	0.0003
Sand	0.0002	0.001
Snow	0.001	0.006
Cereal field	0.001	0.01
Low grass/steppes	0.01	0.04
Descamped	0.02	0.03
Tall grass	0.04	0.1
Terrain with trees	0.1	0.3
Forest	0.1	1
Suburban settlement	1	2

In possession of the roughness and wind speed at 10 meters high, the Logarithmic Law (Equation (1)) of speed extrapolation to altitudes of 80 meters was operated. It is important to clarify that the option for this height is based on the wind patterns intended for large wind turbines.

$$\frac{u(h_2)}{u(h_1)} = \frac{\text{In}\left(\frac{h_2}{z0}\right)}{\text{In}\left(\frac{h_1}{z0}\right)} \tag{1}$$

where:

h_1 = height one;

h_2 = height two;

u = wind speed;

Z_0 = land roughness;

Concomitantly, the annual averages of the extrapolated data were calculated and the municipalities with an annual average above 3 m/s were selected since it is considered the minimum speed for the operation of large wind turbines. Through Equation (2), the available power was estimated among the stations participating in the study under the standardized requirement parameters of a wind turbine with a diameter of 100 meters.

$$P = \frac{1}{2}\rho A_r V^3 C_p \eta \tag{2}$$

where:

ρ = air density (1.225 kg/m^3 at sea level and at 15˚C);

A_r = area swept by the rotor (= D^2/4, D is the rotor diameter);

C_p = aerodynamic coefficient (maximum theoretical value = 0.593);

v = wind speed, in m/s;

η = efficiency of the generator set (~0.93 - 0.98);

Once the methodological strategies adopted in the theoretical process are listed, the main results obtained will be vehemently discussed in the development section.

3. Development

Figure 2, made from the daily average data of the 17 stations analyzed, shows the average wind speeds throughout the seasons of the year, as arranged below.

Through the reading of Figure 2, it is noted that the cities in which the winter season presented higher wind rates were Seropédica, Copacabana, Resende, Jacarepaguá, Itatiaia and Arraial do Cabo. The counties with a predominance of strong winds in spring were Valença, Três Rios, Vila Militar, Rio Claro, Pico do Couto, Macaé and Carmo. Moreover, the cities with predominance in summer wereTeresópolis and Saquarema, with the coincidence of Campos and Xerém presenting the same wind speed for summer and spring. Thus, it is noted that the best seasons of the year for wind were spring and winter, with the middle summer being the worst season. This anomaly is probably due to the SASA operation that in winter approaches the coast of Rio de Janeiro and at the beginning of spring it tends to migrate to the south increasing its intensity and wind rates in the state, especially in coastal cities.

