Scientific Research Publishing

Journal of Geographic Information System, 2024, 16, 367-396
https://www.scirp.org/journal/jgis
ISSN Online: 2151-1969
ISSN Print: 2151-1950

Complementarity of Renewable Energy Resources (Solar, Wind and Hydraulic) in the São Francisco River Basin

Fábio Coutinho, Chigueru Tiba

UFPE, Recife, Brazil
Email: fabiocoutinho07@hotmail.com, chigueru.tiba@ufpe.br

How to cite this paper: Coutinho, F. and Tiba, C. (2024) Complementarity of Renewable Energy Resources (Solar, Wind and Hydraulic) in the São Francisco River Basin. *Journal of Geographic Information System*, **16**, 367-396.
https://doi.org/10.4236/jgis.2024.166022

Received: October 10, 2024
Accepted: November 19, 2024
Published: November 22, 2024

Abstract

The São Francisco River basin is 2368 km long, with an average annual flow of 2846 m^3/s and a drainage area of 639,219 km^2. About 54% of this area lies in Brazil's semi-arid northeast, with annual rainfall between 450 - 800 mm. The basin's hydroelectric capacity is around 10,200 MW, but recent climate phenomena like El Niño and La Niña, worsened by global climate change, have reduced plant capacity factors from 0.70 - 0.80 to 0.35. Hybrid solar and wind systems integrated with hydroelectric plants offer a promising solution, increasing capacity and providing reliable storage through pumped water storage. This study assesses the complementarity of solar, wind, and hydroelectric energy in the São Francisco basin. Data from NASA POWER and CAMS, validated with terrestrial stations, were analyzed using Pearson, Spearman, and Kendall correlations. Results show variable complementarity across time scales, with weak complementarity annually but strong complementarity observed on daily and monthly scales. The study focuses on raw resource data, without considering integration or economic constraints.

Keywords

Hybrid Renewable Energy, Sao Francisco River Basin, Pearson, Spearman and Kendall Correlations Co-Located Plan, Solar, Wind and Hydraulic Generation

1. Introduction

1.1. Research Motivation

Electricity is currently one of the most important aspects of human life. Since it was first introduced, the global demand for it has only increased, and there are no signs that this trend will change. On the contrary, the increase in demand will continue to grow with the electrification of the world's energy matrix. On the other hand, the electricity sources are undergoing major changes. At the moment, 25% of electricity is produced by renewable sources. For the future, the IEA (International Energy Agency) projection is that, by 2050, these sources will account for just over 75% of the electricity produced in the world [1].

This trend towards electricity production based on renewable energies is mainly due to concerns about greenhouse gas emissions reduction and because solar PV is already the most competitive.

In Brazil, the energy matrix is predominantly renewable, mainly due to the large production of hydroelectricity. Approximately 85% of the electricity produced in Brazil comes from renewable sources, as can be seen [2].

Despite Brazil's great hydroelectric potential, if the historical growth rate in electricity consumption prevails, it can be said that in the next decade, no more hydroelectric power will be available for expansion, as installed capacity has already reached 83% [2]. In addition, most of the potential still available is concentrated in the northern region of Brazil, which is characterized by environmentally relevant areas, rich in biodiversity and with the presence of indigenous people (Amazon Rainforest). Thus, the construction of new hydroelectric plants should be in this context, and other energy sources must be carefully contemplated, considering the relationship between society's energy demand and environmental degradation. In this context, other energy sources need to be considered, such as solar and wind energy, which still need to be used while these technologies are fully economically viable [3].

Therefore, the evaluation of these available renewable resources is important for the expansion of the energy matrix, especially if the objective is to make it increasingly green and renewable.

1.2. Study Place

The São Francisco River basin is 2368 km long, has an average annual flow of 2846 m^3/s, a drainage area of 639.219 km^2 and around 54% of this area is in the semi-arid region. The major hydroelectric power stations (Sobradinho to Xingó) are all in the semi-arid region known as the Sub-medium São Francisco, which has an annual rainfall of 450 - 800 mm. The largest plants are in the Paulo Afonso region, where the five plants have approximately 70% of their installed capacity, but these plants do not have storage lakes. In addition, the river's hydroelectric energy potential is almost completely used up.

This vast region consumes the waters of the São Francisco River in multiple ways. They are withdrawing around 278 m^3/s for general consumption, mainly for irrigated agriculture, which consumes a significant amount of 213.7 m^3/s. Other important demands are urban demand, 31.3 m^3/s, industrial demand and 10.2 m^3/s for animal husbandry. This does not include the 26 m^3/s removed by the transposition project [4] and evaporation by hydroelectric lakes. In addition, [5] report that for Três Maria, Sobradinho and Itaparica, the evaporation rate was 42, 147, and 41 m³/s, respectively, on average, considering the period 1999-2018.

In short, the São Francisco River basin is located in a region of low rainfall, high evaporation and high competition for water use with potentially severe conflicts of interest. There are also important changes in the hydrological scenario caused by global warming, which will certainly intensify and make drought periods more frequent (decrease in average annual inflow) [6]. Therefore, water stress could significantly impact food production, human water supply and hydroelectric power generation [5].

The situation described above has been extensively studied using an approach known as the water, energy, and food production/use nexus. The nexus is the study of the connection and interconnection between the three inputs and their synergies, conflicts, and cost benefits when they are managed together [7].

The application of the Nexus concept in the São Francisco basin region leads directly to replacing water used to generate electricity with another abundant and high-quality energy resource, such as solar energy in arid or desert regions. The entire course of the São Francisco River is in the area of high insolation (18 - 20 MJ/m²/day) [8]. If there is a quality wind resource (averages greater than 5 m/S [9]), this can also be considered in most of the northeastern Brazil, which also has excellent wind resources. As a result, several large wind and solar power plants have already been built or are planned in this region, with more than 200 MW of solar power and around 10 GW of wind power installed in the area [10]. If solar or wind generation partially displaces the water currently used, there will be water savings that can be used for other purposes immediately or stored for future use.

Another aspect that deserves consideration is that solar PV and wind generation are inherently intermittent and, as it is not yet economically viable to store electricity in batteries in large systems for long periods, there is a serious dispatch problem, exemplified by the "Duck Curve". This curve consists of the daily profile of energy production, solar or wind, and energy demand, where there is an increasing difference between the peaks of the respective curves as the penetration of intermittent energy increases. This term was coined by the California Independent System Operator (CASIO) and occurs when there is an imbalance between energy demand and supply, represented by the difference between demand and the solar power produced, the orange line, resulting in the pink curve whose shape gives the effect its name. Although this curve is illustrative and does not belong to any specific system, it is quite illustrative. The black curve is equivalent to energy demand, that is, power consumption and the curve. When there is no photovoltaic energy, the difference between the power consumed and the solar power produced (purple curve) coincides with the energy demand. When the solar plant starts operating in the early morning hours, the energy supply rises rapidly, so there is a peak at midday. In contrast, demand, which also increases in the early morning hours, falls sharply at midday. In the late afternoon and early evening, while solar energy production declines rapidly, demand grows quickly, generating a deficit, with the need for rapid power input to avoid shortages. Furthermore, if this mismatch is intensified, there may still be overgeneration around noon, during peak hours [11] [12].

By increasing the penetration of solar or wind energy, the mismatch between the energy produced and the demand required will rise, increasing the "energy belly", and they are intensifying the problem. If we were to consider the Northeast of Brazil as an isolated system, the problem of the "duck curve" would already be occurring, with an average surplus of more than 70 GWh per day in 2023 [10]. What prevents this collapse is that the surplus is fed to the other regions of Brazil. However, the outflow capacity to these regions is already at its limit, so the expansion of installed solar PV and wind power capacity over the next few years will already occur with a significant duck curve effect.

To solve this problem, several solutions can be considered: modifying demand so that peak nighttime hours are shifted to times close to midday (demand-side management); storing surplus production for use at peak times (by electrochemical storage, hydraulic storage, or others); contingency (curtailment); or improving the profile of the generation curve through combined generation (hybrid system).

2. Literature Review

Integrating variable renewables, particularly wind and solar, into the grid has been widely studied, with energy complementarity seen as a key solution for mitigating variability. This concept emerged in the late 1970s when [13] showed that a spatial distribution of wind generators could reduce production variability in California. Using Pearson's correlation coefficient, Kahn established a foundational metric for complementarity, which remains widely used despite some critiques regarding its adequacy [14].

The concept of complementarity was later consolidated by other studies, such as [15]-[17], which created specific indices to assess the spatial, temporal or spatiotemporal complementarities between wind speed and solar irradiation.

Research on the optimal mix of renewable energies often addresses diverse objectives. For example, [18] explored the ideal ratio of solar, wind, and hydropower to minimize supply loss; [19] focused on reducing fossil fuel use; [20] aimed to cut greenhouse gas emissions; and [21] applied economic metrics such as energy cost, ROI, and grid present value.

Achieving the maximum penetration of renewable energies has also become a study criterion, along with the stability of the energy supplied or minimizing the uncertainties of renewable energies, as evaluated by [22], or [23] studied the possibility of 100% of the energy of a small system being supplied by a mix of solar, wind and hydroelectric energy. In agreement [24] concluded that it is possible to supply 65% of the electricity in the Northeast region of Brazil with wind energy alone. If more energy sources are considered, up to 100% of the demand can be supplied by renewable energies; in the same thematic axis [25] studied the behavior of wind and solar power plants with hydroelectric and chemical battery storage when fully supplying demands of several different sizes, they concluded that the hydraulic source could supply the market with the same reliability and lower cost. With similar objectives, [26] also carried out a multi-criteria optimization in a hybrid system (wind, solar and hydroelectric); the criteria were minimizing fluctuation in energy production, maximizing wind and solar energy and economic criteria. Similarly [27] simulated solar and wind power plants in hydroelectric plants on the Wujiang River in China, and using various plant management strategies such as storage, they obtained economic gains and gains in the stability of the energy produced. [28], for example, it evaluated the possibility of converting 100% of Chile's energy matrix into renewable energy using the complementarity between solar and wind energy, which have a complementarity of up to 80% according to Spearman's coefficient.

Because of this potential, there is a lot of research in the area of complementarity that focuses mainly on calculating the correlation between two or more energy modalities, which can increase the system's reliability. The most common techniques are graphical analysis [29] [30], calculation of correlation coefficients [31]-[33] and preparation of correlation maps [15] [30] [34]. There is also research on complementarity with other objectives, such as minimizing energy variability [35] or needing storage [36].

Once complementarity is estimated, it is possible to use this information to design an optimal system to operate under these conditions, such as, [37] who used neural networks to predict the operation of a hybrid plant or [35] that used complementarity data to minimize the variation in electricity produced. [38] used local complementarity in hydroelectric plants to design a hybrid system to minimize the variation in electricity produced. [25] [39] concluded that combining different sources of electricity production can make integration with the electricity grid easier since combined production leads to a relatively controllable and constant total power output. [40] [41] simulated hydroelectric, wind and solar power plants with batteries for extremely dry climates and achieved satisfactory results in terms of energy stability.

This latest study shows that another advantage of investing in energy sources other than hydroelectric is that in Brazil, for example, it is estimated that climate change could reduce hydroelectric potential by 312 - 430 GWh in the dry season [42]. So solar and wind energy can make up for this drop without ceasing to be clean energy. The same is observed for other regions, such as North Africa [43].

Due to the size of Brazil, there is a solar complementarity between its regions, as [44] showed in their study that it is possible to generate total solar energy corresponding to irradiation of 5.2 kWh/m^2/day, with a minimum variance (risk of deficit) of 0.158, using the Markowitz mean-variance model method, where variance is the measure of risk. There is also complementarity between the hydroelectric energy produced in the different regions, reaching a Pearson coefficient of −0.97 and −0.86 for the wind resources available in the different regions [45]. In addition, the Northeast region is even more important in this context, when [46] concluded that the large reservoirs of its plants would be very important in transforming the energy matrix entirely renewable.

Knowledge Gaps

The main objective of all these studies is to increase the share of renewable energies in the energy matrix. Table 1 summarizes the main studies specific to Brazil that have already been commented on. Few published articles and many knowledge gaps exist regarding complementarity metrics, time scales, renewable resource databases, etc. And analysis including three renewable sources. Furthermore, no work has evaluated the three energy modalities at the same time in such a large and relevant region in Brazil.

Table 1. Studies on complementarity of variable renewable energy in Brazil.

