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Complementarity Between Renewable Energy Sources and Regions - Brazilian Case

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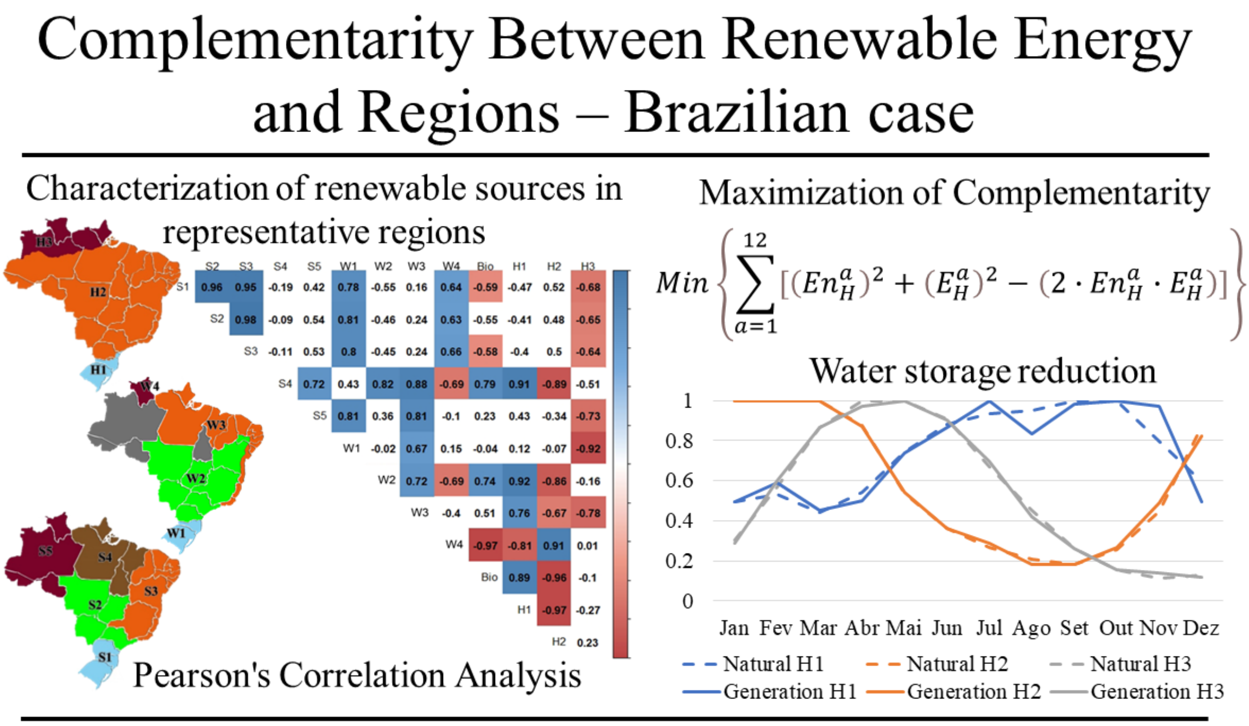
HIGHLIGHTS

- The Brazilian complementarity between renewable sources and region is characterized.
- A model for assessing complementarity between renewable sources is proposed.
- A Pearson's correlation matrix is presented.
- A scenario 100% renewable for the Brazilian in 2050 is presented.
- The seasonality complementarity reduced the demand for water storage.

Abstract: The benefits of complementarity between renewable energy sources have been presented as having a positive impact, but it has been neglected in generation expansion planning studies. In this paper the complementarity between renewable energy sources and regions of Brazil is characterized and the correlation coefficients are analyzed. A methodology is also proposed to optimize the complementarity between the sources, reducing the energy storage requirements. The methodology is applied to the Brazilian case to meet the projected demand for 2050 with a 100% renewable system and the complementarity is analyzed. The characterization of the data allowed us to propose five solar regions, four wind regions, three hydro regions and a region to represent the biomass. It was possible to find complementarity (negative correlation) of: 0.97 between hydro regions; 0.86 between wind and hydro regions and; 0.96 between biomass and hydro. The proposed methodology allowed us to know which regions and their respective technologies best benefit the electrical system, being the North for solar and the Northeast for wind. Finally, it was possible to reduce the demand for water storage with sources and regions that complement the seasonal hydro drought period.

Keywords: Complementarity; generation expansion planning; hydropower; renewable energy sources; water storage.

GRAPHICAL ABSTRACT



INTRODUCTION

Brazil is one of the largest producers of renewable energy sources (RES), ranking third in capacity. This position is only achieved thanks to the large share of hydroelectric plants, where it ranks second in the world [1]. Despite the hydro crisis faced in the last decade, for years the share of hydropower has been above 60% in the electricity sector. At a global level, the hydro sector has faced challenges such as environmental and social acceptance, the reduction in the price of other renewable sources and climate impacts that affect the production of hydropower. It is possible to observe a reduction in the growth of hydropower in recent years, for example, while the total installed capacity growth was 24% in 2020, hydropower generation increased 1.5%. Brazil, after almost a decade adding gigawatts of hydro capacity, commissioned only 213 MW in 2020, mainly caused by environmental impasses [1]. When only hydropower with storage capacity is analyzed, the data is more alarming with the storage rate falling since the 90s in Brazil. Additionally, 70% of the reservoir are concentrated in a small region in Brazil and there is no forecast of construction of large reservoirs in the coming years.