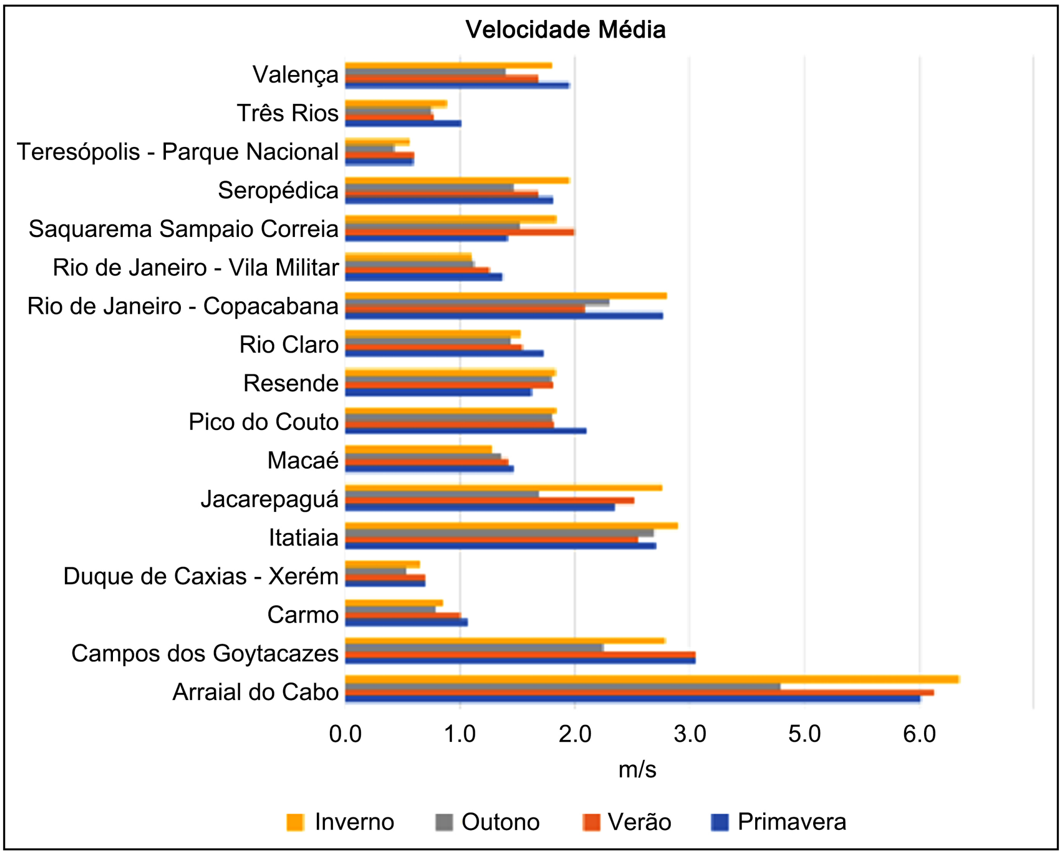

Figure 2. Average wind speeds throughout the seasons of the year.

The measurements obtained for all four seasons of the year in each city were used to create an interpolation map using the Minimum Curvature technique. The interpolation made it possible to cover regions where data were not disposable with information, it allowing the visualization of the wind regime throughout the seasons all over the state, as shown in Figures 3-6.

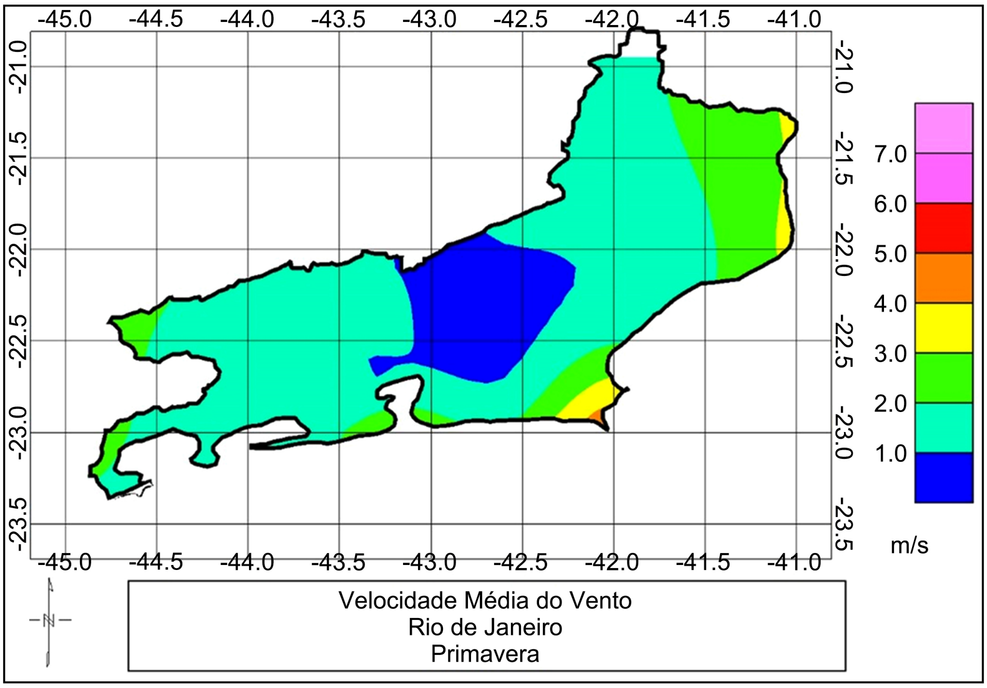

Figure 3. Wind speed interpolated map of Rio de Janeiro in spring.