Reference	Location	Variable Renewable Energy (VRE)	Temporal Scale	Contribution
[15]	Rio Grande do Sul-Brazil	Solar and hydro	Monthly	Creation of a Complementarity creation and Brazilian pioneirism.
[32]	———	Solar e hydro	Daily	Creation of complementarity
[29]	Fernando de Noronha Island-Brazil	Solar and wind	Annual	He applied the concept of correlation on a large time scale in an isolated location where full supply would be possible.
[24]	Northeastern Brazil	wind and hydro	Hours	The study included a large geographical area with long-lasting data.
[19]	Brazil	Solar, wind and hydro	Daily	The aim of this study was to reduce carbon emissions in energy production.
[31]	Brazil offshore	wind and hydro	Quarterly	It analyzed d the availability of energy in a large swathe of the Brazilian territory.
[33]	Rio Grande do Sul-Brazil	Solar, wind and hydro	Monthly	Created an index of stability for more than two energy resources.
[30]	Brazil	wind e hydro	Monthly	I calculate the Correlation throughout Brazil and produced a colour map of the relations between the two countries.
[35]	Rio de Janeiro-Brazil	Solar, wind and hydro	Monthly	Optimized the energy setting to supply a Brazilian state.
[47]	Midwest and Southeast-Brazil	Solar and wind	Monthly	Found the right mix setting to supply a large part of the Brazilian territory.
[5]	Semi-Arid NE-Brazil	Solar and hydro	Annual	Explored the possibility of energy complementation in the São Francisco River to increase security.

For all the above reasons, in this study, we propose to analyze the solar, wind and hydroelectric energy complementarity available in the São Francisco River basin, where the eight largest hydroelectric plants are located, all in the semi-arid region in the São Francisco River sub-middle. Complementarity was assessed by different metrics on different time scales, showing that the results can vary dramatically depending on this last criterion alone. The combination of all these resources in such a wide geographical area and with such massive energy potential as the São Francisco River basin has not yet been studied in Brazil and very little in most of the world; there are only three recent studies in China [27] [41] [48] and one in Brazil [49]. Both explored a large geographic region, but the first two were restricted to intra-daily time scales and the third to monthly scales.

Thus, it was developed according to the flowchart shown in **Figure 1**. It began with the evaluation of the existing renewable energy databases for the region at different time scales. Subsequently, the correlations between these different sources were evaluated at different time scales and with several different metrics: Pearson, Spearman and Kendall coefficients.

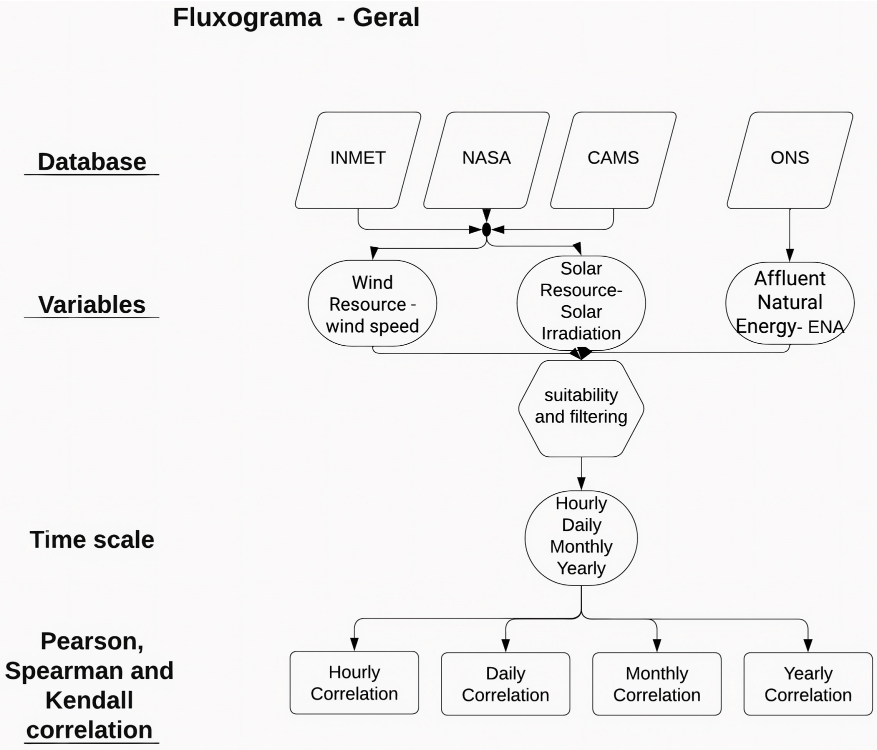


Figure 1. General study development flowchart (source: author).

3. Material and Methods

3.1. Selection and Evaluation of Renewable Energy Resource Databases

Four databases were used to carry out this work: a database for the evaluation of hydroelectric power (banco Operador Nacional do Sistema El’etrico—ONS) and three meteorological databases (Instituto Nacional de Meteorologia-INMET, National Aeronautics and Space Administration—NASA e Copernicus Atmosphere Monitoring-CAMS). These last three were compared to select the most suitable one, taking the criterion of truth as the database measured on the earth's surface. The data used from the INMET database corresponded to the meteorological stations geographically closest to each hydroelectric power plant (**Table 2**).

Table 2. INMET meteorological stations closest to hydroelectric plants.

Hydroelectric plant	INMET station	Distance to the power station
Três Marias	Três Marias	10 km
Sobradinho	Petrolina	40 km
Luiz Gonzaga	Floresta	70 km
Complexo Paulo Afonso/Xingó	Ibimirin	100 km

The plants in the Paulo Afonso, Moxotó and Xingó complex are physically close to each other, all within a maximum radius of 40 km, so the same station was considered representative of all of them. The comparison for the validation of the NASA and CAMS banks was made by directly comparing incident solar irradiation and wind speed with data from the INMET terrestrial weather station.

3.1.1. Hydropower

Table 3 shows the main hydroelectric plants on the river, as well as their reservoir sizes and installed capacities.

Table 3. Main hydroelectric plants on the São Francisco River.

Hydroelectric	Location	Reservoir size (m^3)	Capacity output (MW)
Três Marias	Três Marias-MG	21×10^9	396
Sobradinho	Sobradinho-BA	341×10^9	1050
Luiz Gonzaga	Petrolândia-PE	11×10^9	1480
Complexo Paulo Afonso/Moxotó	Paulo Afonso-BA	1×10^9	4300
Xingó	Piranhas-Al	13×10^6	3162

The hydropower data used here was provided by the National Electricity System Operator (ONS) [10]) which is the body responsible for coordinating and controlling the operation of electricity generation and transmission facilities in the National Interconnected System (SIN). This database is very robust, with daily operational data for practically all the generation projects in the SIN. From the start of its operation to the present day. The metric used to evaluate the hydroelectric resource is Affluent Natural Energy (ENA), the hydroelectric energy potentially available at a given hydroelectric plant. It is calculated based on various factors, such as precipitation, evaporation, storage conditions and the geographical characteristics of the river basin. In short, ENA is the energy produced by the plant considering its affluent natural flow and its generation capacity with its quota of 65% of the useful volume [10].

3.1.2. Solar and Wind Energy

To assess the available solar and wind energy, data on horizontal global solar irradiance and wind speed provided by the National Meteorological Institute (INMET), the National Aeronautics and Space Administration (NASA) and Copernicus Atmosphere Monitoring (CAMS) were used:

1) Database of the National Meteorological Institute (INMET)—Weather stations collect this data on the earth's surface. Weather stations collect meteorological variables from minute to minute that are integrated and made available in hourly averages. A typical station is shown in **Figure 2** and consists of the following sensors: thermometers and psychrometers to record air temperature and pressure; anemometers installed at 10 meters to record wind speed and direction; and a pyranometer to record incident global solar irradiation.

Figure 2. Typical meteorological station—INMET [50].

2) NASA-POWER database, whose solar irradiance has been modelled with satellite images. The data is available in various temporal resolutions (hour, day, month or year), and the spatial resolution of the data is 0.5˚ × 0.5˚ latitude and longitude or approximately 111.12 × 112.12 km at the equator. The wind speed is available for 10 or 50 meters.

3) The CAMS—Copernicus Atmosphere Monitoring Service database has the same characteristics as the previous one but differs in origin. The databases modelled with satellite images cover practically the entire earth's surface and are long-lived, with initial availability before the 2000s and ending at present.

4. Database Preparation

The National System Operator's (ONS) hydrological database practically has no supply failures in the time window corresponding to the period from 2000 to 2023, which was chosen for this study. Considering all the hydroelectric plants, the failure rate was less than 0.01%, which is why the missing data was not replaced.

Satellite databases of solar irradiance and wind speed from both NASA and CAMS are available, with missing data filtered and filled in for the time window between 2000 and 2023.

In the INMET database, supply failures, duplication, unrealistic values and different data acquisition windows for each location near the hydroelectric plants were found. The measures adopted in this case were:

- Missing point data was replaced by the average of points from adjacent days;
- Missing long series caused the exclusion of all the days to which they belong;
- Duplicate data was excluded;
- Physically impossible or unrealistic data (negative values, wind speeds greater than 20 m/s or irradiation greater than extraterrestrial) were excluded;
- INMET's ground stations became operational only in 2008, 2000, 2009, and 2005 for Três Maria, Sobradinho, Luiz Gonzaga, and the complete Paulo Afonso and Xingó stations, respectively.

After filtering and adjusting the measured data from INMET, it was found that 90% of the data from the potentially collectable series was covered.

The satellite databases were validated against ground data.

4.1. Complementarity of Renewable Energy Resources

There are different ways of conceptualizing and quantifying complementarity between renewable energy sources, so other methods were used in this work to assess the various facets of complementarity. Complementarity on an hourly scale was evaluated only for solar and wind energy due to the need for hourly data for hydroelectric plants. The various metrics used are presented in the following sections.

4.1.1. Pearson's Correlation

Pearson's coefficient assesses the correspondence between any two data series. It varies between +1 and −1, where +1 means that the quantities are completely similar. When it is equal to −1, the quantities are completely complementary, and when the coefficient is equal to zero, it implies the absence of a linear relationship between the series. In practice, this index considers the first derivative of the curves to which it is applied. It is one of the most widely used techniques for exploring the association between variables in numerous research fields, from the social sciences to the natural sciences. It is the literature's most commonly used metric for assessing energy complementarity. Some of the advantages of this Correlation are:

- Sensitivity for Detecting Linear Relationships: Pearson's Correlation is highly sensitive for identifying linear relationships between variables. This makes it particularly useful when trying to quantify the degree and direction of a linear relationship;
- This is an intuitive interpretation since the coefficient varies linearly between −1 and +1: Pearson's correlation coefficient varies from −1 to 1, where −1

indicates a perfect negative linear relationship, 0 indicates no linear relationship, and 1 indicates a perfect positive linear relationship. This intuitive scale makes it easier to interpret the results.

The disadvantages of using this metric include:

- Sensitivity to outliers and non-linearities: Pearson's Correlation is sensitive to extreme values (outliers) and assumes a linear relationship between the variables. When the data is not linear, Pearson's Correlation can provide distorted estimates;
- Requires Normal Distribution: Pearson's Correlation assumes the data follows a normal distribution. If this assumption is not met, the results of the Pearson correlation may not be reliable. An important observation is that wind speed has a distribution known as Weibull;
- Limitations for Ordinal or Categorical Data: Pearson's Correlation is more appropriate for continuous variables and may not be suitable for analyzing relationships in ordinal or categorical data.

Pearson's Correlation is defined by Equation (1):

$$\rho = \frac{\sum_{i=1}^{n} (x_i - \overline{x})(y_i - \overline{y})}{\sqrt{\sum_{i=1}^{n} (x_i - \overline{x})^2} \sqrt{\sum_{i=1}^{n} (y_i - \overline{y})^2}} \tag{1}$$

where:

- x_i and y_i are the values of the variables;
- $\overline{x}$ and $\overline{y}$ are the arithmetic means of both variables.

Although Pearson's Correlation is a powerful tool for analyzing linear relationships between variables, it is essential to consider its limitations and suitability for the specific analysis context. In situations where the data does not meet Pearson's Correlation assumptions, other correlation measures, such as Spearman's or Kendall's Correlation, may be more appropriate for capturing the underlying relationships between variables.