To make this situation even worse, the use of hydropower is subject to seasonality, as the annual rainfall cycle forces the system to store water in the wet season (December to April) to be used in the dry season (May to November) and ensure continuity in energy production [2]. In addition, there have been periods of drought for more than two years and in the future, climate change will also be responsible for a reduction in river flow, compromising more than half of hydropower generation [3]. Furthermore, hydroelectric reservoir are also responsible for balancing variations in demand, hydro seasonality and variable renewable energies sources (VRES) [4]. It is evident that new strategies need to be included in energy planning, as hydroelectric plants alone will not be able to guarantee security in energy supply. Diversification in the energy matrix can ensure the security of the system against climate change, however, alone does not solve the energy storage problem and may require an increase in storage capacity.

Complementarity between RES can be presented as a solution to reduce the need for energy storage. For example, in Australia, the complementarity between wind and solar energy reduces intermittency [5] and in California, the daily and annual complementarity between solar and wind energy contributes to reducing the requirement for backup systems [6]. In the south of the Iberian Peninsula, the combination of wind and solar energy smooths the variability of these sources and in 71% of cases the variations are opposite, ensuring the complementarity of these sources [7]. In Brazil, there is hydro complementary between southern and the rest of the country [8], the dry period (when hydropower plants produce less) also coincides with the sugarcane harvest and the highest incidence of winds [9]. It was also found that combined solar and wind energy are complementary to hydropower in Northeast Brazil [10] and verified hydro-wind complementarity [8,11].

In order to have an energy transition towards a 100% renewable and reliable system, it will be necessary to explore the synergy that exists between hydropower and VRES. Regional complementarity allows variability smoothing and improves forecasting of these energy sources [12]. Complementarity between regions increases system security and reduces costs, for example, the geographic diversification of wind farms reduces the variability of this source [13]. Additionally, complementarity between sources reduces demand for storage, for example, it has been found that optimized solar-wind complementarity in the Northeast can reduce demand for energy storage [14].

Many researchers have found in complementarity the solution for the integration of RES, and some studies have been conducted for the Brazilian case. Despite this, complementarity is not yet an integrated goal within the generation expansion planning (GEP) in many countries, as they use mono-objective models and simplified model with annual energy demand [15], typical weeks [16], or a day is represented by a few groups of hours[17]. The Brazilian Expansion Planning has been using the Investment Decision Model since 2017, however, this model does not integrate the complementarity [19]. The hydropower operation is optimized using the NEWAVE model, being it a hydrothermal model [20]. Others researchers have formulation models to Brazilian case with greenhouse gas emission impact [21], however, without complementarity analyses.

As a result, this paper presents an analysis of the complementarity between renewable sources and Brazilian regions. For this, meteorological data from 27 Automatic Meteorological Stations (AMS) and hydrological data from 264 measurement sites are used. Representative regions are defined for each of the RES (Biomass, Wind, Hydro and Solar) and the Pearson correlation between them is analyzed. A methodology to reduce the need for energy storage in expansion and operation planning is proposed. The model should optimize the complementarity between the sources, reducing the need for water storage. A case study is presented to apply this methodology in the Brazilian case The present study the analysis is centered on the characterization of complementarity in Brazil.

The methodology and input data are presented in Section 2. In Section 3 the results are presented, discussed and compared with other studies. Finally, Section 4 summarizes the paper and highlights its main conclusions.

METHODOLOGY

The characterization of the data was divided into two steps. In the first step, the data were processed and based on the heterogeneity and homogeneity between the locations, representative regions were defined for each type of renewable source. In the second step, the daily and monthly averages of the climatological data for each region were calculated and the results were transformed into capacity factors.

Definition of Regions

Brazil is divided into five regions (North, Northeast, Midwest, Southeast and South), composed by twenty-six states. In this research, the climatological historical series for the entire Brazilian territory were analyzed, with all data obtained from government sources [23,24]. However, there are more than 300 river inflow measurement sites and more than 400 meteorological stations with solar and wind data since 1961, making it unreasonable to use all of them, requiring the choice of stations representative of the regions of interest. Therefore, meteorological data from twenty-seven AMS and hydrological data from 264 measurement sites were analyzed, reducing them at the end of the analysis. The National Electric Energy Agency divides Brazilian territory into eight basins and 79 hydrographic sub-basins. The National Water Resources Council divides the territory into twelve hydrographic basins [25]. For each basin, the most representative hydroelectric plant (highest correlation) defined in [8] and used the daily historical series of inflows (1931-2014) of the ten plants available in [23].

Figure 1 presents the monthly average of the normalized inflow (divided by the average of the corresponding basin), for the average year, of the representative plants. It is possible to verify three distinct annual behaviors, which justifies the division of the territory in three representative regions.