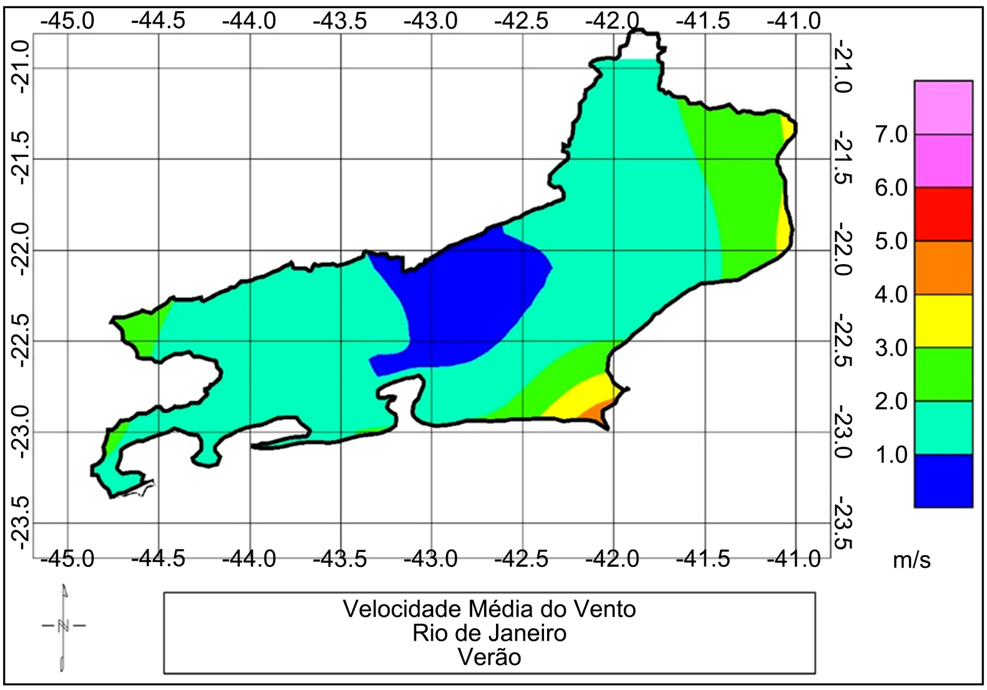

Figure 4. Wind speed interpolated map of Rio de Janeiro in summer.

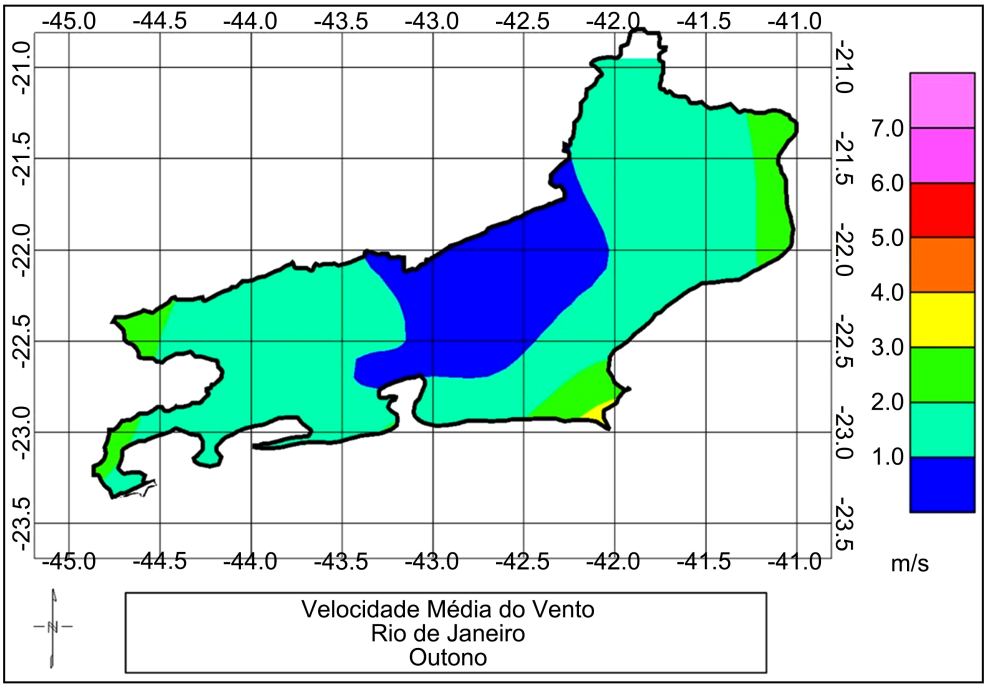

Figure 5. Wind speed interpolated map of Rio de Janeiro in autumn.