4.1.2. Spearman's Correlation

Spearman's Correlation, also known as rank index, is a non-parametric measure that assesses the monotonic relationship between variables, *i.e.* how much the variables involved tend to vary simultaneously but not at a constant rate. Instead of taking into account the exact values of the variables, it is based on the order or ranking of the data. This method is especially useful when the data does not follow a normal distribution or when there are outliers, making it more robust when the assumptions of Pearson's coefficient are not met. The advantages of Spearman's Correlation include:

- Robustness to outliers: Spearman's Correlation is less sensitive to extreme values than Pearson's coefficient, making it a preferable choice in data sets with outliers;
- Requires no assumptions about distribution: While Pearson's coefficient requires the data to follow a normal distribution, Spearman's Correlation is non-parametric and makes no assumptions about the distribution of the data,

making it more applicable in a variety of situations;

- Suitable for Ordinal and Categorical Data: Spearman's Correlation can be applied to numerical data as well as ordinal and categorical data, extending its usefulness in various research areas;

The disadvantages of using this technique include:

- Loss of Information: By considering only the order of the data, Spearman's Correlation can lose valuable information about the magnitude of the differences between the values of the variables;
- Less Sensitivity for Detecting Linear Relationships: Compared to Pearson's coefficient, Spearman's Correlation may need to be more sensitive for detecting linear relationships between variables, especially in data sets that exhibit strong linear relationships.

Spearman's correlation formula can be seen in Equation (2):

$$r_\delta = \frac{\operatorname{cov}\left(rg_X, rg_Y\right)}{\sigma_{rg_X}\sigma_{rg_Y}} \tag{2}$$

where:

- $\operatorname{cov}\left(rg_X, rg_Y\right)$ is the covariance of the variables in ranks;
- σ_{rg_X} and σ_{rg_Y} re the standard deviations of the variables in rank.

In summary, Spearman's Correlation offers a robust and versatile approach to assessing the relationship between variables, especially when the data does not meet the assumptions of Pearson's coefficient. However, it is important to consider its limitations and suitability for the specific analysis context before opting for this method over Pearson's coefficient.

4.1.3. Kendall's Correlation

Kendall's Correlation, also known as Kendall's tau, is a non-parametric measure that assesses the agreement of classifications between variables. Like Pearson's Correlation, Kendall's Correlation is better suited to capturing monotonic associations that may not necessarily be linear, so it has similar applications. Among the advantages of the Kendall correlation are:

- Robustness to outliers: Like the Spearman's correlation, the Kendall's correlation is less sensitive to extreme values, making it a preferable choice in data sets with outliers;
- Requires no assumptions about distribution: Like Spearman's Correlation, Kendall's Correlation is non-parametric, which means that it makes no assumptions about the distribution of the data, making it more suitable for data that does not follow a normal distribution;
- Suitable for Ordinal and Categorical Data: Kendall's Correlation applies not only to numerical data but also to ordinal and categorical data, extending its usefulness in various analysis contexts.

The disadvantages of using this technique include:

- Less Sensitivity to Detecting Linear Relationships: Like Spearman's Correlation, Kendall's Correlation can be less sensitive to detecting linear relationships between variables, which can be a limitation in certain analysis contexts;

- More complex interpretation: The interpretation of Kendall's Correlation can be more complex than that of Pearson's coefficient, especially for those less familiar with measures of agreement between classifications.

Kendall's coefficient is defined by considering $(x_1, y_1), (x_2, y_2), \cdots, (x_n, y_n)$ a set of observations of variables X and Y, respectively, such that all the values of (x_i) and (y_i) are unique. Any pair of observations (x_i, y_i) and (x_j, y_j) is concordant if the classifications of both elements agree with each other, *i.e.* if $x_i > x_j$ and $y_i > y_j$ or $x_i < x_j$ and $y_i < y_j$, otherwise the pair is discordant. The equation for Kendall's coefficient is given by Equation (3):

$$\tau = \frac{(\text{quantidade de pares concordantes}) - (\text{quantidade de pares discordantes})}{n(n-1)/2} \quad (3)$$

where n is the number of pairs.

In summary, Kendall's Correlation also offers a valuable alternative to Pearson's coefficient, especially when a rank order better captures the relationship between variables than a direct linear relationship.

Due to the similarity between the Spearman and Kendall correlations, there is a need to explain the difference between them: Unlike Spearman's Correlation, Kendall's Correlation takes into account the magnitude of the variables, which is unimportant for the analysis of gross resources because the variables are in different units. In addition, Kendall's Correlation is more suitable for small samples. Therefore, all three relationships were used in this study.

5. Results and Discussions

5.1. Database Evaluation

The similarity between the databases was checked using the Pearson correlation coefficient. The NASA and CAMS solar irradiance and wind speed databases are practically identical, as the Pearson correlation coefficient between them is always greater than +0.98% in all 4 locations presented, as seen in **Table 4** and **Table 5**.

Regarding the stations closest to the hydroelectric power stations, such as Três Marias and Sobradinho, the satellite banks have greater similarities than the more distant stations. The similarity between the satellite databases for all the quantities evaluated was always very close to +1, which means that these data are strongly similar. When compared with INMET's terrestrial data, NASA's data has always a slight advantage, achieving faintly higher rates than the CAMS data. **Table 4** shows that similarity in solar irradiation is very strong in all locations, even where the weather stations are further away from the ground station. Regarding wind speed, **Table 5** shows that the similarity is slightly lower than solar irradiation. Still, it remains very strong in all locations, with the exception of the Paulo Afonso Complex, where the Correlation reached the lowest value of +0.61, which can still be considered a good similarity. The great geographical distance between the hydroelectric plant and the INMET station explains this.

Table 4. Pearson index for solar irradiation between the analyzed databases.

Hydropower Plant of Três Marias			
	INMET	NASA	CAMS
INMET	1.00	0.82	0.81
NASA	0.82	1.00	0.99
CAMS	0.77	0.99	1.00
Hydropower Plant of Sobradinho			
INMET	1.00	0.97	0.97
NASA	0.97	1.00	0.99
CAMS	0.97	0.99	1.00
Hydropower Plant of Luiz Gonzaga			
INMET	1.00	0.91	0.88
NASA	0.91	1.00	0.98
CAMS	0.88	0.98	1.00
Hydropower Plant of P. Afonso			
INMET	1.00	0.96	0.98
NASA	0.96	1.00	0.98
CAMS	0.98	0.98	1.00

Table 5. Pearson index for wind speed between the analyzed databases.

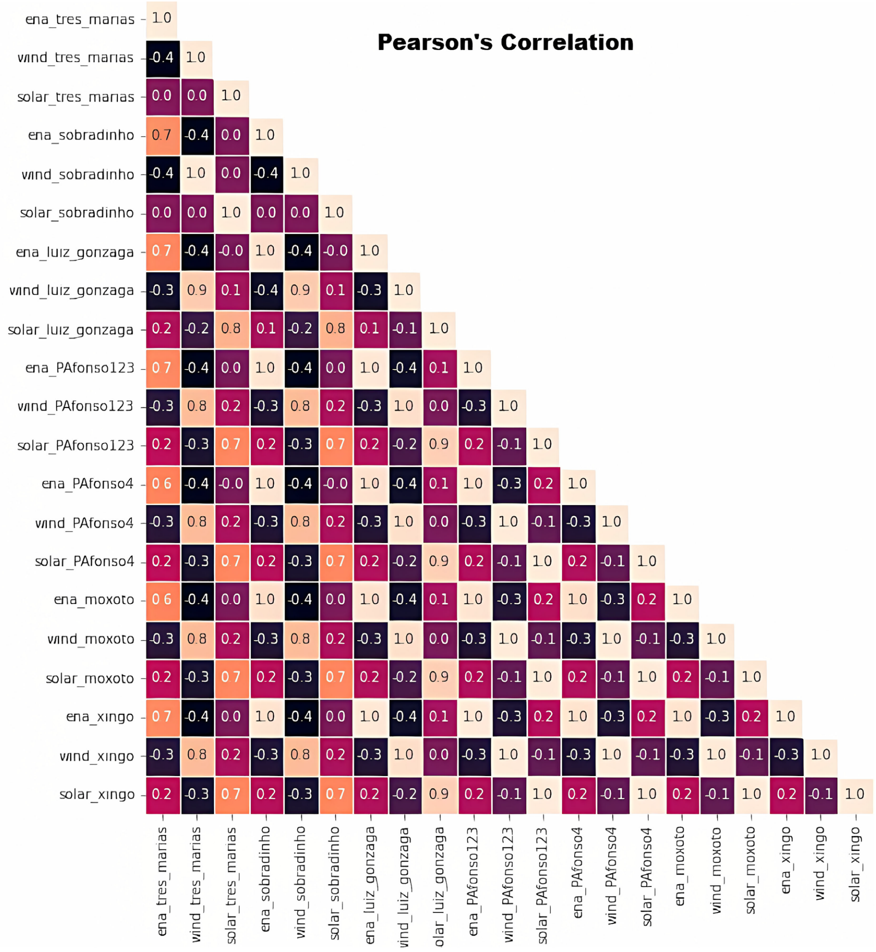
Hydropower Plant of Três Marias			
	INMET	NASA	CAMS
INMET	1.00	0.89	0.88
NASA	0.89	1.00	0.99
CAMS	0.88	0.99	1.00
Hydropower Plant of Sobradinho			
INMET	1.00	0.86	0.86
NASA	0.86	1.00	0.99
CAMS	0.86	0.99	1.00
Hydropower Plant of Luiz Gonzaga			
INMET	1.00	0.90	0.88
NASA	0.90	1.00	0.98
CAMS	0.88	0.98	1.00
Hydropower Plant of P. Afonso			
INMET	1.00	0.61	0.60
NASA	0.61	1.00	0.98
CAMS	0.60	0.98	1.00

As seen above, the satellite databases were validated with the terrestrial database. So, for the rest of the work, the data used was from the NASA database, as it has a slight advantage over CAMS. The basic idea behind the validation was to use NASA's solar irradiance and wind speed data, which would make it possible to use it to generalize throughout the semi-arid region of Northeast Brazil.

5.2. Complementary Energy Resources

5.2.1. Global Correlation (Period 2000-2023)

The complementarities of renewable energy resources were analyzed for co-located plants and between spatially distributed plants using the Pearson, Spearman, and Kendall index, calculated between the years 2000 and 2023 and called global for clarity and conciseness. **Figures 3-5** show the global Pearson, Spearman, and Kendall correlations, all on a daily scale.