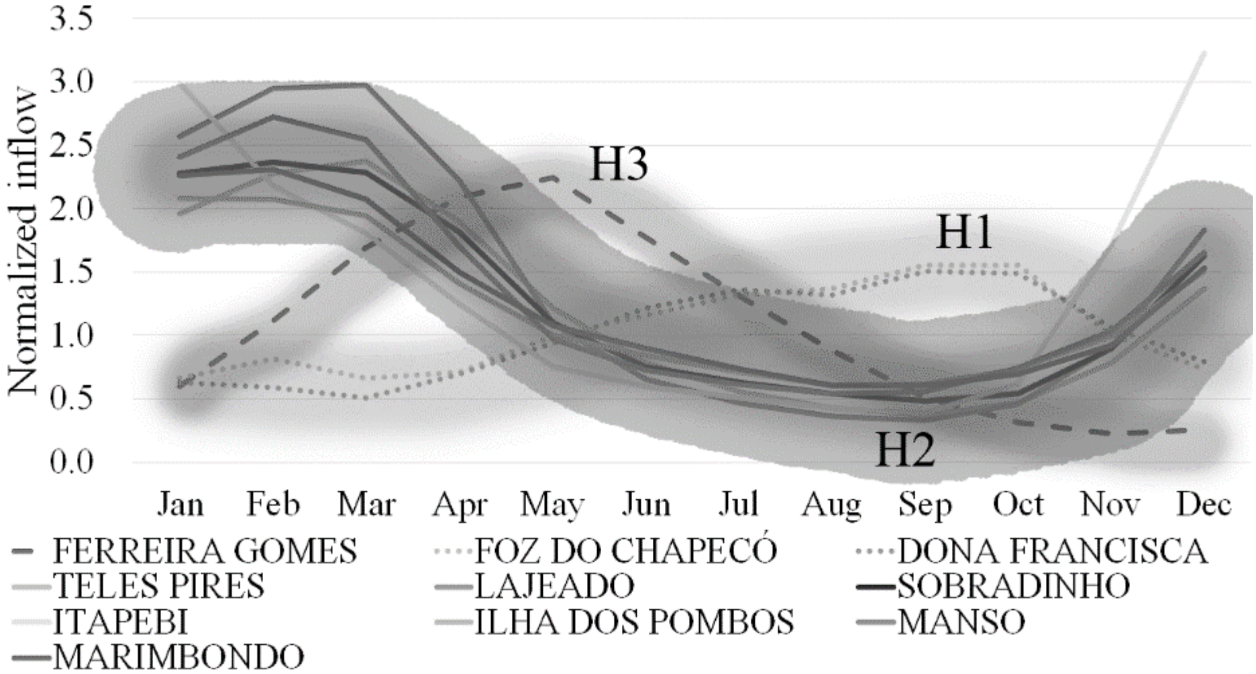


Figure 1. Normalized average inflow for the 10 basins (1931-2014).

For wind speed and solar radiation, twenty-seven meteorological stations were chosen throughout the Brazilian territory and close to power plants and/or places with great wind or solar energy potential [24]. In the first step, the daily averages for a period of 90 days were used, with the purpose of reducing the number of meteorological stations, eliminating those that are close and that have a high correlation. In the second step, the monthly averages for a period of three years were used and the correlation between the Brazilian states was verified, making it possible to reduce the number of meteorological stations to twelve. The use of more than one station per region was decided to improve the quality of the results, to minimize the errors in the readings of the meteorological stations and to have an average representation of the regions. Figure 2 presents two examples of analyses carried out, the first for the daily average of solar radiation (a) and the second for the monthly average of wind speed (b).

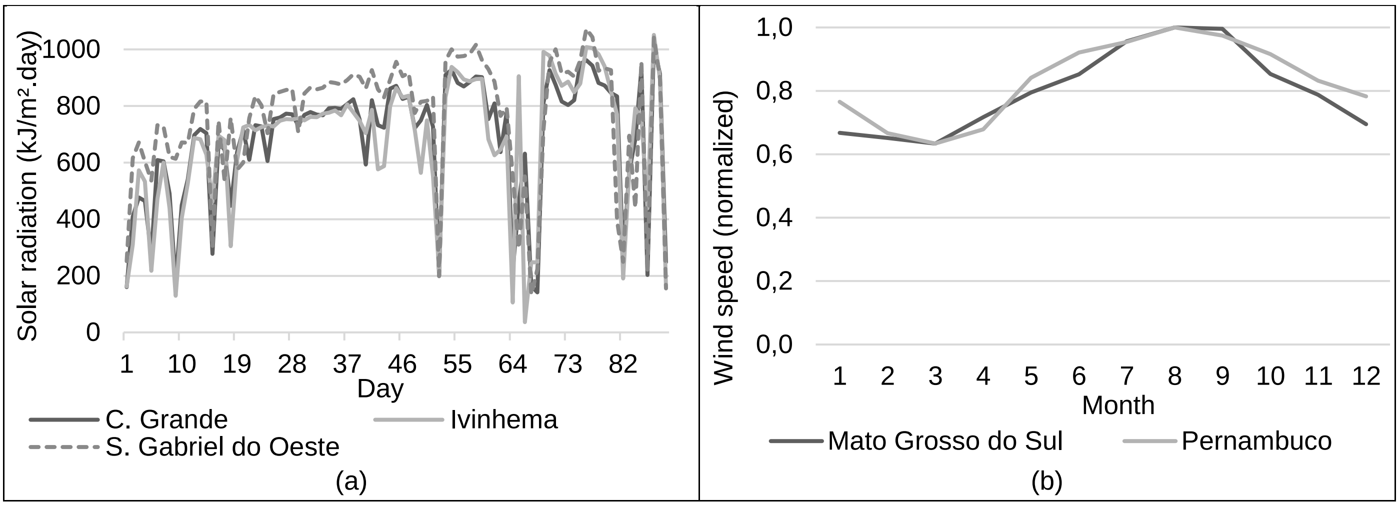


Figure 2. (a) First step – daily average; (b) Second step – monthly average.

For the wind speed calculations, the cubic mean was used to avoid an underestimation of the wind power potential:

$$\overline{v_a} = \left(\frac{1}{n} \sum_{j=1}^{n} \left(v_j \right)^3 \right)^{1/3} \quad , \qquad \forall a \tag{1}$$

where $\overline{v_a}$ is the average wind speed of the month a, v_j is the wind speed in the instant *j* and *n* is the number of the valid values in the month a.