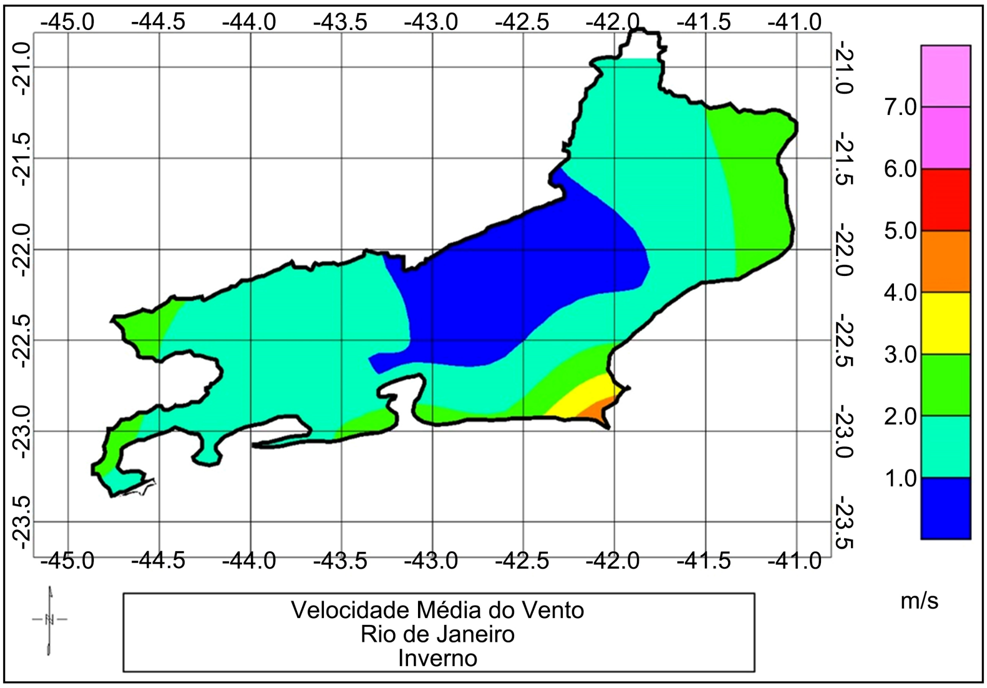

Figure 6. Wind speed interpolated map of Rio de Janeiro in winter.

In general, those maps present higher wind speeds in the Baixada Litorânea and on the east coast of the Norte Fluminense region. The Serrana and Centro-Sul regions of Rio de Janeiro had the lowest wind rates, and, as for the seasons of the year, the best indices were verified in descending order: spring, summer, winter and autumn.

Figure 7 sets forth the extrapolation of the average wind speeds into 80 meters, initially obtained at 10 meters. In order for the result to be achieved, Table 2 and Equation (1) were used as data processing methods.

In line with the above figures of average wind speed in Rio de Janeiro, there is a patterning of the regional wind expectation by seasons, even at high altitudes. This analysis is reinforced by the peaks evidenced at the station, which are consistent with the speed curves for optimized energy production, as seen in Figure 8.

As stated in Figure 7, Arraial do Cabo presented an average wind speed close to 10 m/s, which is very close to the nominal operating speed of large, wind turbines.

Based on these statistics, the meteorological stations with the best average wind speed were selected for a further projection of power. For these, Figure 9 presents a power data simulation obtained intended for a typical large wind turbine with a diameter of 100 meters and winds extrapolated to 80 m.

