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TECHNICAL ANALYSIS OF COMPLEMENTARITY OF ENERGY GENERATION FROM SOLAR-WIND PLANTS IN RIO GRANDE DO NORTE

Leslye Soares Ferreira
Gabriel Ivan Medina Tapia
Federal University of Rio Grande do Norte, Technology Center - Natal
leslyesoares@gmail.com, gmedinat@ct.ufrn.br

Abstract. This work analyzes the complementarity of energy production from solar-wind power plants, intending to optimize a hybrid power plant that results in a more uniform generation and can meet the energy demand. For the study, it was considered that the hybrid plant is located in the state of Rio Grande do Norte, using a climate database in the Typical Meteorological Year format referring to this location. Complementary analyzes were carried out for three years, from 2017 to 2019. In the analysis of temporal complementarity, the Pearson Correlation Coefficient (PCC) was used, and an algorithm was developed in the MATLAB software that performs the temporal analysis. Three temporal analyzes were carried out: (i) analysis of the complementarity of energy production between wind and solar resources over the three years; (ii) analysis of the daily complementarity of wind and solar energy production; (iii) analysis of the complementarity between total energy production and energy demand in the region. As a result, the PCC of wind and solar energy production over three years is 0.5723. The average complementarity of solar and wind energy production over a day is 0.6157. This indicates a positively moderate relationship, which indicates that the production of wind and solar energy have similar behavior in the study region. In the optimization analysis of a plant, the configuration that presented the best complementarity with energy demand was that of a solar plant.

Keywords: wind energy, solar energy, temporal complementarity, Pearson Correlation Coefficient.

1. INTRODUCTION

The hydroelectric power plant sector has the largest share in the Brazilian electricity matrix, accounting for a share of 59.4 % (ABSOLAR, 2021). However, seasonal variations affect the production of electricity, so it is necessary to use thermoelectric plants to make up for these losses. The big problem with the use of thermoelectric power is that they are responsible for emitting amounts of greenhouse gases. In recent years the investment in wind and solar energy has been growing enormously, actually, the percentage of participation of wind and solar resources in the Brazilian electric matrix is, respectively, 9.9 % and 1.8 % (ABSOLAR, 2021).

Despite the predominance of water sources in the Brazilian electricity matrix, solar and wind energy are the sources with the highest growth expectations until 2050 (Bullard, 2018). The increased use of these sources has been driven by climate change, making an investment in clean energy production necessary. However, both sources are susceptible to seasonal variations that greatly influence electricity generation. With this in mind, we seek to analyze the complementarity between the two sources so that energy production does not have drastic changes throughout the year. Assuming the existence of complementarity between solar and wind sources, the combination of these sources in a hybrid plant is seen as an attenuating alternative for the variations suffered by them (Hoicka and Rowlands, 2011).

The present work aims to analyze the solar-wind complementarity over three years, evaluating the attenuation in the energy production curve and the fulfillment of energy demand. For this study, the state of Rio Grande do Norte, located in the region of Brazil, which has one of the best potentials for solar and wind energy, was selected.

2. METHODOLOGY

To analyze the complementarity of a hybrid solar-wind plant has developed an algorithm in MATLAB software, which performs simulations for different cases. These cases are based on the percentage share of wind and solar energy, which can range from 100% to 0%. The Tab. 1 presents the cases analyzed in this study.

In the simulation of the plant, an installed capacity of 42 MW was selected. To obtain the energy production for each source, an estimate was made based on solar and wind speed data.

For the study of complementarity, there are a number of metrics that can be applied to the study, some of which

Table 1. Composition of simulated cases in the analysis.

Case	Solar (%)	Wind (%)
1	0	100
2	10	90
3	20	80
4	30	70
5	40	60
6	50	50
7	60	40
8	70	30
9	80	20
10	90	10
11	100	0

are: Kendall correlation coefficient (KCC), Pearson correlation coefficient (PCC), cross-correlation and complementarity indices. In order to avoid redundancies, the PCC was selected for this study.

For the analysis of load service, a study of the complementarity between the power demand curve and the total energy produced in each case was carried out. The purpose of this analysis is to verify which configuration has the best complementarity with the load required to meet the system under analysis, the absolute value of the data not being relevant, but the relative variation.

2.1 Estimate of energy produced by solar source

The estimate of solar energy production is of fundamental importance for this study. It uses data on solar irradiation, ambient temperature and some specifications of the photovoltaic module.

According to Bett and Thornton (2016), the output power of a solar power plant is expressed by Eq. (1), in which $\eta_{rel}(G,T)$ is the efficiency of the system under operating conditions, η_{STC} is the efficiency under standard test conditions, η_e is the efficiency of the other equipment, A is the total area of the solar panel and G is the global horizontal irradiation (Weschenfelder, 2019).