After these analyses, the country was divided into different regions for each type of source, namely: three hydro (Figure 3.a), four wind (Figure 3.b) and five solar (Figure 3.c). In the analysis carried out, heterogeneity was verified in regions of the same state. For example, the State of Bahia (comprised of the Northeast-Southeast Coastal Zone and the Northeast-Southeast Elevations) was divided into two wind regions (W2 and W3), the same happening with State of Pernambuco. In the black region (Figure 3.b) the wind speed is very low and therefore this region will not be considered in the wind analysis. For biomass, the sugar-energy industry was taken as a reference (it corresponds to more than 70% of this market). Therefore, the country was not divided into regions and taking into account that a small portion of this production (located in the north-northeast region) has the harvest carried out in the off-season and which was considered, but which does not justify the division into regions [26].

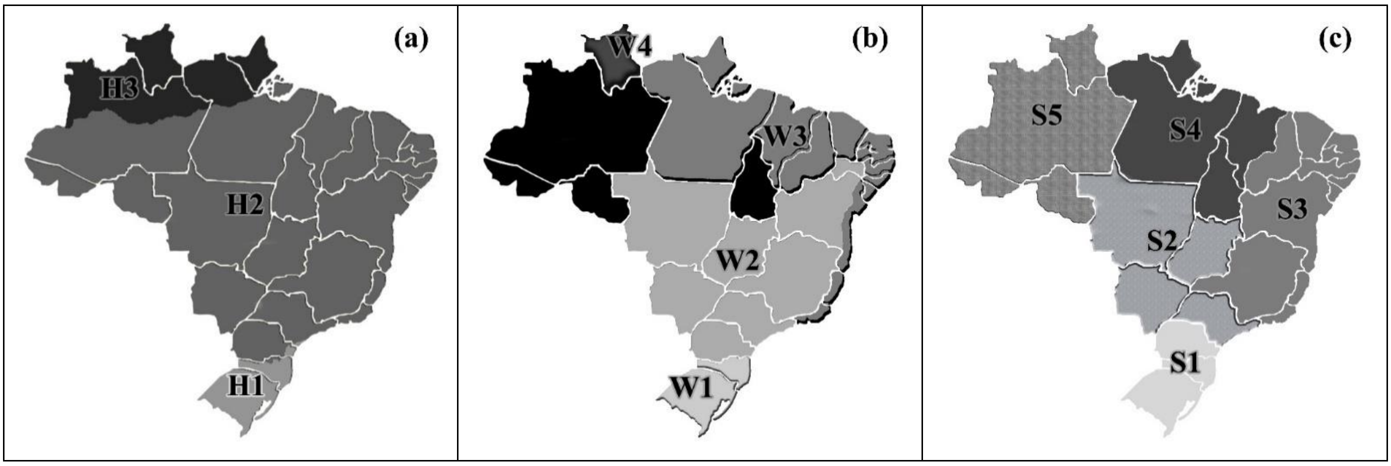


Figure 3. Division of regions according to annual behaviour for: (a) Hydro; (b) Wind and; (c) Solar.

Capacity Factor

In order to allow comparison between different energy sources, all data were converted to a dimensionless unit, the Capacity Factor (CF). The CF is the ratio between the average power output and the installed power. The wind speeds were measured at 10 meters and the final data were extrapolated up to the hub height of 100 meters:

$$\frac{v(z)}{v(z_r)} = \frac{\ln\left({}^{z}/_{z_0}\right)}{\ln\left({}^{z_r}/_{z_0}\right)} \tag{2}$$

where $v(z)$ is the wind speed [in m/s] at height z, $v(z_r)$ is the wind speed [in m/s] at reference height z_r, z is the desired height [in m] to be extrapolated to, z_r is the height [in m] for which the wind speed is available and z_0 is the surface roughness length. The chosen z_0 was 0.1 m.

The average power output of wind energy calculated by Equation (3).

$$P = 0.5 \cdot \rho \cdot A_T \cdot v^3 \cdot \eta_E \tag{3}$$

where ρ is the air density (1.225 kg/m^3, under normal conditions of pressure and temperature); A_T is the cross-sectional area of the turbine rotor (in m^2); η_E is the conversion efficiency (in %) and; v is the wind speed (in m/s). Equation (1) is valid only for the operating zone between the cut-in speed and the rated speed. It was defined 4 m/s for cut-in, 25 m/s for cut-out and 12 m/s for rated speed and considered a turbine of 3 MW with a rotor diameter of 90 meters to calculate the CF.

The average power output of solar energy is calculated by Equation (4), considering an efficiency of 14% for the photovoltaic system.

$$P = \frac{R \cdot A_p \cdot \eta_S}{3.6 \cdot 10^3} \tag{4}$$

where R is the hourly solar radiation (in J/m^2); A_p is the useful area of the photovoltaic panels (in m^2) and η_S is the conversion efficiency (in %).

The CF of hydropower can be calculated by Equation (5).

$$CF \approx Q/Q_p \quad (5)$$

where Q is the natural inflow of the river (in m^3/s) and; Q_p is the project inflow (in m^3/s) of the hydro plant.

The FC of the biomass plants was calculated using the monthly averages of production and the installed power for the reference year.

Pearson Correlation

The Pearson correlation coefficient measures the degree of linear correlation between two variables and assumes values between 1 and -1. When there is strong complementarity, the value is close to -1, which means that when one variable increases, the other decreases. The significance level is the probability of rejecting the null hypothesis when it is true and can be expressed by the *p-value*. The result can be of weak significance (p > 0.05), strong (0.01 < p < 0.05), or very strong (p < 0.01). In this analysis, the level of significance was considered due to the low intramonth variation of solar energy in the regions close to the equator.