According to what was observed in Figure 7, the only municipalities with averages found above the cut-offline of 3 m/s (Figure 8) were Arraial do Cabo, Campos dos Goytacazes—Farol de São Thomé, Itatiaia, Jacarepaguá, Pico do Couto and Rio de Janeiro—Copacabana. In this way, it is verified, through the presented average wind speed, that the favorable scenario for the use of the wind resource for the generation of electric energy in large wind turbines occurs in the region of Arraial do Cabo. It is considered that the other stations did not present simulated data of sufficient power for optimized use of a wind turbine.

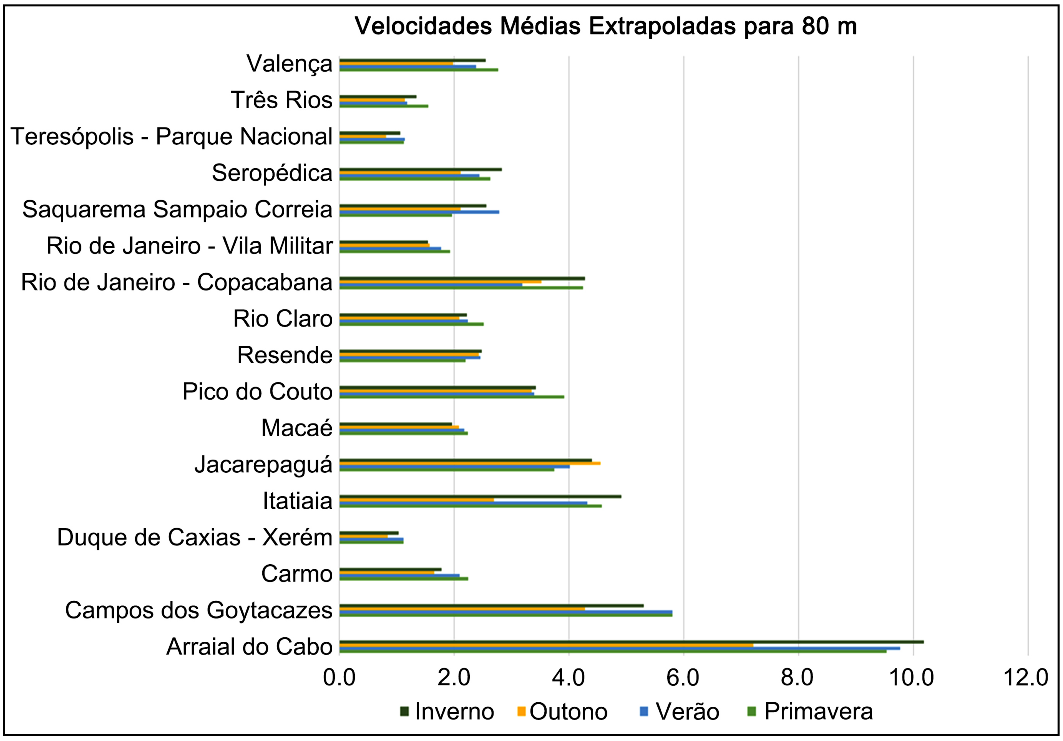

Figure 7. Average wind speeds extrapolated to 80 meters referring to the seasons.

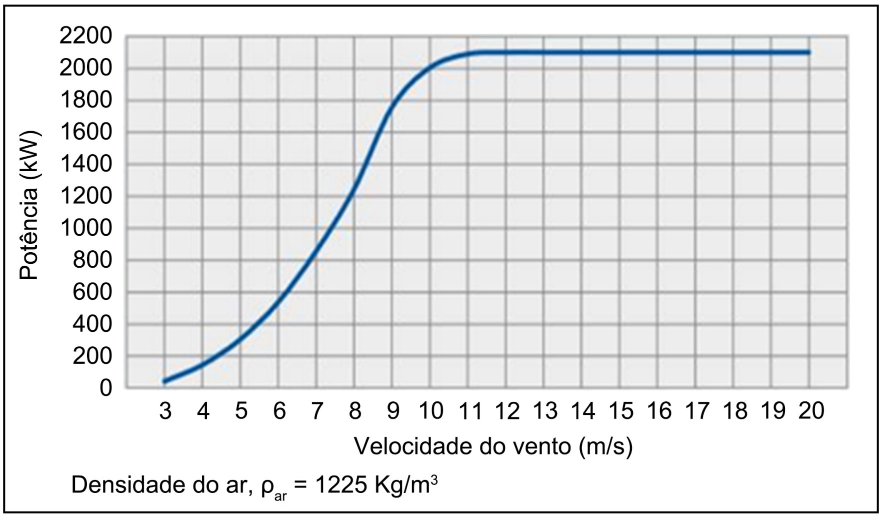

Figure 8. Power curve for the turbine AWG 110 2.1 [8].