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

The efficiency under standard test conditions is given by Eq. (2), where $G_{STC} = 1000\ W/m^2$ and the standard test temperature is 25^oC.

$$\eta_{STC} = \frac{P_{STC}}{AG_{STC}} \tag{2}$$

The system efficiency is given by Eq. (3), where the constants present in the equation are specified in Tab. 2, which are specific for photovoltaic modules made of crystalline silicon (Bett and Thornton, 2016).

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

Table 2. Coefficient for photovoltaic module made of crystalline silicon.

Coefficient	Value
α	$4.2x10^{-3}\ K^{-1}$
β	$-4.6x10^{-3}\ K^{-1}$
c_1	0.033
c_2	-0.0092

The component G' is equal to the ratio between G and G_{STC}, and $\Delta T_{mod} = T_{mod} - T_{STC}$, where T_{mod}, temperature of photovoltaic module, is given by Eq. (4).

$$T_{mod} = T + (T_{NOCT} - T_0)\frac{G}{G_0} \tag{4}$$

The reference values T_0 and G_0 are, respectively, $20\ ^oC$ and $800\ W/m^2$. According to Weschenfelder (2019), a value used for T_{NOCT}, found in modules made of crystalline silicon, is $48\ ^oC$.

2.2 Estimate of energy produced by wind source

The relationship between wind speed and generated power is based on the wind turbine power curve. This curve is divided into three sections: the first being the region where the speed is below the cut-in, which is the starting speed of the wind turbine operation; the second section is the operating region where the power varies with the wind speed; and the third section is the region where the power remains constant until the cut-out speed, which is the turbine shutdown speed (Weschenfelder, 2019). The output power model used in this study is the linear model, Eq. (5), which is based on the input velocity, V_i, on the nominal velocity, V_n, and at the nominal power, P_n.

$$P(V) = a + bV + cV^2 \qquad (5)$$

In this model, the speed can vary between V_i and V_n, values outside this range being disregarded. Since the model is linear, the constant c is null, whereas the other constants, a and b, are expressed by Eq. (6) and Eq. (7), respectively .

$$a = \frac{P_n \cdot V_i}{(V_i - V_n)} \qquad (6)$$

$$b = \frac{P_n}{(V_n - V_i)} \qquad (7)$$

2.3 Data and parameters for the simulation

For the simulation, observational meteorological data from an automatic station of INMET (National Institute of Meteorology) located in the city of Natal, Rio Grande do Norte, were used. This data is provided through a table in TMY (Typical Meteorological Year) format which has hourly data for a full year. For the analysis, data from the years 2017 to 2019 were selected.

For the load service analysis, the subsystem of the region being analyzed, the northeast subsystem, was selected. Data were obtained from a table from the National Electric System Operator (ONS). Monthly data were collected for the years 2017 to 2019. The Fig. 1 shows the load curve of the northeast subsystem for the three years studied.
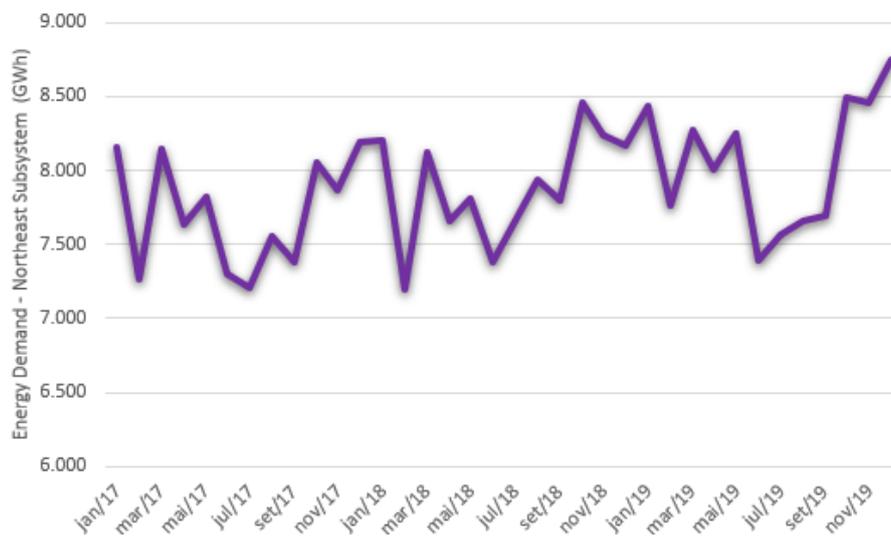

Figure 1. Northeast subsystem energy demand curve.