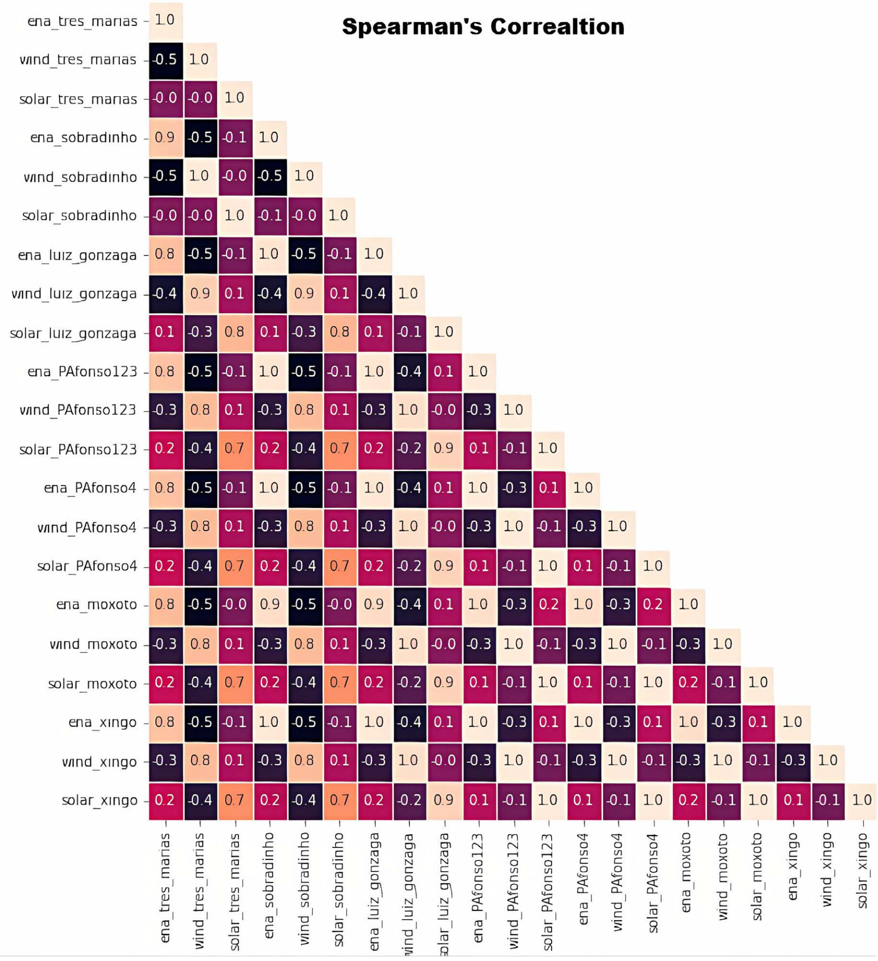


Pearson's Correlation

	ena_tres_marias	wind_tres_marias	solar_tres_marias	ena_sobradinho	wind_sobradinho	solar_sobradinho	ena_luiz_gonzaga	ind_luiz_gonzaga	olar_luiz_gonzaga	ena_PAfonso123	wind_PAfonso123	solar_PAfonso123	ena_PAfonso4	wind_PAfonso4	solar_PAfonso4	ena_moxoto	wind_moxoto	solar_moxoto	ena_xingo	wind_xingo	solar_xingo
ena_tres_marias	1.0																				
wind_tres_marias	-0.4	1.0																			
solar_tres_marias	0.0	0.0	1.0																		
ena_sobradinho	0.7	-0.4	0.0	1.0																	
wind_sobradinho	-0.4	1.0	0.0	-0.4	1.0																
solar_sobradinho	0.0	0.0	1.0	0.0	0.0	1.0															
ena_luiz_gonzaga	0.7	-0.4	-0.0	1.0	-0.4	-0.0	1.0														
wind_luiz_gonzaga	-0.3	0.9	0.1	-0.4	0.9	0.1	-0.3	1.0													
solar_luiz_gonzaga	0.2	-0.2	0.8	0.1	-0.2	0.8	0.1	-0.1	1.0												
ena_PAfonso123	0.7	-0.4	0.0	1.0	-0.4	0.0	1.0	-0.4	0.1	1.0											
wind_PAfonso123	-0.3	0.8	0.2	-0.3	0.8	0.2	-0.3	1.0	0.0	-0.3	1.0										
solar_PAfonso123	0.2	-0.3	0.7	0.2	-0.3	0.7	0.2	-0.2	0.9	0.2	-0.1	1.0									
ena_PAfonso4	0.6	-0.4	-0.0	1.0	-0.4	-0.0	1.0	-0.4	0.1	1.0	-0.3	0.2	1.0								
wind_PAfonso4	-0.3	0.8	0.2	-0.3	0.8	0.2	-0.3	1.0	0.0	-0.3	1.0	-0.1	-0.3	1.0							
solar_PAfonso4	0.2	-0.3	0.7	0.2	-0.3	0.7	0.2	-0.2	0.9	0.2	-0.1	1.0	0.2	-0.1	1.0						
ena_moxoto	0.6	-0.4	0.0	1.0	-0.4	0.0	1.0	-0.4	0.1	1.0	-0.3	0.2	1.0	-0.3	0.2	1.0					
wind_moxoto	-0.3	0.8	0.2	-0.3	0.8	0.2	-0.3	1.0	0.0	-0.3	1.0	-0.1	-0.3	1.0	-0.1	-0.3	1.0				
solar_moxoto	0.2	-0.3	0.7	0.2	-0.3	0.7	0.2	-0.2	0.9	0.2	-0.1	1.0	0.2	-0.1	1.0	0.2	-0.1	1.0			
ena_xingo	0.7	-0.4	0.0	1.0	-0.4	0.0	1.0	-0.4	0.1	1.0	-0.3	0.2	1.0	-0.3	0.2	1.0	-0.3	0.2	1.0		
wind_xingo	-0.3	0.8	0.2	-0.3	0.8	0.2	-0.3	1.0	0.0	-0.3	1.0	-0.1	-0.3	1.0	-0.1	-0.3	1.0	-0.1	-0.3	1.0	
solar_xingo	0.2	-0.3	0.7	0.2	-0.3	0.7	0.2	-0.2	0.9	0.2	-0.1	1.0	0.2	-0.1	1.0	0.2	-0.1	1.0	0.2	-0.1	1.0

Figure 3. Global Pearson index for all renewable energies considered in all large plants on the SF river (source: author).

Figures 3-5 show that all the correlations behave similarly, and there is no drastic difference between them. The correlation values are rounded to one decimal place for better visualization in the graphs, so the biggest difference is 0.2. Therefore, in this section, the most detailed analysis was based only on Spearman's Correlation, Figure 4, which, as you know, is the most robust of the three: it tolerates "outliers", does not require the assumption of linearity and does not require the distribution to be normal. It should be remembered here that the distribution of wind speed is of the Weibull type.



Spearman's Correaltion

	ena_tres_marias	wind_tres_marias	solar_tres_marias	ena_sobradinho	wind_sobradinho	solar_sobradinho	ena_luiz_gonzaga	wind_luiz_gonzaga	solar_luiz_gonzaga	ena_PAfonso123	wind_PAfonso123	solar_PAfonso123	ena_PAfonso4	wind_PAfonso4	solar_PAfonso4	ena_moxoto	wind_moxoto	solar_moxoto	ena_xingo	wind_xingo	solar_xingo
ena_tres_marias	1.0																				
wind_tres_marias	-0.5	1.0																			
solar_tres_marias	-0.0	-0.0	1.0																		
ena_sobradinho	0.9	-0.5	-0.1	1.0																	
wind_sobradinho	-0.5	1.0	-0.0	-0.5	1.0																
solar_sobradinho	-0.0	-0.0	1.0	-0.1	-0.0	1.0															
ena_luiz_gonzaga	0.8	-0.5	-0.1	1.0	-0.5	-0.1	1.0														
wind_luiz_gonzaga	-0.4	0.9	0.1	-0.4	0.9	0.1	-0.4	1.0													
solar_luiz_gonzaga	0.1	-0.3	0.8	0.1	-0.3	0.8	0.1	-0.1	1.0												
ena_PAfonso123	0.8	-0.5	-0.1	1.0	-0.5	-0.1	1.0	-0.4	0.1	1.0											
wind_PAfonso123	-0.3	0.8	0.1	-0.3	0.8	0.1	-0.3	1.0	-0.0	-0.3	1.0										
solar_PAfonso123	0.2	-0.4	0.7	0.2	-0.4	0.7	0.2	-0.2	0.9	0.1	-0.1	1.0									
ena_PAfonso4	0.8	-0.5	-0.1	1.0	-0.5	-0.1	1.0	-0.4	0.1	1.0	-0.3	0.1	1.0								
wind_PAfonso4	-0.3	0.8	0.1	-0.3	0.8	0.1	-0.3	1.0	-0.0	-0.3	1.0	-0.1	-0.3	1.0							
solar_PAfonso4	0.2	-0.4	0.7	0.2	-0.4	0.7	0.2	-0.2	0.9	0.1	-0.1	1.0	0.1	-0.1	1.0						
ena_moxoto	0.8	-0.5	-0.0	0.9	-0.5	-0.0	0.9	-0.4	0.1	1.0	-0.3	0.2	1.0	-0.3	0.2	1.0					
wind_moxoto	-0.3	0.8	0.1	-0.3	0.8	0.1	-0.3	1.0	-0.0	-0.3	1.0	-0.1	-0.3	1.0	-0.1	-0.3	1.0				
solar_moxoto	0.2	-0.4	0.7	0.2	-0.4	0.7	0.2	-0.2	0.9	0.1	-0.1	1.0	0.1	-0.1	1.0	0.2	-0.1	1.0			
ena_xingo	0.8	-0.5	-0.1	1.0	-0.5	-0.1	1.0	-0.4	0.1	1.0	-0.3	0.1	1.0	-0.3	0.1	1.0	-0.3	0.1	1.0		
wind_xingo	-0.3	0.8	0.1	-0.3	0.8	0.1	-0.3	1.0	-0.0	-0.3	1.0	-0.1	-0.3	1.0	-0.1	-0.3	1.0	-0.1	-0.3	1.0	
solar_xingo	0.2	-0.4	0.7	0.2	-0.4	0.7	0.2	-0.2	0.9	0.1	-0.1	1.0	0.1	-0.1	1.0	0.2	-0.1	1.0	0.1	-0.1	1.0

Figure 4. Global Spearman index for all renewable energies considered in all large plants on the SF river (source: author).

In principle, by analyzing the energy resources for each location separately (co-located analysis), it was possible to see the following relationships:

- Três Marias had a strong complementarity of −0.5 between hydro and wind energy. There was no notable relationship between the other energy modalities in this location;
- In Sobradinho, a strong complementarity of −0.5 exists between wind and hydroelectric energy. There was also a weak complementarity of −0.1 between solar and hydroelectric energy;
- In Luiz Gonzaga, there was complementarity between wind and hydroelectric energy, ranging from −0.3 to −0.1, and there was no significant complementarity between the other energy sources;

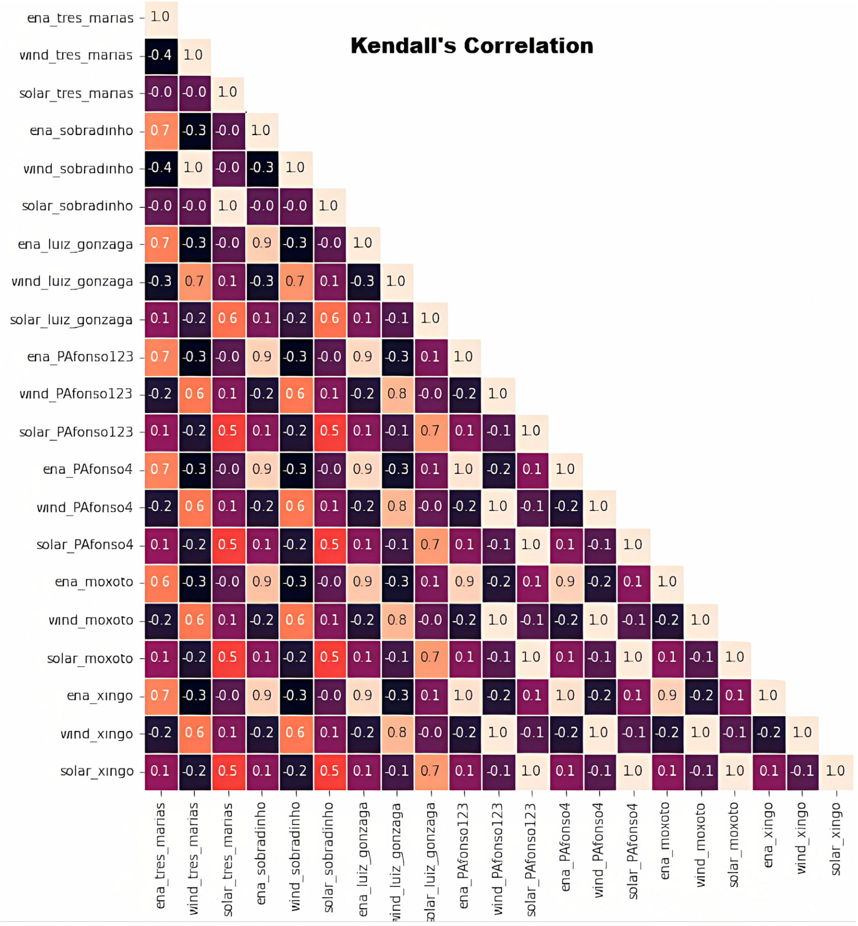


Figure 5. Kendall index for all renewable energies considered in all large SF river plants (source: author).

- The plants that make up the Paulo Afonso complex (Paulo Afonso I, II, III and IV, Xingó and Moxotó) have perfect similarity between the available hydroelectric power since all the plants are located on the same stretch of river, so they can be considered a single site for this analysis. In this case, there was an average complementarity of −0.3 between wind and hydroelectric energy and a weak complementarity of −0.1 between solar and wind power.

[30] calculated a Pearson index of up to −0.98 (clearly overestimated) between wind and hydroelectric energy in regions of the São Francisco River, which contrasts sharply with the results obtained here, which are a maximum of −0.7. The discrepancy can be explained by the much older database used by Cantão, which dates from 1961 to 2013, and was created in old INMET stations that could only take three measurements a day. Another notable difference was the use of monthly hydroelectric flow measurements.

Other authors, such as [24] or [5], have not calculated these indexes and also captured a relationship of energy complementarity involving solar, wind, and hydroelectric energy in some locations along the São Francisco River. The overall Correlation corroborates this, showing some degree of complementarity between solar and wind power, as in Paulo Afonso, for example. It is also worth pointing out that some complementarity relationships will be more easily exposed when analyzed using other time metrics.

