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MAP OF COMPLEMENTARITY OF SOLAR-WIND ENERGY IN THE STATE OF RIO GRANDE DO NORTE

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Abstract. *The northeast region of Brazil is rich in solar and wind resources, which means that this region has great potential for generating electricity through these sources. Knowing that these sources, as well as water resources, have a seasonal behavior, it is of great importance to study their correlation. Knowing the standard behavior of wind-solar resources allows optimizing hybrid plants so that, even if one of the resources is low, the plant continues to produce the same amount of electricity without major variations. The objective of this work is to develop a map of the complementarity of solar-wind energy in Rio Grande do Norte in order to verify the relationship between both resources in several cities in the state. For the study, we used a climate database in the Typical Meteorological Year format referring to several points in this location. These data were used to estimate the energy generation from solar and wind sources, according to the base literature. In the temporal complementarity analysis, the Pearson Correlation Coefficient (PCC) was selected for data from a complete meteorological year, with the values of the calculated coefficients applied in the temporal analyses. At the end of the study, it was concluded that more than half of the cities analyzed have the minimum of complementarity between renewable resources, and the city that has the highest level of complementarity is Vera Cruz with a PCC of 0.6704.*

Keywords: *Solar energy, Wind energy, Temporal complementarity.*

1. INTRODUCTION

The Brazilian electricity matrix is quite diversified, with participation of both renewable and non-renewable sources. One of the most prominent sectors in the energy matrix is hydroelectric power plants. Despite being responsible for a large portion of the matrix, the water source is susceptible to periods of drought that can make its use unfeasible. In addition, this type of plant requires large transmission lines so that it can meet the electrical needs of various regions of Brazil (Rezende, 2020). These factors make the generation of electric energy, by water sources, unstable and expensive.

The sector of hydroelectric plants is responsible for approximately 56 % of the energy matrix, however with the advance of wind energy this value has been decreasing more and more. Currently, the wind energy sector occupies a share of approximately 11.8 %, including an increase of 1.9 % in relation to last year, in addition this sector has great growth expectations for this year (ABEEólica, 2022). The Brazilian region that has the most wind farms is the northeast region, where 80 % of the plants are located, with Rio Grande do Norte being the state with the highest concentration of plants. The northeast region is known for having one of the best winds in the world for energy production (ABEEólica, 2022).

Another renewable source that has been gaining ground is the solar energy sector. Currently, the sector has approximately 15.8 GW operating in Brazil, with a 7.8 % share in the energy matrix. Rio Grande do Norte occupies the 15th place in the ranking of installed power with a power of 244.4 MW, with the state of Minas Gerais in first place with 1787.6 MW of installed power (ABSOLAR, 2022).

It is important to highlight that both renewable sources bring numerous benefits, some of which are: income generation, does not generate pollution, does not emit CO₂, generation of jobs, among others. Despite the benefits and advantages of using these renewable sources, they are also subject to seasonal variations that can cause instability and affect energy generation. Given this fact, studies on the temporal complementarity between both solar and wind energies have advanced more and more. Many studies seek to understand the complementarity of these sources and even combine them in a hybrid plant, so that this plant has maximum stability so that there are no large variations in energy generation.

The objective of the present work is to carry out an analysis about the complementarity between wind and solar sources

in the state of Rio Grande do Norte (RN), aiming to create a map that describes the behavior of this complementarity in various parts of the state. For this analysis, data from 116 cities in RN will be used.

2. METHODOLOGY

Aiming at producing the map and analyzing the complementarity of wind and solar sources, an algorithm was developed that performs the analysis of the data, estimates the energy production based on them and calculates the complementarity between them. For the estimation of wind and solar energy generation, a wind turbine model and a photovoltaic plate model were chosen, which have their specifications described, respectively, in Tab. 1 and Tab. 2.

Table 1. Model and specifications of the wind turbine.

Wind turbine	Vesta V150
Nominal power	4.2 MW
Rotor height	125 m
Start speed	3 m/s
Shutdown speed	22.5 m/s

Table 2. Model and specifications of the photovoltaic module.

Photovoltaic module	Canadian CS3U 345P
Nominal Power	345 W
Operating voltage	38.6 V
Operating current	8.94 A
Efficiency	17.39 %
Dimensions	2000 x 992 x 40 mm
Weight	22.5 kg

It is important to highlight that the calculation of complementarity does not depend on the number of wind turbines or photovoltaic panels, but on the generation potential of these sources, for this reason in this analysis only one equipment of each was simulated, so that in this study it was not taken into consideration situations that can affect energy generation such as wake effect and shading.