Complementarity Formulation

To ensure energy demand by maximizing the complementarity between sources, it is necessary to maximize the use of these resources. In this study, hydropower ensures the role of providing flexibility to the system because it is a predictable source in the long term. Its generation can be managed through the storage of water in the reservoirs, an assumption that can also be verified in other works, such as [27–29]. One way to maximize complementarity is to find a combination that minimizes curtailment and deficit [27], or that minimizes the production of thermal plants [28], or minimizes the cost of stored energy [30]. However, in countries with large reservoirs, such as Brazil, these optimization models do not optimize the inflow of hydroelectric plants or the use of reservoirs. Due to higher power capacity, hydropower plants are free to have a production shape that is completely different from the natural inflow shape.

One way to maximize complementarity is to find the optimal combination that takes advantage of the natural inflow of rivers [30]. In [22] a multi objective problem is proposed to maximize complementarity and reduce expansion cost. However, in this paper the focus is to analyze the complementarity, reducing water waste and the need to store water for the following months, being a single objective problem without cost impact. In Equation (6) the distance between the generation curve and the natural energy curve is minimized.

$$Min\left\{\sum_{a=1}^{12}[(En_H^a)^2 + (E_H^a)^2 - (2 \cdot En_H^a \cdot E_H^a)]\right\} \quad (6)$$

where a is the index of the month (a = 1, … ,12); En_H^a is the natural energy (MWh/month) that inflows in rivers in month a and; E_H^a is the energy generation (MWh/month) in hydropower in month a. The energy generation by the hydropower and the natural energy that inflows in the rivers in the year of analysis can be calculated in Equation (7-8).

$$En_{Hj}^a = CFn_{Hj}^a \cdot P_{Hj} \cdot H^a \ , \quad (a = 1,2,\dots,12), \ (j = 1,2,3) \quad (7)$$

$$E_{Hj}^a = CF_{Hj}^a \cdot P_{Hj} \cdot H^a \ , \quad (a = 1,2,\dots,12), \ (j = 1,2,3) \quad (8)$$

where CFn_{Hj}^a is the average capacity factor of month a for the natural inflow of region H_j; CF_{Hj}^a is a decision variable representing the average capacity factor of month a of region H_j; P_{Hj} is a decision variable that represents the total power output (MW) of hydropower in region H_j in the projection year (2050 in this work) and; H^a is the total hours (h/month) in month a.

Constraint (9) guarantees the monthly balance between production and consumption. Constraints (10-11) ensure daily balance for summer and winter, respectively.

$$L^a - \sum_{i=1}^{I} CF_i^a \cdot P_i \cdot H^a = 0 \quad , \qquad \forall a \quad (9)$$

$$L\_s^h - \sum_{i=1}^{I} CF\_s_i^h \cdot P_i = 0 \quad , \qquad \forall h \tag{10}$$

$$L\_w^h - \sum_{i=1}^{I} CF\_w_i^h \cdot P_i = 0 \quad , \quad \forall h \tag{11}$$

L^a is the energy consumption (MWh/month) in month a; L_s^h and L_w^h are the daily summer and winter demand (consecutively) in the hour h; CF_i^a is the average capacity factor of each technology and region i in month a; $CF\_s_i^h$ and $CF\_w_i^h$ are the capacity factors of technology and region i for the average summer and winter day (respectively) in the hour h; i represents the type of technology and region (i = 1, 2, … , 12 and 13 for H1, H2, … , S5 and biomass); *h* is the hour index and; P_i is a decision variable that represents the total power output (MW) of the technology and region i in the projection year. Due to CF of the hydropower are decision variables, Equations (9-11) are non-linear equality equations.

The equality constraint (12) ensures that the energy generation by the hydropower, in the year of the complementarity analysis, is equal to the energy inflow of the rivers, in order to avoid the depreciation of the reservoirs and the curtailment.

$$\sum_{a=1}^{12} CF_i^a H^a = \sum_{a=1}^{12} CFn_i^a H^a, \quad (i = H1, H2, H3) \tag{12}$$

Constraints (13-14) ensure that the volume of water turbined during the day is proportional to the volume turbined annually.

$$\sum_{a=1}^{6} CF_i^a H^a = 181 \cdot \sum_{h=1}^{24} FC\_s_i^h \quad , \qquad (i = H1, H2, H3) \tag{13}$$

$$\sum_{a=7}^{12} CF_i^a H^a = 184 \cdot \sum_{h=1}^{24} FC\_w_i^h \quad , \qquad (i = H1, H2, H3) \tag{14}$$

The nonlinear inequality constraint (15) ensures the maximum and minimum storage limit.

$$\alpha R_{Hj}^{max} \leq EA_{Hj}^a \leq R_{Hj}^{max} \quad , \ \forall a, j \tag{15}$$

EA_{Hj}^a is the energy (MWh) that is stored in the reservoirs of region Hj, in month a and can be calculated by Equation (10); R_{Hj}^{max} is the maximum energy storage capacity (MWh) in the reservoirs in the Hj region and; α is the minimum reserve energy (%) required in the reservoirs. In this paper, a minimum reserve of 20% was considered in relation to the maximum storage capacity. Equation (16) represents the hydro balance of the reservoirs, but in the form of stored energy.

$$EA_{Hj}^a = En_{Hj}^a - E_{Hj}^a + EA_{Hj}^{a-1}, \quad \forall a, j \tag{16}$$

En_{Hj}^a and E_{Hj}^a are calculated in Equation (7-8); EA_{Hj}^a is the initial energy of the reservoirs. Constraints (17-20) refer to the limits of the decision variables.