About the analysis of spatially distributed renewable energy resources (intra-plants), the following conclusions were reached:

- There are some strongly complementary relationships, such as −0.5 between the wind power available at Três Marias and the hydroelectric power throughout the middle and lower São Francisco, represented by all the other plants;
- There is also complementarity between hydroelectric power in Sobradinho and wind power in Luiz Gonzaga, reaching −0.4. Wind power in Sobradinho is also complementary to hydroelectric power and solar power in Luiz Gonzaga, with correlation indexes ranging from −0.3 to −0.5;
- The hydroelectricity in the Paulo Afonso complex also has a similarity between −0.4 and −0.5 to the wind energy available in Sobradinho and Três Marias. Between wind power in the Paulo Afonso complex and hydroelectricity in Sobradinho and Luiz Gonzaga, there is a similarity of −0.3. Also, in the Paulo Afonso complex, the wind power available in this location is a complementarity of −0.3, with all the hydroelectric power available in all the other locations.

There is also complementarity between hydroelectric power in Sobradinho and wind power in Luiz Gonzaga, reaching −0.4. Wind power in Sobradinho is also complementary to hydroelectric power and solar power in Luiz Gonzaga, with correlation indexes ranging from −0.3 to −0.5. Hydroelectricity in the Paulo Afonso complex also has complementarity ranging from −0.4 to −0.5. From the above, it can be concluded that there is a significant complementarity of −0.5 between different renewable resources for spatially distributed hybrid systems.

5.2.2. Monthly Correlation (Grouped by Month for the Period 2000-2023)

Kendall's Correlation was chosen for this analysis because of the advantages above over Pearson's Correlation. The series analyzed for each month only had 24 pairs of points, which could cause problems when calculating the Spearman correlation due to the small sample size. It should also be noted that the analyses carried out here refer only to co-located plants. All **Figures 6-9** were made in the same way. In them, the monthly averages of each month of the 24 years were calculated for the energy resources in all modalities and grouped in a list with the averages of the 24 January, 24 February and so on. Then, the Kendall correlation index was calculated for each month of the list for all possible combinations of the resources taken two by two.

The monthly Kendall correlation for Três Marias is shown in **Figure 11**. Where hydroelectric and solar energies, **Figure 6(a)**, have strong complementarity throughout the spring and summer (Sept-Dec and Dec-Mar), reaching a maximum of approximately −0.6. Between hydroelectric and wind energies, **Figure 6(b)**, for half the year, these energy modalities are complementary, although the index is low or average; only October is complementarity strong. Between solar and wind energy, **Figure 6(c)**, there is complementarity for six months, but it is weak, reaching −0.2 in the best of the cases.

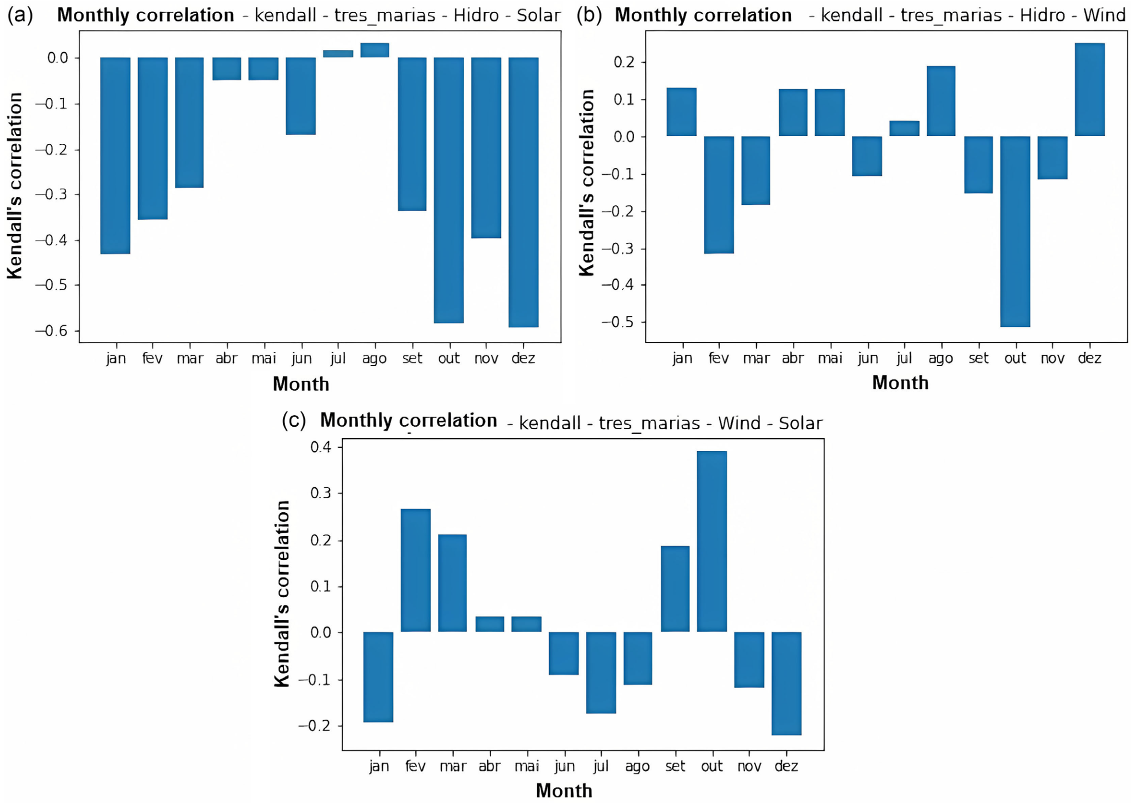


Figure 6. Monthly Kendall index—Três Maias Plant.

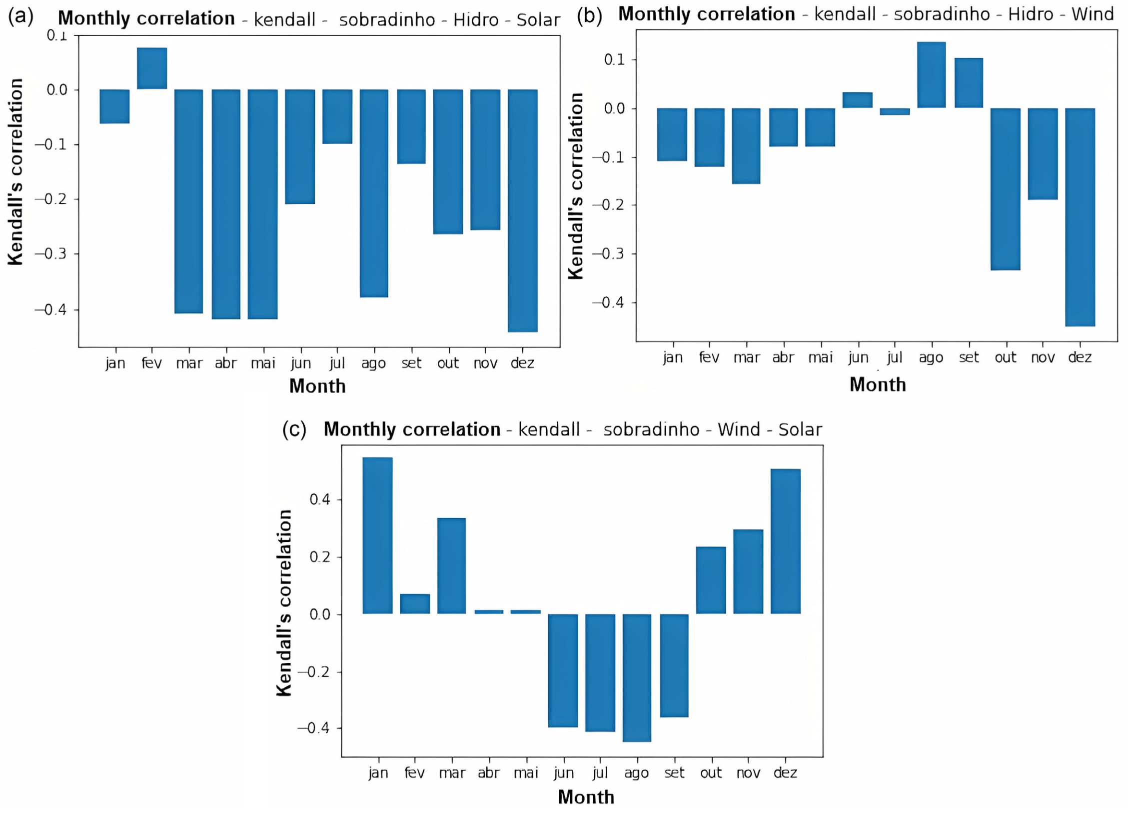


Figure 7. Monthly Kendall index—Sobradinho Plant.

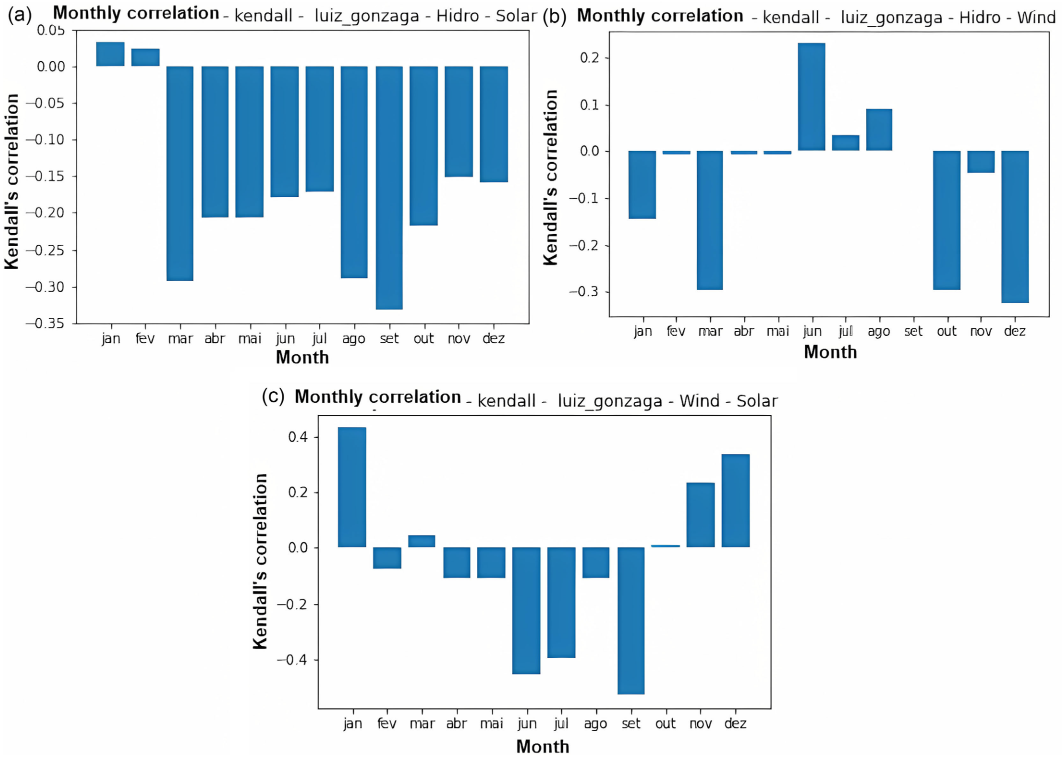


Figure 8. Monthly Kendall index—Luiz Gonzaga Plant.

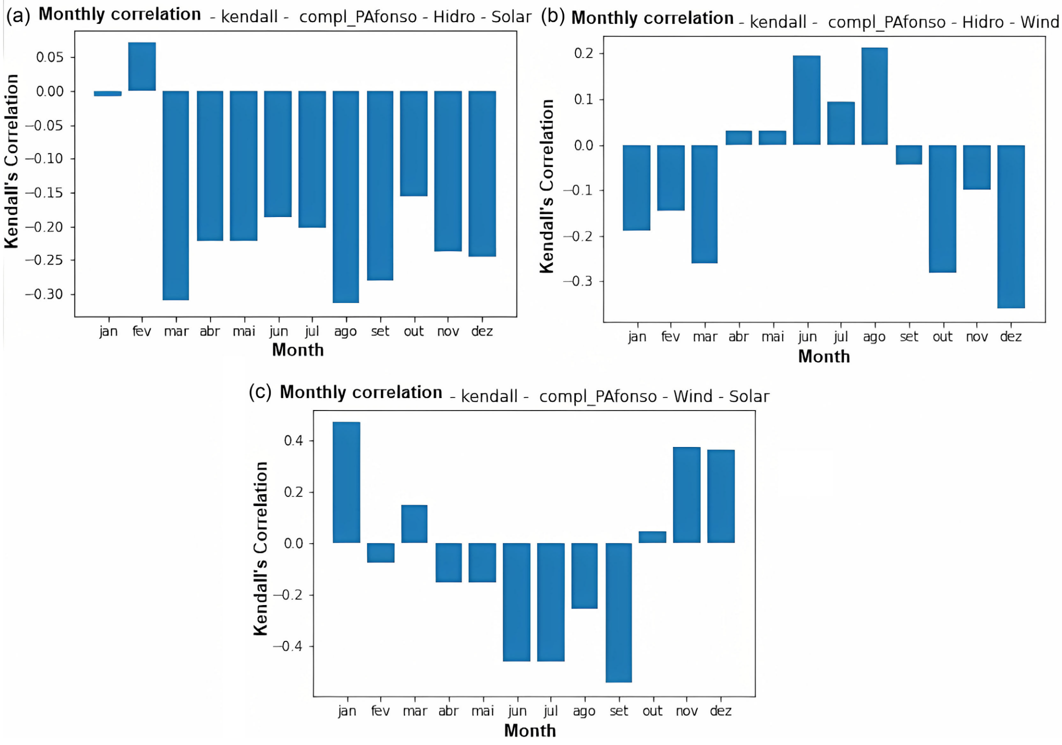


Figure 9. Monthly Kendall index—Complexo P. Afonso Plant.