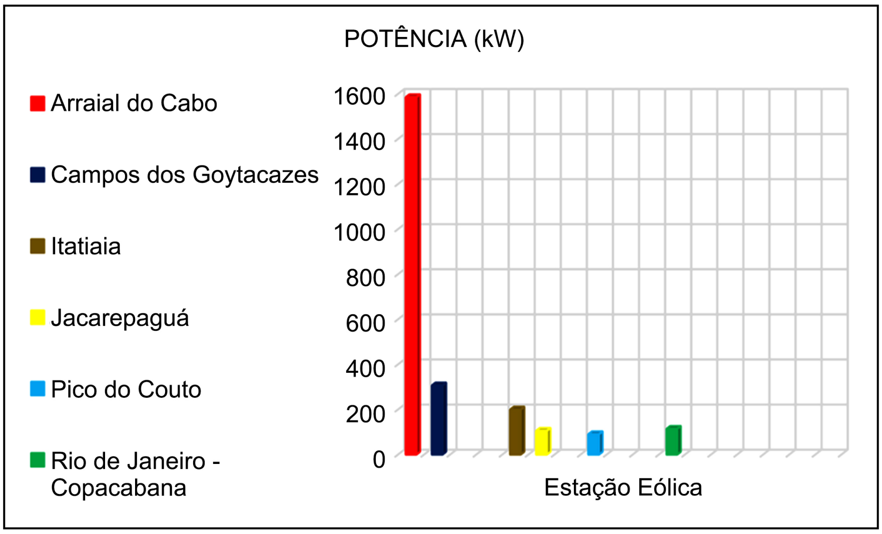

Figure 9. Potency for stations with an average annual speed greater than 3 m/s.

4. Conclusions

It has established the initial intention of evaluating the Rio de Janeiro potential of availability of wind energy for use in the generation of electric energy; it is concluded that the proposed objective was successful, given, mainly, that this work measured the wind data of 17 stations distributed in the Rio de Janeiro state. Thus, it is noteworthy that, due to the lack of INMET coverage, data from São Francisco de Itabapoana and surrounding regions were not used, which impacted the estimate of wind speed in the coastal area of Norte Fluminense. It is known, on the other hand, that the particular region has a high wind performance throughout the year, reinforced by the presence of the only wind farm in the state the Gargaú Wind Farm.

Therefore, it was found that the highest wind intensities occur in the Baixada-Litorânea and on the east coast of the Norte Fluminense region, where the Arraial do Cabo meteorological station stands out in its potential for a possible installation of a wind farm or use of small wind turbines, in order to contribute to the preservation of the environment. It was also found that the wind potential is not uniform in all seasons of the year, with autumn being the period with the lowest potential and spring the one with the highest.

It is observed that INMET has only one automatic rain gauge in the city of São Francisco de Itabapoana and, therefore, it is suggested that further research perform inference by grid algorithms to obtain an estimative of local wind data, using, of course, the station located in the municipality of Campos dos Goytacazes. By doing this, it would cover up the missing data of an impactive region to the eolic sector of Rio de Janeiro state, it complementing the achieved results.

Hence, it is expected that this work can contribute to professionals and scholars interested in the area. Likewise, it is emphasized, complementing the above paragraph, that municipalities such as Campos's dos Goytacazes and Itatiaia have sufficient wind resources to take advantage of the wind as mechanical potential energy but lack greater intensity for an optimized conversion into electrical energy.

It all boils down to the conclusion of Arraial do Cabo being the adequate municipality to be invested in when taking the eolic path of the green energy segment. The other 16 studied stations failed to show enough wind potential for these cities to receive investments in eolic turbines or wind farms, making them less attractive for this energy production sector.

Conflicts of Interest

The authors declare no conflicts of interest.

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