$$Pin_i \leq P_i \leq P_i^{max}, \ \forall i \tag{17}$$

$$CF_i^{min} \leq CF_i^a \leq 1 \quad , \ \forall a, \ (i = H1, H2, H3) \tag{18}$$

$$CF_i^{min} \leq CF\_s_i^h \leq 1 \quad , \ \forall h, \ (i = H1, H2, H3) \tag{19}$$

$$CF_i^{min} \leq CF\_w_i^h \leq 1 \quad , \ \forall h, \ (i = H1, H2, H3) \tag{20}$$

Constraints (17) refers to the minimum and maximum expansion power restrictions, for each technology and region i, due to the maximum exploitable potential in the country. Pin_i is the installed power (MW) of technology and region i in the reference year and; P_i^{max} is the estimated maximum potential (MW) for technology and region i. Constraints (18-20) limit the annual and daily CF of the hydropower, with CF_i^{min}

being the minimum flow in the region Hj to avoid environmental impacts and ensure other services performed by the river.

In long-term studies, there is no need to detail every element of the system (e.g., converter details, AC or DC power flow, etc.), and simplifying the model can facilitate the solution. The detail of the problem depends on the tools and algorithms available for its solving and the required accuracy [31].

RESULTS AND DISCUSSION

National Analysis

In this section, the values presented are the weighted national averages. Figure 4 presents the average annual capacity factor curve for each source and load.

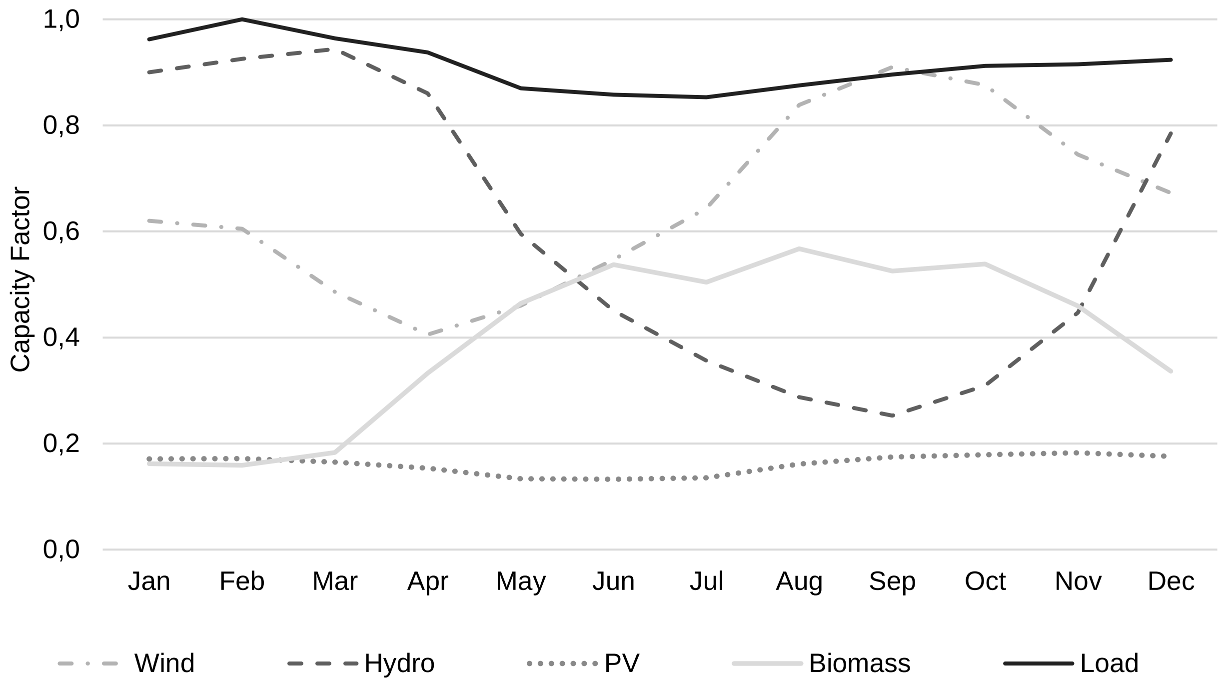


Figure 4. Annual average CF curve (global average).

Photovoltaic generation is practically constant throughout the year. This is because Brazil is located close to the equator, thus presenting a much lower seasonality than that observed in central Europe. Biomass and wind power are complementary to hydropower, as verified in other works [8,26]. For biomass and hydro, a high negative correlation (complementarity) was observed (-0.94).

Regional Analysis

Luz [22] found that when the national average is used, the benefits of intraregional complementarity is lost. In the study, the fact of considering the regional division halved the demand for energy storage and allowed a greater integration of solar energy. Given the importance of regional data, in this section the results will be presented according to the division shown in Figure 3. Figure 5 shows the curves of capacity factors by region and by renewable source. As the biomass was not divided into regions, the same result presented in Figure 4 will be used for this source.

In Figure 5(a), a strong complementarity between the H1-H2 hydro regions can be observed, with a negative correlation of -0.97 (Figure 6). Although H2 represents 89% of the total hydro capacity and H1 only 10%, that is, H1 does not have enough capacity to compensate H2 seasonality. Nevertheless, in addition to H1, the wind regions EW2 (-0.86) and EW3 (-0.67) are also complementary to H2. For solar energy (Figure 5.b), the further south, the greater the coefficient of variation (CV) is, being 31% for S1, a variation that is reduced as the region is closer to the equator. For instance, S5 has 9% for CV, thus, for purposes of complementarity, S3-S4-S5 have a CV less than 15% and they will be ignored (the CV of H2, for instance, is 69%). As a result, S3-S4-S5 regions can provide constant annual generation without seasonality. Table 1 presents the detailed CF data.