Figure 7 shows the monthly Kendall correlation for Sobradinho. The hydroelectric and solar energies, Figure 7(a), complement each other for the entire year, except February. Between hydroelectric and wind energy, **Figure 7(b)**, there is also complementarity for most of the year, although less intense. Between solar and wind energy, **Figure 7(c)**, complementarity only occurs between June and September and varies between −0.3 and −0.4.

The monthly Kendall correlation for Luiz Gonzaga is shown in **Figure 8**; similarly to Sobradinho, hydroelectric and solar energy **Figure 8(a)** complement eachydroelectric and wind energy were complementary only in 5 months, in spring and summer. Between solar and wind energy, **Figure 8(c)**, there was complementarity for most of the year, especially in winter and early spring; the result is approximately −0.4.

The monthly Kendall correlation for the Paulo Afonso Complex is shown in **Figure 9**. Due to their proximity, there is a great similarity between the behavior of the monthly Correlation of the Paulo Afonso Complex and Luiz Gonzaga.

It can be seen that on a monthly scale, there is complementarity for practically the whole year in the São Francisco River basin. The highlight is the Três Marias hydroelectric plant, where the Correlation reaches −0.6 with an average of −0.5 in the hottest months of the year. The other locations also have good complementarity indexes, with an average of around −0.3.

It should be noted that analyses on this time scale are unprecedented in Brazil and rare worldwide.

5.2.3. Monthly Energy Potential per Renewable Energy Source

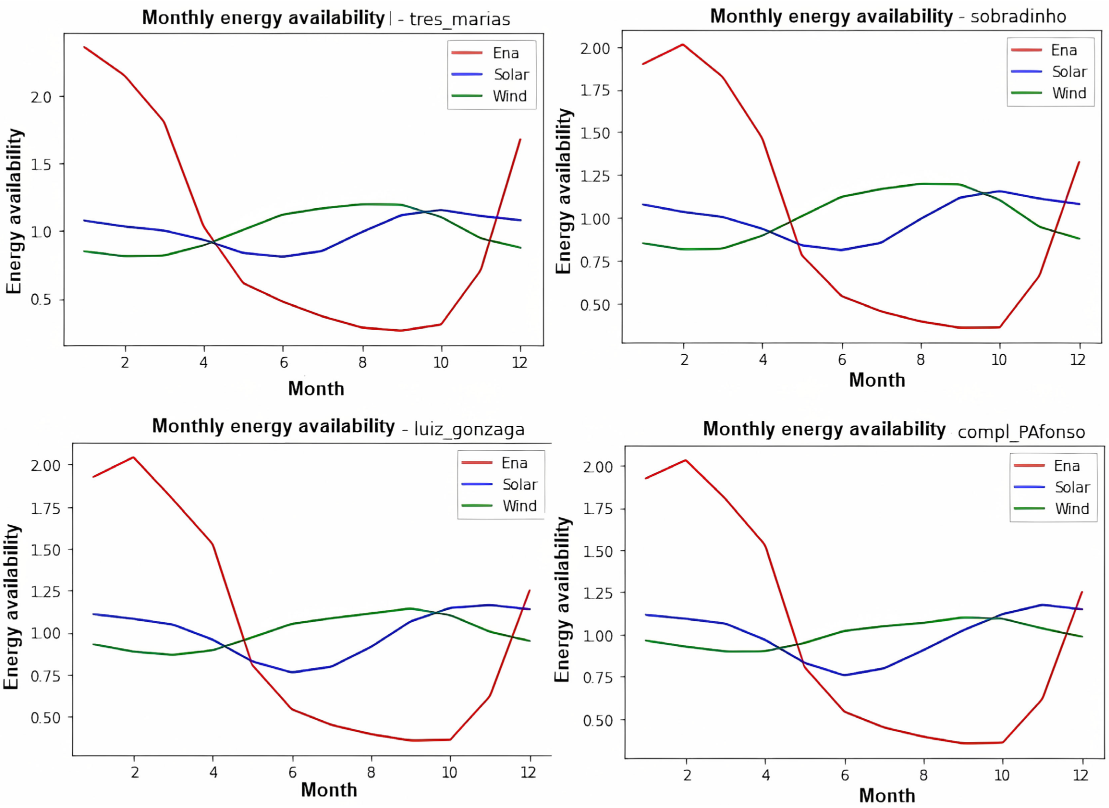


Figure 10. Energy availability.

The average monthly energy potential normalized by the average for each renewable energy source is shown in **Figure 10**. This graph was made from the monthly average of all resource modalities. For better visualization, each curve relative to each energy modality was divided by its average; thus, the physical unit of the resource was suppressed, making it possible to evaluate the shape of the curve.

The similarity between the annual profiles for all 24 years is remarkable. The peak in hydroelectric energy potential occurs between December and February, and the valley occurs between June and October. The greatest variability also occurs with the end, so the greater constancy of the other modalities has a beneficial effect on this time scale. In addition, the high magnitude of solar and wind energy in the low-energy months also produces a complementary effect.

The graphical analysis of this figure shows that complementary hydroelectricity is most important between April and October, when the ANS is low, which is the case in all locations, although less so in Três Marias.

5.2.4. Seasonal Daily Profile

The daily seasonal profiles for each location (plant co-located) are shown in **Figures 11-14**. The behavior of the inlet hydraulic flow is not illustrated in the figures because the temporal resolution of the ONS database does not include hourly data. Solar irradiation is in Wh/m^2, and wind speed is in m/s at a height of 50 meters, both from the POWER-NASA database. To improve visualization, the units have been normalized with their maximum and minimum values occupying the same location on the ordinate axis of the graphs.

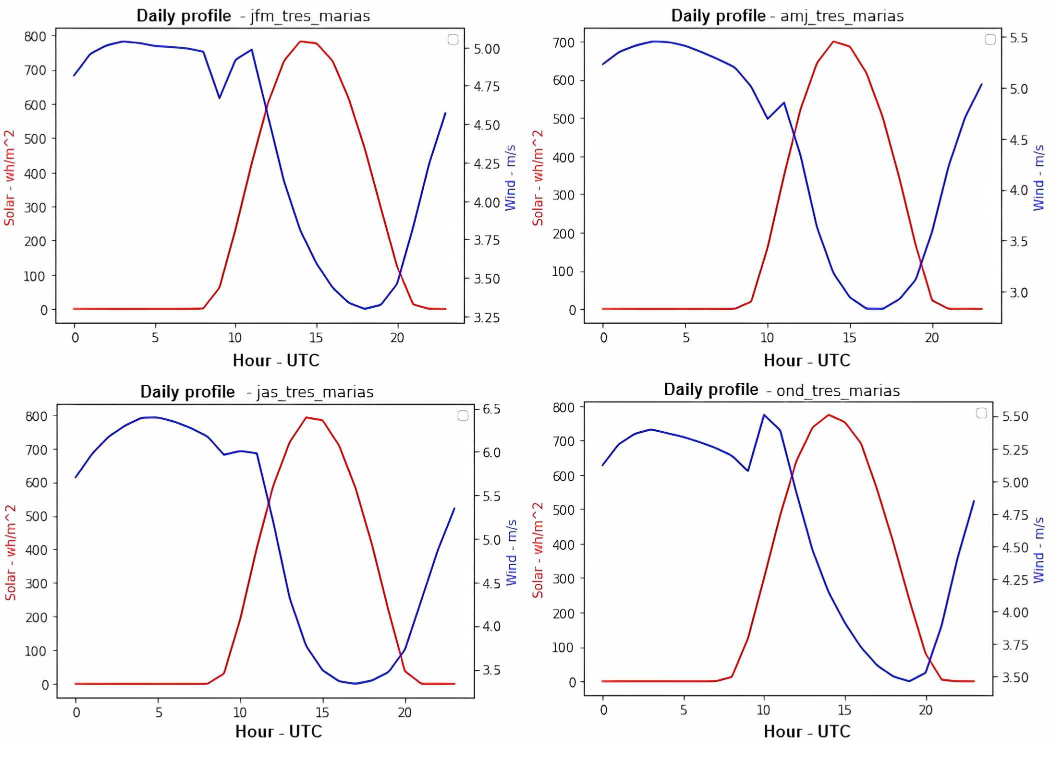


Figure 11. Daily seasonal profile (solar irradiation and wind speed)—Três Marias Plant (source: author).

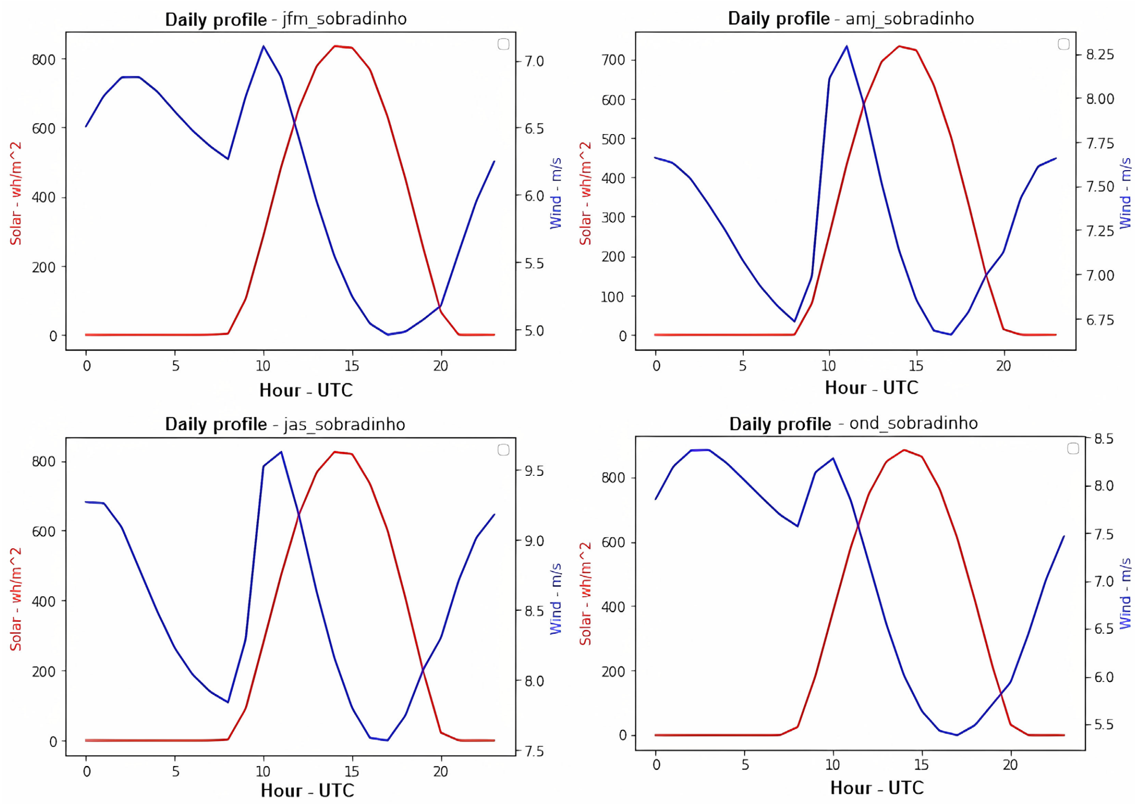

Daily profile - jfm_sobradinho
Daily profile - amj_sobradinho
Daily profile - jas_sobradinho
Daily profile - ond_sobradinho

Figure 12. Daily seasonal profile (solar irradiation and wind speed)—Sobradinho Plant (source: author).