2.1 Solar energy estimate

The estimation of solar energy production is important in this analysis, as it will indicate the energy generation potential that this resource has. It is worth noting that energy generation can also vary depending on the photovoltaic module, so only one model was selected to be applied in all regions.

For this estimate, we chose to use the equation proposed by Bett and Thornton (2016), which estimates the power generated, P_G , based on the efficiency of the system under operating conditions, $\eta_{rel}(G, T)$, on the horizontal global irradiation, G , on the area of the photovoltaic module, A , on the efficiency of the module under test conditions, η_{STC} , on the efficiency of the other equipment, η_e . The generated power expression is described by Eq. (1), and Eq. (1) represents the efficiency under standard test conditions, where $G_{STC} = 1000 \text{ W/m}^2$ and the test temperature is 25°C .

$$P_G = \eta_{rel}(G, T) \eta_{STC} \eta_e A G \quad (1)$$

$$\eta_{STC} = \frac{P_{STC}}{A G_{STC}} \quad (2)$$

The calculation of the system efficiency is performed based on Eq. (3), where α , β , c_1 and c_2 are data from the photovoltaic module, and G' and ΔT_{mod} are described, respectively, in Eq. (4) and Eq. (5) (Bett and Thornton, 2016).

$$\eta_{rel}(G, T) = (1 + \alpha \Delta T_{mod}) \left(1 + c_1 \ln(G') + c_2 \ln(G')^2 + \beta \Delta T_{mod} \right) \quad (3)$$

$$G' = \frac{G}{G_{STC}} \quad (4)$$

$$\Delta T_{mod} = \left(T + (T_{NOCT} - T_0) \frac{G}{G_0} \right) - T_{STC} \quad (5)$$

The values of the coefficients of the selected photovoltaic module are in Tab. 3. To calculate the T_{mod} , the values of 20°C , 800 W/m^2 and 48°C , respectively, were used for G_0 , T_0 and T_{NOCT} (Weschenfelder, 2019).

Table 3. Coefficient for photovoltaic module made of crystalline silicon.

Coefficient	Value
α	$4.2 \times 10^{-3} K^{-1}$
β	$-4.6 \times 10^{-3} K^{-1}$
c_1	0.033
c_2	-0.0092

2.2 Estimate of energy produced by wind source

In order to estimate the power generated by the wind source, Eq. (6) was used, which considers the wind speed, the rated speed and the rated power of the wind turbine. The values of a and b can be calculated by Eq. (7) and Eq. (8), respectively.

$$P(V) = a + bV + cV^2 \quad (6)$$

$$a = \frac{P_n \cdot V_i}{(V_i - V_n)} \quad (7)$$

$$b = \frac{P_n}{(V_n - V_i)} \quad (8)$$

The relationship presented above was established based on the power curve of a wind turbine that is divided into three regions, the first being before the cut-in, in which the wind speed is not enough to make the wind turbine work, the second is the turbine operating region in which power varies with wind speed and the third is the region where power is constant regardless of wind speed variation (Weschenfelder, 2019).

2.3 Calculation of complementarity

To calculate complementarity, there are several metrics that can be used, such as Kendall's correlation coefficient (KCC), Pearson correlation coefficient (PCC), complementarity indices, cross-correlation, among others. According to the literature used in this study, the PCC is widely used in temporal complementarity analyses, for this reason we chose to use this metric (Weschenfelder, 2019; Campos, 2020).

Pearson correlation coefficient is a metric used to measure the level of correlation between two sets of data, being suitable for data that have linear behavior. The coefficient value can range from -1 to 1, where -1 indicates a strong and negative correlation and 1 indicates a strong and positive correlation. When the coefficient has a positive value it means that the data set have similar behaviors, so that when one decreases the other too. For negative values, the behavior between the two data sets is opposite, so when one decreases the other increases.

The absolute value of the coefficient represents the level of complementarity. A Pearson correlation coefficient in the range of $0 \leq PCC < 0.3$ indicates that the data have an insignificant correlation, for the range of $0.3 \leq PCC < 0.5$ the correlation is weak, of $0.5 \leq PCC < 0.7$ the correlation is moderate, from $0.7 \leq PCC < 0.9$ the correlation is strong, finally, for coefficient values greater than or equal to 0.9 the correlation is considered very strong.