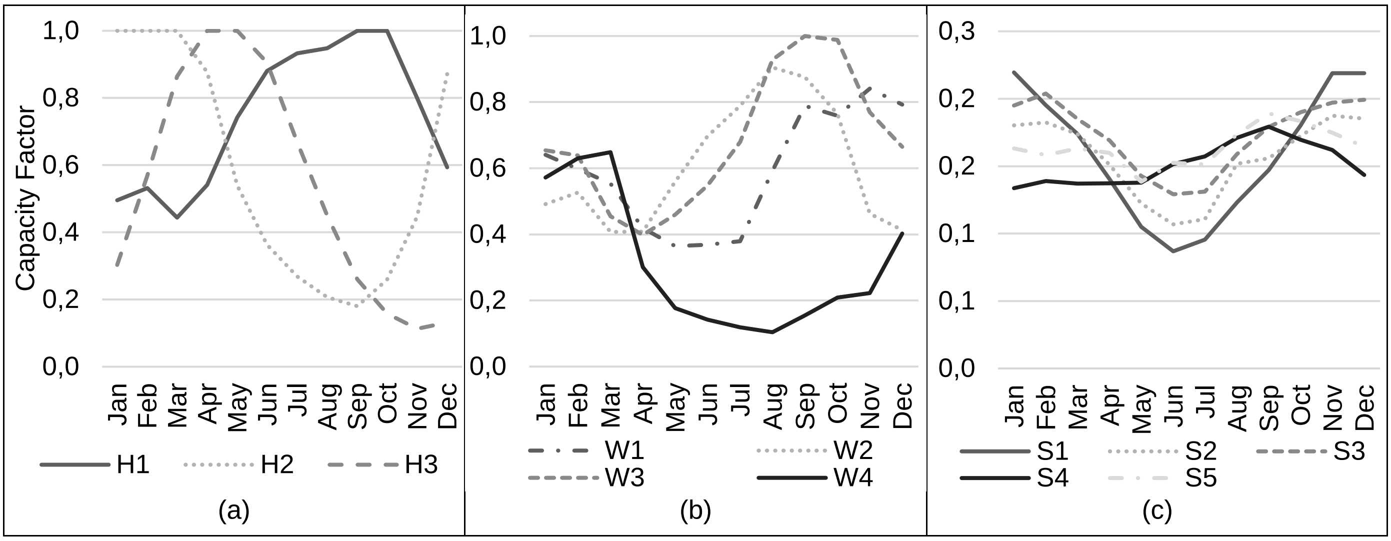


Figure 5. CF curve by region for an average year: (a) hydro; (b) wind power and; (c) solar.

Table 1: Capacity Factor for each technology and region

Region	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
H1	0.46	0.54	0.44	0.49	0.68	0.80	0.89	0.91	1.00	1.00	0.71	0.52
H2	0.98	0.99	0.98	0.89	0.56	0.39	0.30	0.25	0.23	0.28	0.46	0.80
H3	0.30	0.57	0.86	1.00	1.00	0.91	0.67	0.45	0.26	0.16	0.11	0.13
W1	0.64	0.60	0.55	0.42	0.36	0.37	0.38	0.59	0.79	0.76	0.84	0.79
W2	0.49	0.53	0.41	0.41	0.56	0.70	0.79	0.90	0.88	0.76	0.46	0.41
W3	0.65	0.64	0.45	0.40	0.46	0.55	0.68	0.93	1.00	0.99	0.77	0.66
W4	0.57	0.63	0.65	0.30	0.18	0.14	0.12	0.10	0.15	0.21	0.22	0.40
S1	0.22	0.20	0.17	0.14	0.11	0.09	0.10	0.12	0.15	0.18	0.22	0.22
S2	0.18	0.18	0.17	0.15	0.12	0.11	0.11	0.15	0.16	0.17	0.19	0.19
S3	0.20	0.20	0.18	0.17	0.14	0.13	0.13	0.16	0.18	0.19	0.20	0.20
S4	0.13	0.14	0.14	0.14	0.14	0.15	0.16	0.17	0.18	0.17	0.16	0.14
S5	0.16	0.16	0.16	0.16	0.14	0.15	0.15	0.17	0.19	0.18	0.17	0.16
Bio	0.16	0.16	0.18	0.33	0.46	0.54	0.50	0.57	0.53	0.54	0.46	0.34

In Figure 6 is possible to observe that there is complementarity between regions (e.g., ~~E~~W2-~~E~~W4; H1-H2), between sources from the same region (e.g., H2-[~~E~~W2-~~E~~W3]) and between different sources and regions (e.g., H3-[S1-~~E~~W1]). Pearson correlation coefficients with strong or very strong significance are highlighted in color in Figure 6. This analysis showed how important it is to include complementarity between regions and between sources in expansion planning.