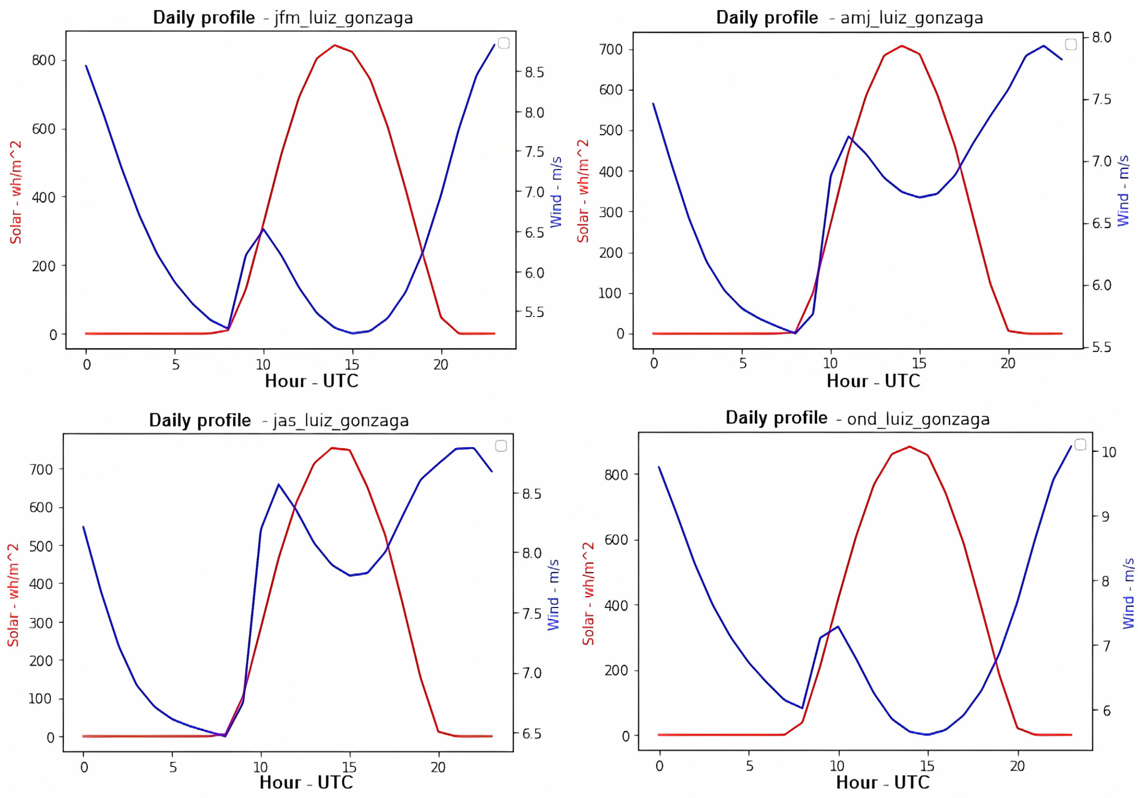

Daily profile - jfm_luiz_gonzaga
Daily profile - amj_luiz_gonzaga
Daily profile - jas_luiz_gonzaga
Daily profile - ond_luiz_gonzaga

Figure 13. Daily seasonal profile (solar irradiation and wind speed)—Luiz Gonzaga Plant (source: author).

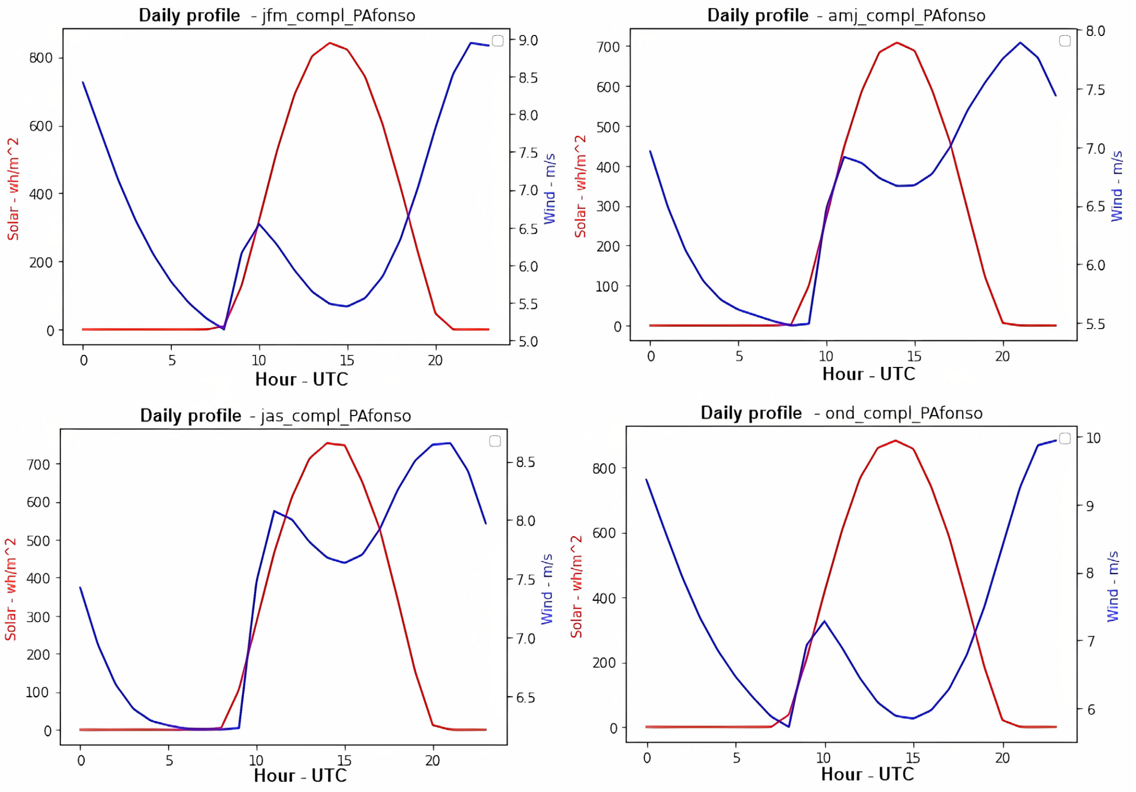


Figure 14. Daily seasonal profile (solar irradiation and wind speed)—Complexo Paulo Afonso Plant (source: author).

Therefore, the standard day was calculated for each quarter of the year, in order to verify the hourly behavior of solar and wind resources varying with the seasonality of the year.

5.2.5. Três Marias

The quarterly daily profile of the behavior of solar irradiation and wind speed at the Três Marias plant can be seen in Figure 11. For the sake of complementarity, the further apart the peaks of the wind speed (blue) and solar irradiation (red) curves are, the better the complementarity. Throughout the year, the highest wind speeds occur at night, and the lowest occur close to solar noon, which benefits daily complementarity. In addition, the increase in wind speed at dusk reduces the effect of the "duck curve".

5.2.6. Sobradinho

The quarterly daily profile of solar irradiation and wind speed at the Sobradinho plant can be seen in Figure 12.

In this case, throughout the year, the resources are very similar; the peak wind speed always occurs just before sunrise and in the first and last quarters, the wind remains strong, which further benefits complementarity daily. When it gets dark, the problem of the "duck curve" is also mitigated by the rising wind speed.

5.2.7. Luiz Gonzaga

Figure 13 shows the quarterly daily profile of solar irradiation and wind speed at the Luiz Gonzaga plant.

In Luiz Gonzaga, the peak wind speed also occurs with a lag about solar noon, although from April to September, wind speeds are also high close to solar noon. Even so, throughout the year, the rapid increase in wind speed as the sun goes down greatly mitigates the effect of the "duck curve", and among the locations studied, this is where this effect is most evident, with the maximum magnitude of wind speed occurring in the early hours of the night.

5.2.8. Paulo Afonso and Xingó Complex

Figure 14 shows the quarterly daily profile of solar irradiation and wind speed behavior for the Paulo Afonso Complex.

Again, the Luiz Gonzaga site is strongly similar due to its geographical proximity, so all the considerations there also apply to the Paulo Afonso Complex.

6. Conclusions

To assess energy complementarity in the São Francisco River basin, the various NASA POWER and CAMS databases, estimated using satellite images, proved to be just as robust as the data provided by terrestrial weather stations (INMET) located close to the energy projects. The NASA POWER and CAMS databases have a Pearson index always above +0.61 and mostly greater than 0.97 for the plants located in the middle reaches of the São Francisco River. Thus, solar and wind irradiation data from NASA and CAMS can be used reliably when the analysis requires greater spatial granularity or in adjacent regions of the semi-arid northeast. It should be noted that solar and wind irradiation data from INMET weather stations are geographically discrete and heterogeneously distributed, with low spatial density. The interpretation of complementarity or similarity between different energy modalities, or data series in general, depends on several factors, from the metric chosen to the temporal resolution of the data. Although with the data used in this work, the differences are relatively small, they can be relevant when detailing the design of a hybrid power plant. For this reason, despite the more common use of Pearson's Correlation, this work evaluated Spearman's and Kendall's correlations, which have advantages in terms of robustness, not being restricted to linear problems and being suitable for non-normal distributions

Also, the time metric chosen (time scale) can drastically alter the complementarity relationship. It was found, for example, that there is no overall complementarity between hydroelectric and solar energy in any of the locations analyzed, but rather, there is a weak similarity. However, when calculated daily or monthly, a strong complementarity was observed throughout the year. As for the relationship between wind and hydroelectric energy, although it shows some degree of global complementarity, the monthly analysis shows strong complementarity, especially in some specific months where the flow of the São Francisco basin is low.

Finally, the relationship between wind and solar energy proves to be very beneficial on the hourly scale, thanks to higher wind speeds at night, thus mitigating the problem of the "duck curve". However, this relationship only stands out on the other time scales.

It is important to note that no study in the literature covers an area as wide and important for an entire macro-region as the São Francisco River basin on different time scales (annual, monthly, seasonal and daily) since most are concerned at most with the monthly scale and how these can modify the values of the correlation coefficients, even transforming a relationship of similarity into complementarity.

This article stands out globally as one of the few that evaluates all three energy resources—hydroelectric, solar, and wind—simultaneously for the same location and across various time scales. Despite using statistical indices as metrics, despite the various indices already created, those already existing are sufficient for this evaluation. Additionally, there is no universal index that works for different time scales or in various locations. Moreover, at the Brazil level, there are no studies that analyze such a large area with several large-scale hydroelectric plants, making it easier to implement solar and wind plants.

One limitation of this study is that it only analyzed the resources in their raw form, not taking into account the difficulties of integrating energy produced by different sources nor the various operational or economic constraints. These topics will be explored in future studies. Thus, the interaction between plants could motivate a future study, as well as strategies aimed at optimizing some advantage in the use of combined energy modalities, that is, discovering strategies to optimize water usage or saving energy for a specific time of year or even a specific time of day.

Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

References

[1] IEA (2021) World Energy Outlook 2021. https://www.iea.org/reports/world-energy-outlook-2021/

[2] BEN (2023) Balan¸co energ'etico nacional.

[3] USEIA (2023) Cost and Performance Characteristics of New Generating Technologies, Annual Energy Outlook 2023.

[4] ANA (2024) Agência nacional das Aguas. https://www.gov.br

[5] Ferraz de Campos, É., Pereira, E.B., van Oel, P., Martins, F.R., Gonçalves, A.R. and Costa, R.S. (2021) Hybrid Power Generation for Increasing Water and Energy Securities during Drought: Exploring Local and Regional Effects in a Semi-Arid Basin. *Journal of Environmental Management*, **294**, Article ID: 112989. https://doi.org/10.1016/j.jenvman.2021.112989

[6] IPCC (2023) Intergovernmental Panel on Climate Change. https://www.ipcc.ch/report/ar6/syr/

[7] Simpson, G.B. and Jewitt, G.P.W. (2019) The Development of the Water-Energy-Food Nexus as a Framework for Achieving Resource Security: A Review. *Frontiers in*

Environmental Science, **7**, Article 8. https://doi.org/10.3389/fenvs.2019.00008

[8] Pereira, E.B., Martins, F.R., Gonçalves, A.R., Costa, R.S., Lima, F. d., Rüther, R., Abreu, S.D., Tiepolo, G.M., Pereira, S.V. and Souza, J.D. (2017) Atlas brasileiro de energia solar, São josé dos Campos: Inpe 1.