Pearson's correlation coefficient can be calculated by Eq. (9), in which x_i and y_i represent the i th value of each data set, whereas \bar{x} and \bar{y} represent the average of each set.

$$PCC = \frac{\sum_{i=1}^n (x_i - \bar{x}) \cdot (y_i - \bar{y})}{\sqrt{\sum_{i=1}^n (x_i - \bar{x})^2} \sqrt{\sum_{i=1}^n (y_i - \bar{y})^2}} \quad (9)$$

2.4 Data and parameters for the simulation

For the analysis proposed in this study, tables of Typical Meteorological Year (TMY) of several cities located in the state of Rio Grande do Norte (RN) were used. TMY tables are spreadsheets with hourly data for a complete meteorological year that represent the typical behavior of that region.

This data was taken from the European Commission website. The data has values of latitude, longitude, altitude, date and time, dry bulb temperature, relative humidity, global horizontal irradiance, direct irradiance, horizontal diffuse irradiation, wind speed and wind direction.

3. RESULTS

Based on the methodology described, after processing the data sheets, the algorithm returned a list with the Pearson correlation coefficient for each analyzed city. The Tab. 4 presents a list of the ten cities with the lowest PCC. In which all

have an insignificant coefficient. The Tab. 5 presents a list of the ten largest Pearson correlation coefficient, all of which are moderate.

Table 4. List of cities with the smallest PCC.

City	PCC
Tibau	-0.0518
Porto do Mangue	-0.0312
Cruzeta	0.0971
Ouro-Branco	0.1031
Serra Negra do Norte	0.1387
São Fernando	0.1468
São João do Sabugi	0.1494
Triunfo	0.1538
Upanema	0.1554
Itajá	0.1569

Table 5. List of cities with the largest PCC.

City	PCC
Vera Cruz	0.6704
Arez	0.6600
Taipú	0.6507
Nova Cruz	0.6500
Goianinha	0.6465
São José do Mipibu	0.6461
Santo Antônio	0.6439
Ielmo Marinho	0.6403
Ceará-Mirim	0.6350
Pureza	0.6282

The Tab. 6 shows the percentage of cities according to the level of complementarity. In the table it is possible to verify that 26.72 % of the analyzed cities have a moderate correlation and 29.31 % have a weak level of complementarity. Analyzing the tables, it is possible to notice that only two cities have a negative PCC, so what predominates in the region is that the generation of wind and solar energy have a similar and proportional behavior.

Table 6. Percentage of cities by correlation level.

Interval	%
$-0.3 < PCC \leq 0$	1.72
$0 \leq PCC < 0.3$	43.96
$0.3 \leq PCC < 0.5$	29.31
$0.5 \leq PCC < 0.7$	26.72
$0.7 \leq PCC < 0.9$	0
$0.9 \leq PCC < 1$	0

Finally, after obtaining the data, the map presented in Fig. 1 was produced, which shows the behavior of the complementarity of each analyzed city. Observing the graph, it is possible to notice that the cities that have a moderate PCC are located in the east and southwest of the state. On the other hand, cities located near the center of the state have a weak or insignificant correlation.

4. CONCLUSION

This work consists of analyzing the behavior of the complementarity between wind and solar energy generation in the state of Rio Grande do Norte. The objective is to establish and identify the relationship between the two renewable sources, so that one can supply the other in low periods. To perform this analysis, data from cities in the state were selected, being 116 cities, in addition to selecting a photovoltaic plate model and a wind turbine model. Based on these data, it was possible to estimate the power generated by both renewable sources studied using as a basis the equations