As a simulation parameter, a wind turbine model and a solar panel model were chosen. The selected models and their specifications are presented in Tab. 3 and Tab. 4.

Table 3. 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 4. 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

2.4 Pearson Correlation Coefficient (PCC)

The Pearson correlation coefficient is a metric that measures the correlation between two continuous variables, widely used in the study of temporal complementarity between solar and wind resources (Weschenfelder, 2019; Campos, 2020). This coefficient must be applied to data sets that have linear behavior, because for non-linear cases the coefficient will not have an adequate representation. PCC is expressed by Eq. (8).

$$CCP = \frac{\sum_{i=1}^{n}(x_i - \bar{x}) \cdot (y_i - \bar{y})}{\sqrt{\sum_{i=1}^{n}(x_i - \bar{x})^2}\sqrt{\sum_{i=1}^{n}(y_i - \bar{y})^2}} \tag{8}$$

The x_i and the y_i represent the i-th samples of each set, $\bar{x}$ and $\bar{y}$ represent the mean values of each sample.

As a result, this coefficient has values between 1 and -1, which correspond, respectively, to a strong and positive correlation, and a strong and negative correlation. When the correlation is strong and positive, this indicates that the two variables increase or decrease together, whereas when the correlation is strong and negative, the indication is that when one variable increases, the other decreases, and the inverse is also valid.

The strength of the correlation between each set varies according to the absolute value of the coefficient. For an absolute value of PCC greater or equal to 0.9, we have a very strong correlation, for values between $0.7 \leq CCP < 0.9$, the correlation is strong, for values between $0.5 \leq CCP < 0.7$, correlation is moderate, for $0.3 \leq CCP < 0.5$, the correlation is weak, and for values between $0 \leq CCP < 0.3$ the correlation is negligible (Weschenfelder, 2019).

In developing the algorithm, the following analyzes were performed: complementarity of energy produced from wind and solar sources; complementarity of the total energy produced and the energy load; and daily complementarity of solar and wind energy production. In the analysis of the complementarity between wind and solar resources, negative values of the Pearson correlation coefficient are expected, as a more uniform energy production without major variations is desired. In the analysis of complementarity between the total energy produced by the plant and the energy load, positive values of complementarity are expected, so that when there are peaks and falls in energy demand, the plant will be able to supply the demand.

3. RESULTS

The first analysis of temporal complementarity is based on the energy produced by solar and wind sources, in which the energy produced by each source was calculated and Pearson correlation coefficient was applied. As described in the methodology, eleven cases were simulated, but these scenarios do not influence this first analysis, because regardless of the number of wind turbines or photovoltaic modules, the curve will be the same, changing only the values. For the first analysis, the Pearson correlation coefficient is 0.5723, which indicates a moderate positive correlation, that is, when the production of wind energy increases, the production of solar energy also increases. Fig. 2 presents the curves of energy produced monthly over three years.

The curves presented have a similar behavior, which is in agreement with the PCC result. As seen in Fig. 2, the month of october has a great increase in the production of wind and solar energy, while the month of april has the lowest values.

The second analysis is based on the energy demand of the northeast subsystem and the total energy produced by the sources. In this analysis, the Pearson correlation coefficient varies according to the case. Fig. 3 presents the monthly wind and solar energy production curves for the eleven scenarios described.

In the image, it is possible to verify the change in the energy curves as the participation of each source varies, in addition to the behavior of each of them during the thirty-six months analyzed. Tab. 5 presents the results of the Pearson correlation coefficient from the first and second analysis.