[9] EnergyData.info (2024) Global Wind Atlas. https://globalwindatlas.info/en

[10] ONS (2021) Operador nacional do sistema el'etrico. http://www.ons.org.br/paginas/energia-agora/reservatorios

[11] Howlader, H.O.R., Sediqi, M.M., Ibrahimi, A.M. and Senjyu, T. (2018) Optimal Thermal Unit Commitment for Solving Duck Curve Problem by Introducing CSP, PSH and Demand Response. *IEEE Access*, **6**, 4834-4844. https://doi.org/10.1109/access.2018.2790967

[12] Denholm, P., O'Connell, M., Brinkman, G. and Jorgenson, J. (2015) Over-Generation from Solar Energy in California. A Field Guide to the Duck Chart. National Renewable Energy Laboratory.

[13] Kahn, E. (1978) Reliability of Wind Power from Dispersed Sites: A Preliminary Assessment. Lawrence Berkeley Laboratory.

[14] Pedruzzi, R., Silva, A.R., Soares dos Santos, T., Araujo, A.C., Cotta Weyll, A.L., Lago Kitagawa, Y.K., *et al.* (2023) Review of Mapping Analysis and Complementarity between Solar and Wind Energy Sources. *Energy*, **283**, Article ID: 129045. https://doi.org/10.1016/j.energy.2023.129045

[15] Beluco, A., de Souza, P.K. and Krenzinger, A. (2008) A Dimensionless Index Evaluating the Time Complementarity between Solar and Hydraulic Energies. *Renewable Energy*, **33**, 2157-2165. https://doi.org/10.1016/j.renene.2008.01.019

[16] Cantor, D., Mesa, O. and Ochoa, A. (2022) Complementarity Beyond Correlation. In: Jurasz, J. and Beluco, A., Eds., *Complementarity of Variable Renewable Energy Sources*, Elsevier, 121-141. https://doi.org/10.1016/b978-0-323-85527-3.00003-0

[17] Perini de Souza, N.B., Cardoso dos Santos, J.V., Sperandio Nascimento, E.G., Bandeira Santos, A.A. and Moreira, D.M. (2022) Long-Range Correlations of the Wind Speed in a Northeast Region of Brazil. *Energy*, **243**, Article ID: 122742. https://doi.org/10.1016/j.energy.2021.122742

[18] Ma, T., Yang, H., Lu, L. and Peng, J. (2015) Optimal Design of an Autonomous Solar-Wind-Pumped Storage Power Supply System. *Applied Energy*, **160**, 728-736. https://doi.org/10.1016/j.apenergy.2014.11.026

[19] Schmidt, J., Cancella, R. and Pereira, A.O. (2016) An Optimal Mix of Solar PV, Wind and Hydro Power for a Low-Carbon Electricity Supply in Brazil. *Renewable Energy*, **85**, 137-147. https://doi.org/10.1016/j.renene.2015.06.010

[20] Haikarainen, C., Pettersson, F. and Saxén, H. (2019) Optimising the Regional Mix of Intermittent and Flexible Energy Technologies. *Journal of Cleaner Production*, **219**, 508-517. https://doi.org/10.1016/j.jclepro.2019.02.103

[21] Awan, A.B., Zubair, M., Sidhu, G.A.S., Bhatti, A.R. and Abo-Khalil, A.G. (2018) Performance Analysis of Various Hybrid Renewable Energy Systems Using Battery, Hydrogen, and Pumped Hydro-Based Storage Units. *International Journal of Energy Research*, **43**, 6296-6321. https://doi.org/10.1002/er.4343

[22] Zhang, L., Xin, H., Wu, J., Ju, L. and Tan, Z. (2017) A Multiobjective Robust Scheduling Optimization Mode for Multienergy Hybrid System Integrated by Wind Power, Solar Photovoltaic Power, and Pumped Storage Power. *Mathematical Problems in Engineering*, **2017**, Article ID: 9485127. https://doi.org/10.1155/2017/9485127

[23] Yimen, N., Hamandjoda, O., Meva'a, L., Ndzana, B. and Nganhou, J. (2018)

Analyzing of a Photovoltaic/Wind/Biogas/Pumped-Hydro Off-Grid Hybrid System for Rural Electrification in Sub-Saharan Africa—Case Study of Djoundé in Northern Cameroon. *Energies*, **11**, Article 2644. https://doi.org/10.3390/en11102644

[24] de Jong, P., Kiperstok, A., Sánchez, A.S., Dargaville, R. and Torres, E.A. (2016) Integrating Large Scale Wind Power into the Electricity Grid in the Northeast of Brazil. *Energy*, **100**, 401-415. https://doi.org/10.1016/j.energy.2015.12.026

[25] Guezgouz, M., Jurasz, J. and Bekkouche, B. (2019) Techno-Economic and Environmental Analysis of a Hybrid PV-WT-PSH/BB Standalone System Supplying Various Loads. *Energies*, **12**, Article 514. https://doi.org/10.3390/en12030514

[26] Gao, J., Zheng, Y., Li, J., Zhu, X. and Kan, K. (2018) Optimal Model for Complementary Operation of a Photovoltaic-Wind-Pumped Storage System. *Mathematical Problems in Engineering*, **2018**, Article ID: 5346253. https://doi.org/10.1155/2018/5346253

[27] Wang, Z., Fang, G., Wen, X., Tan, Q., Zhang, P. and Liu, Z. (2023) Coordinated Operation of Conventional Hydropower Plants as Hybrid Pumped Storage Hydropower with Wind and Photovoltaic Plants. *Energy Conversion and Management*, **277**, Article ID: 116654. https://doi.org/10.1016/j.enconman.2022.116654

[28] Muñoz-Pincheira, J.L., Salazar, L., Sanhueza, F. and Lüer-Villagra, A. (2024) Temporal Complementarity Analysis of Wind and Solar Power Potential for Distributed Hybrid Electric Generation in Chile. *Energies*, **17**, Article 1890. https://doi.org/10.3390/en17081890

[29] dos Anjos, P.S., da Silva, A.S.A., Stošić, B. and Stošić, T. (2015) Long-term Correlations and Cross-Correlations in Wind Speed and Solar Radiation Temporal Series from Fernando De Noronha Island, Brazil. *Physica A*: *Statistical Mechanics and its Applications*, **424**, 90-96. https://doi.org/10.1016/j.physa.2015.01.003

[30] Cantão, M.P., Bessa, M.R., Bettega, R., Detzel, D.H.M. and Lima, J.M. (2017) Evaluation of Hydro-Wind Complementarity in the Brazilian Territory by Means of Correlation Maps. *Renewable Energy*, **101**, 1215-1225. https://doi.org/10.1016/j.renene.2016.10.012

[31] Silva, A.R., Pimenta, F.M., Assireu, A.T. and Spyrides, M.H.C. (2016) Complementarity of Brazil's Hydro and Offshore Wind Power. *Renewable and Sustainable Energy Reviews*, **56**, 413-427. https://doi.org/10.1016/j.rser.2015.11.045

[32] Beluco, A., Kroeff de Souza, P. and Krenzinger, A. (2012) A Method to Evaluate the Effect of Complementarity in Time between Hydro and Solar Energy on the Performance of Hybrid Hydro PV Generating Plants. *Renewable Energy*, **45**, 24-30. https://doi.org/10.1016/j.renene.2012.01.096

[33] Borba, E.M. and Brito, R.M. (2017) An Index Assessing the Energetic Complementarity in Time between More than Two Energy Resources. *Energy and Power Engineering*, **9**, 505-514. https://doi.org/10.4236/epe.2017.99035

[34] Petrakopoulou, F., Robinson, A. and Loizidou, M. (2016) Simulation and Analysis of a Stand-Alone Solar-Wind and Pumped-Storage Hydropower Plant. *Energy*, **96**, 676-683. https://doi.org/10.1016/j.energy.2015.12.049

[35] De Oliveira Costa Souza Rosa, C., Costa, K., Da Silva Christo, E. and Braga Bertahone, P. (2017) Complementarity of Hydro, Photovoltaic, and Wind Power in Rio De Janeiro State. *Sustainability*, **9**, Article 1130. https://doi.org/10.3390/su9071130

[36] François, B., Hingray, B., Raynaud, D., Borga, M. and Creutin, J.D. (2016) Increasing Climate-Related-Energy Penetration by Integrating Run-of-the River Hydropower to Wind/Solar Mix. *Renewable Energy*, **87**, 686-696. https://doi.org/10.1016/j.renene.2015.10.064

[37] Jurasz, J. (2017) Modeling and Forecasting Energy Flow between National Power Grid and a Solar-Wind-Pumped-Hydroelectricity (PV-WT-PSH) Energy Source. *Energy Conversion and Management*, **136**, 382-394. https://doi.org/10.1016/j.enconman.2017.01.032

[38] Bhandari, B., Lee, K., Lee, C.S., Song, C., Maskey, R.K. and Ahn, S. (2014) A Novel Off-Grid Hybrid Power System Comprised of Solar Photovoltaic, Wind, and Hydro Energy Sources. *Applied Energy*, **133**, 236-242. https://doi.org/10.1016/j.apenergy.2014.07.033

[39] Zhou, Y., Zhao, J. and Zhai, Q. (2021) 100% Renewable Energy: A Multi-Stage Robust Scheduling Approach for Cascade Hydropower System with Wind and Photovoltaic Power. *Applied Energy*, **301**, Article ID: 117441. https://doi.org/10.1016/j.apenergy.2021.117441

[40] Wang, X., Virguez, E., Mei, Y., Yao, H. and Patiño-Echeverri, D. (2022) Integrating Wind and Photovoltaic Power with Dual Hydro-Reservoir Systems. *Energy Conversion and Management*, **257**, Article ID: 115425. https://doi.org/10.1016/j.enconman.2022.115425

[41] Zhou, S., Han, Y., Zalhaf, A.S., Chen, S., Zhou, T., Yang, P., *et al.* (2023) A Novel Multi-Objective Scheduling Model for Grid-Connected Hydro-Wind-PV-Battery Complementary System under Extreme Weather: A Case Study of Sichuan, China. *Renewable Energy*, **212**, 818-833. https://doi.org/10.1016/j.renene.2023.05.092

[42] Teotónio, C., Fortes, P., Roebeling, P., Rodriguez, M. and Robaina-Alves, M. (2017) Assessing the Impacts of Climate Change on Hydropower Generation and the Power Sector in Portugal: A Partial Equilibrium Approach. *Renewable and Sustainable Energy Reviews*, **74**, 788-799. https://doi.org/10.1016/j.rser.2017.03.002

[43] Jurasz, J., Guezgouz, M., Campana, P.E., Kaźmierczak, B., Kuriqi, A., Bloomfield, H., *et al.* (2024) Complementarity of Wind and Solar Power in North Africa: Potential for Alleviating Energy Droughts and Impacts of the North Atlantic Oscillation. *Renewable and Sustainable Energy Reviews*, **191**, Article ID: 114181. https://doi.org/10.1016/j.rser.2023.114181

[44] Tapia Carpio, L.G. (2021) Mitigating the Risk of Photovoltaic Power Generation: A Complementarity Model of Solar Irradiation in Diverse Regions Applied to Brazil. *Utilities Policy*, **71**, Article ID: 101245. https://doi.org/10.1016/j.jup.2021.101245

[45] Luz, T.J.D., Vila, C.U. and Aoki, A.R. (2023) Complementarity between Renewable Energy Sources and Regions—Brazilian Case. *Brazilian Archives of Biology and Technology*, **66**, e23220442. https://doi.org/10.1590/1678-4324-2023220442

[46] Brandão, S.Q., Rego, E.E., Pillar, R.V. and de Carvalho, R.N.F. (2024) Hydropower Enhancing the Future of Variable Renewable Energy Integration: A Regional Analysis of Capacity Availability in Brazil. *Energies*, **17**, Article 3339. https://doi.org/10.3390/en17133339

[47] de Oliveira Costa Souza Rosa, C., da Silva Christo, E., Costa, K.A. and Santos, L.d. (2020) Assessing Complementarity and Optimising the Combination of Intermittent Renewable Energy Sources Using Ground Measurements. *Journal of Cleaner Production*, **258**, Article ID: 120946. https://doi.org/10.1016/j.jclepro.2020.120946

[48] Lei, H., Liu, P., Cheng, Q., Xu, H., Liu, W., Zheng, Y., *et al.* (2024) Frequency, Duration, Severity of Energy Drought and Its Propagation in Hydro-Wind-Photovoltaic Complementary Systems. *Renewable Energy*, **230**, Article ID: 120845. https://doi.org/10.1016/j.renene.2024.120845

[49] Nogueira, E.C., Morais, R.C. and Pereira, A.O. (2023) Offshore Wind Power Potential in Brazil: Complementarity and Synergies. *Energies*, **16**, Article 5912.

https://doi.org/10.3390/en16165912

[50] INMET (2024) Instituto nacional de meteorologia. https://portal.inmet.gov.br