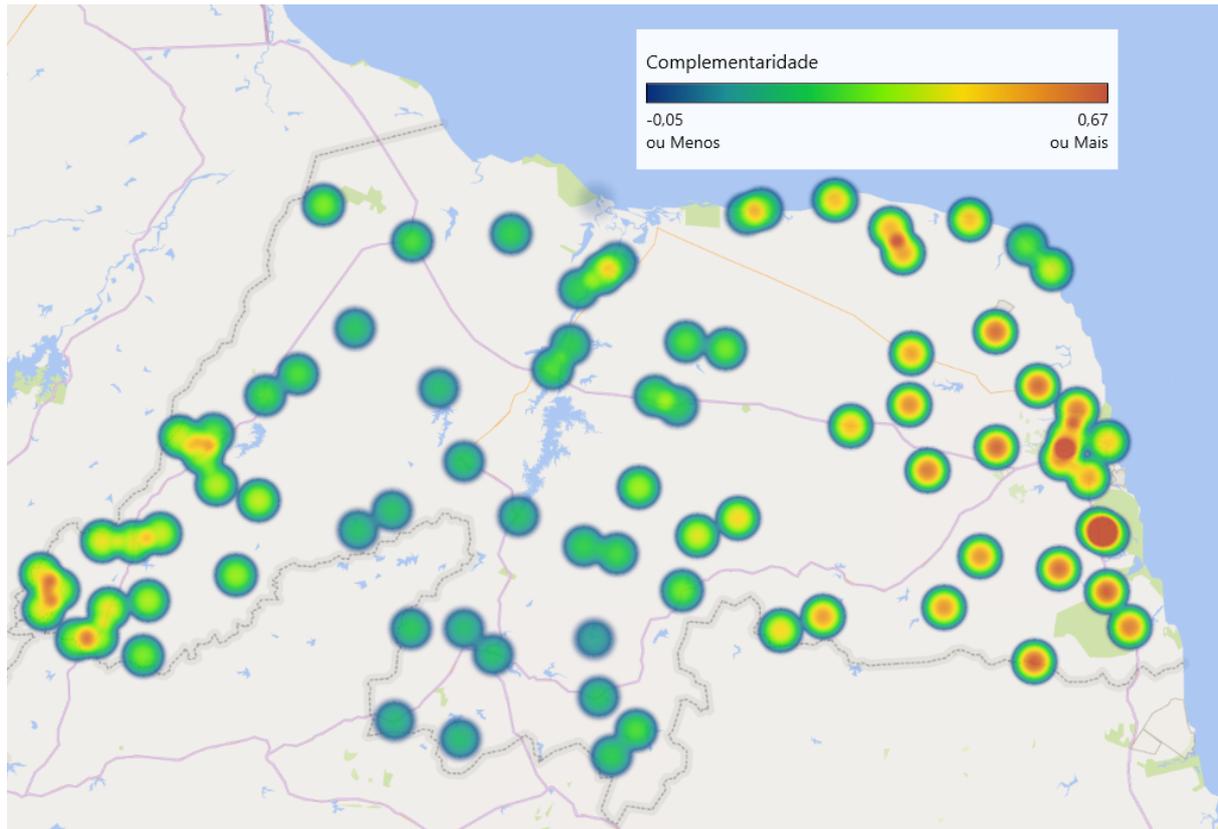


Figure 1. Map of the complementarity between solar and wind energy.

recommended by Bett and Thornton (2016) and Weschenfelder (2019). To calculate the complementarity, Pearson's Correlation Coefficient was selected as a metric, which is widely used in temporal complementarity analyses.

As a result, the PCC of each analyzed city was obtained, thus enabling the construction of the map. In Tab. 4 it is possible to visualize the ten cities with the lowest coefficient values. It is important to note that only two cities have a negative coefficient and all are located in the northern region of the map, the other cities listed in the table are located in the south center of the state. The negative coefficient indicates that the energy from the wind and the sun have opposite behaviors, but its absolute value is so small that it is considered insignificant, thus it is defined that in these cities there is no complementarity between renewable resources.

In Tab. 5 it is possible to verify the ten cities with the highest PCC, and the vast majority of cities are located in the eastern region of the state. In the table it is possible to notice that the highest coefficient is that of the city of Vera Cruz, with a value of 0.6704. This positive coefficient indicates that the solar and wind resource have a similar behavior, so that when one increases, the other also increases. Analyzing the absolute value, we have that the complementarity in this city is moderate, that is, it exists, but it is not considered strong.

The Tab. 6 shows the percentage of cities by level of complementarity. It can be noted that no city has a complementarity considered strong or very strong. We have that 26.72 % of the cities have a complementarity considered moderate and 29.31 % have a weak complementarity. The rest of the cities have a complementarity considered insignificant. Based on this, it can be concluded that in more than half of the cities analyzed there is a considerable level of complementarity between renewable resources.

The Fig. 1 presents the map of complementarity between wind and solar energy, in which it is possible to verify the disposition of cities and regions that have the highest and lowest levels of complementarity. Looking at the map, we see that the cities with the highest PCC values are located in the extreme east and west of the state, and the east region has a greater number of cities with a high level of complementarity. In the central region of the state, the largest concentration of cities with low PCC is located.

At the end of the work, it can be concluded that in the state of Rio Grande do Norte there is a relationship of complementarity between the renewable resources analyzed, but none of the cities used in the study presented a strong complementarity. We can also conclude that the potential for wind and solar generation has similar behavior, given that the vast majority of cities have a positive PCC. It is important to highlight that this study used data from a typical meteorological year, so that any adverse or unforeseen situation can affect the complementarity relationship between wind and solar energy. Another factor that is important to be taken into account is that the Pearson Correlation Coefficient is sensitive to

outliers and extreme values, and these values can affect the calculation of complementarity.

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