In the table it is possible to verify that the case eleven, which has only the participation of the solar source, is the one with the highest PCC, and this relationship is considered moderately strong. The case one, which has only the participation of the wind source, is the scenario that has the lowest complementarity value. Cases one to four have negligible PCC, from five to nine the correlation is considered weak. Fig. 4 shows the energy demand and total energy produced curves for case eleven and one.
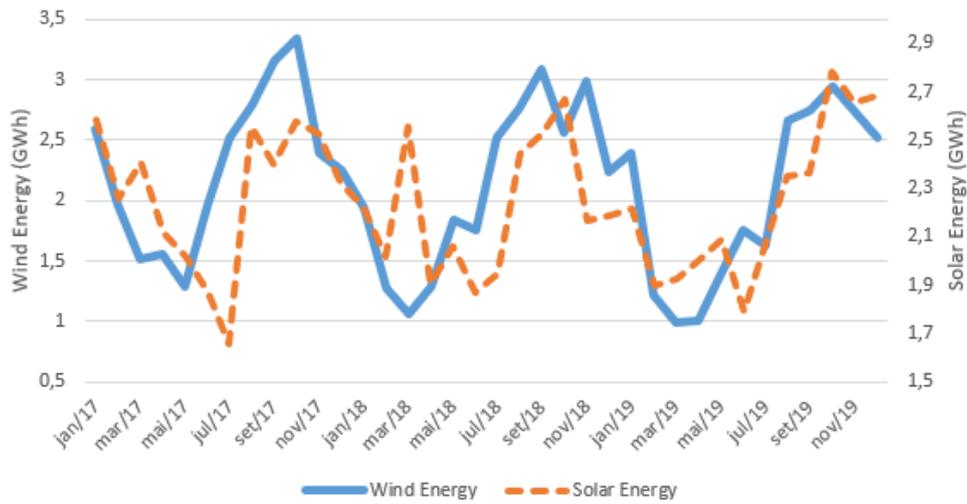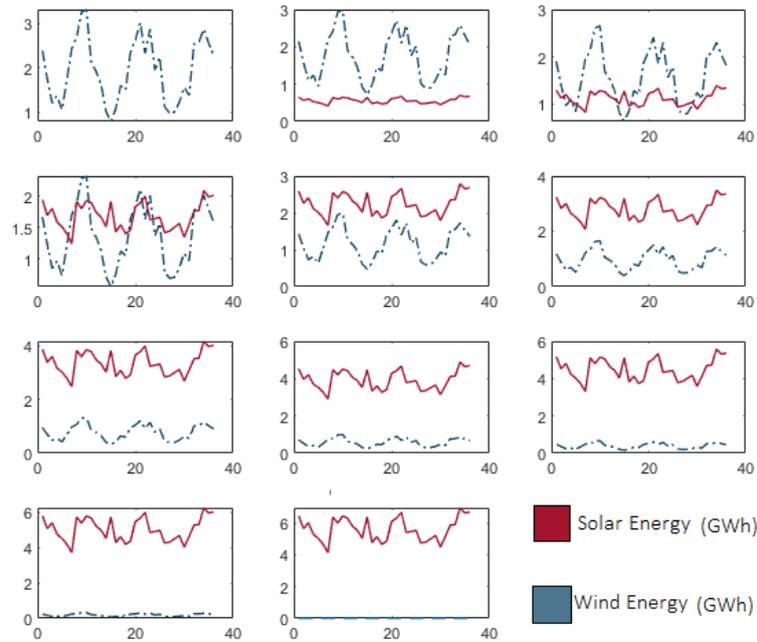
Figure 2. Wind energy x Solar energy.

Figure 3. Solar and wind energy production curves.

Table 5. Pearson correlation coefficient of the cases.

Case	Solar (%)	Wind (%)	PCC (Solar x Wind)	PCC (Total energy x Energy demand)
1	0	100	——	0.1437
2	10	90	0.5723	0.1773
3	20	80	0.5723	0.2147
4	30	70	0.5723	0.2561
5	40	60	0.5723	0.3012
6	50	50	0.5723	0.3495
7	60	40	0.5723	0.3996
8	70	30	0.5723	0.4495
9	80	20	0.5723	0.4965
10	90	10	0.5723	0.5377
11	100	0	——	0.5705

The last analysis performed was the complementarity of the daily production of solar and wind energy, in which the
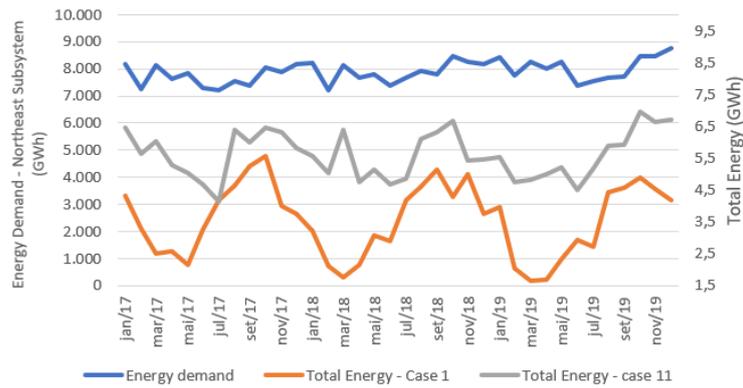
Figure 4. Energy demand curve and total energy curve.

daily average of the three years studied is 0.6157. This value indicates a positively moderate relationship. Fig. 5 shows the monthly average of daily complementarities.
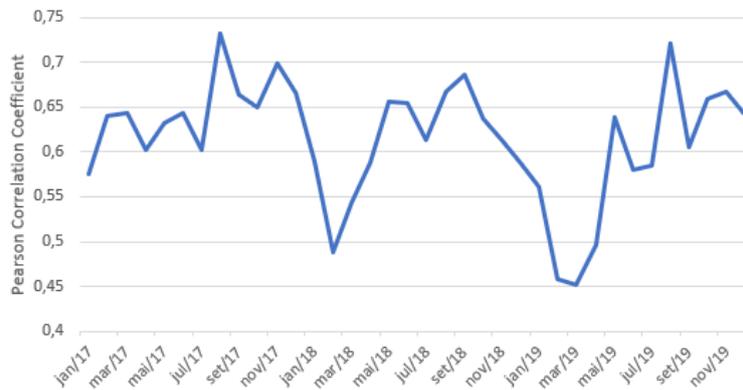

Figure 5. Average monthly PCC curve.

Through the graph it is possible to verify that the greatest monthly average complementarity belongs to the month of September.

4. CONCLUSION

The use of wind and solar sources is the fastest growing in recent years. However, these resources suffer from seasonal variations, which can affect energy production. Many studies on wind-solar complementarity have been carried out with the aim of joining these sources in a hybrid power plant that has a uniform energy output.

Based on this, this study was carried out with the aim of analyzing the complementarity of the production of wind-solar energy in order to establish the existence of this relationship. Eleven different scenarios were also established, in which each case has a different percentage share of wind and solar sources. These cases were used to simulate different configurations of a power plant, which were submitted, together with the region's energy demand, to temporal complementarity analysis.

This study used meteorological data from the city of Natal in Rio Grande do Norte. Data from the years 2017 to 2019 were selected. The energy demand data used correspond to this same period of time.

The first analysis performed was the correlation between solar-wind resources over the three years. As a result, a PCC of 0.5723 was obtained, which indicates a moderate correlation. Analyzing the graph in Fig. 2, it is possible to verify that both curves have similar behavior.

As a way to complement this analysis, a study of the complementarity between wind and solar resources was carried out over the course of a day, which resulted in an average PCC of 0.6157. That is, just like the annual analysis, the daily analysis also showed a significant correlation, but the relationship was expected to be negative.

The other analysis made was the complementarity of the energy produced by these resources and the energy demand. Tab. 5 shows different values for each scenario studied. The case that presented the greatest complementarity with the energy demand was the one with 100 % of solar source share.

Finally, it is possible to conclude that for the installation of a plant whose objective is to supply the demand of the studied region, the best option would be a solar plant. Although the complementarity between solar and wind resources are

relevant, a negative relationship was expected, so that the system's output energy would be smoother and more uniform, without major changes in production.

Unfortunately, this work was limited by the lack of data, which made it impossible to develop a complete profile of complementarity in the state of Rio Grande do Norte. This limitation also made it impossible to verify the fluctuations around the hourly averages, which is extremely important for this article, because within this range there can be peaks of wind speed that have a great influence on the production of wind energy.

For future research, it is recommended to investigate the complementarity in other cities in the state of Rio Grande do Norte in order to build a more complete profile of the region. Another important line of study would be the assembly of a hybrid plant configuration, applying a wake effect on the wind turbines and shading on the photovoltaic plates in order to verify the impacts of these effects on energy production and what is the best layout for this plant.

5. REFERENCES

ABSOLAR, 2021. "Infográfico absolar". Associação Brasileira de Energia Solar Fotovoltaica. 15 Jun. 2021 <http://www.absolar.org.br/infografico-absolar.html>.

Bett, P.E. and Thornton, H.E., 2016. "The climatological relationships between wind and solar energy supply in britain". *Renewable Energy*, Vol. 87, No. 1, pp. 96–110.

Bullard, N., 2018. "Two power sources rule in a sunny, windy 21st century". Bloomberg Quint. 22 Jun. 2018.

Campos, R.A., 2020. *Análise da complementaridade de geração entre usinas solar e eólica e o papel do armazenamento de energia para usinas híbridas*. Ph.D. thesis, Graduate Program in Mechanical Engineering, Federal University of Santa Catarina, Florianópolis, Brasil.

Hoicka, C.E. and Rowlands, I.H., 2011. "Solar and wind resource complementarity: Advancing options for renewable electricity integration in ontario, canada". *Renewable Energy*, Vol. 36, No. 1, pp. 97–107.

Weschenfelder, F., 2019. *Avaliação da complementaridade dos recursos eólico e solar baseada em dados de reanálise e cenários de mudanças climáticas*. Ph.D. thesis, Graduate Program in Mechanical Engineering, Federal University of Pernambuco, Recife, Brasil.

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