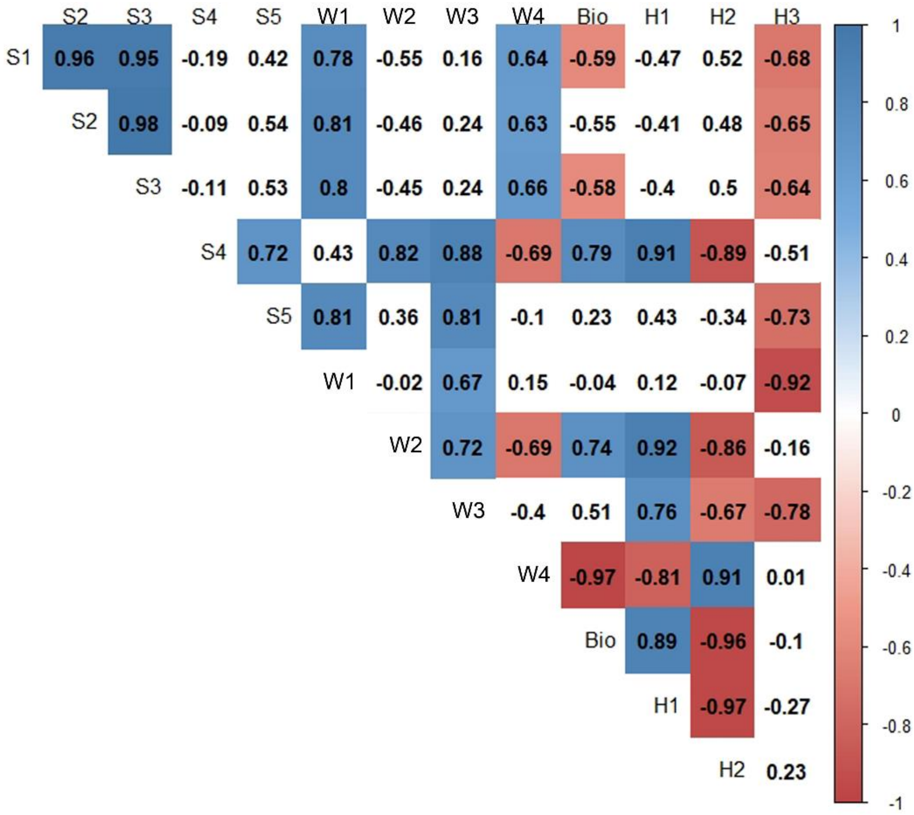


Figure 6. Pearson correlation matrix for the annual CF curves.

Complementarity Optimization

In this section, the results of the optimization of complementarity are presented when regional climatic heterogeneity is considered, i.e., divisions into regions are considered. In this analysis, the current installed power and the maximum expansion capacity by technology and region were considered. It was not allowed to increase the capacity of the reservoirs, only the generation capacity. The demand forecast for 2050 is considers and must be ensured by a 100% renewable system.

When the national average data is used, the maximum variation of the generation in relation to the natural inflow was 10.7%, representing an annual storage of 22.3 TWh. In this scenario, biomass increased reaching the maximum expansion limit and solar power grew from 3 GW to 51.5 GW. Table 2 presents the share for each source in the national scenario.

Table 2. Share in installed power by source (national scenario)

Hydro	Wind	Solar	Biomass
37.1%	40.2%	4.1%	18.6%

In the reginal scenario, it was possible to reduce the participation of hydropower when compared to an approach that uses the national average instead of the regions defined in this study. Figure 7(a) presents the composition of the electricity matrix in 2050 and in Figure 7(b), the annual generation profile of hydropower is presented.

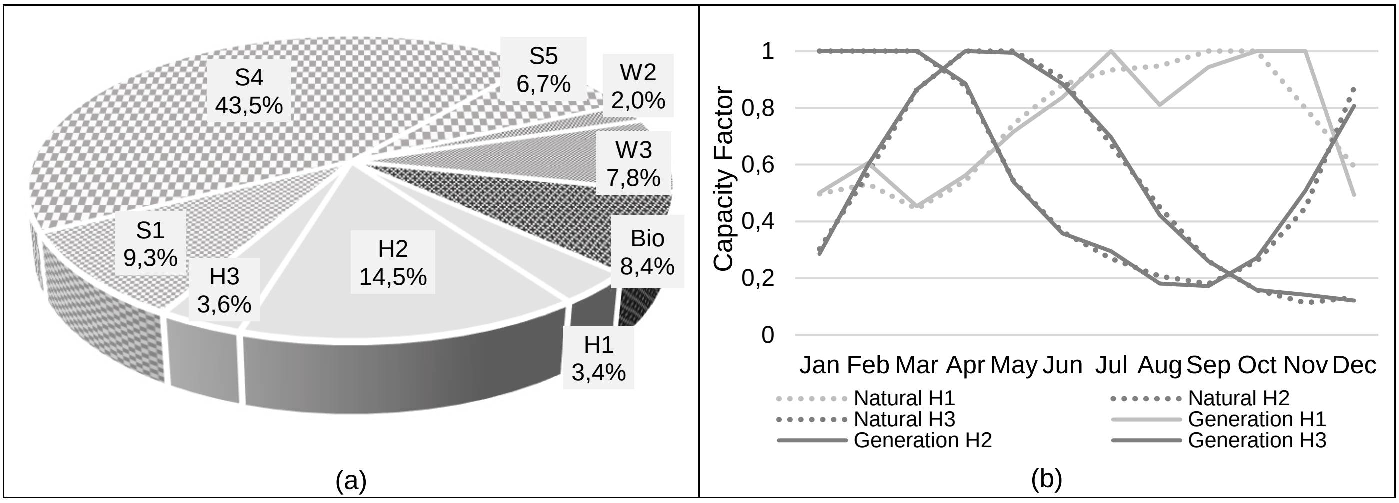


Figure 7. (a) Share in installed power by source and region. Values below 1% were omitted; (b) Natural inflow vs. hydropower generation profile.

The objective of this paper is to optimize complementarity, without considering the economic aspects. Thus, regional analysis allows us to understand which regions can offer benefits to optimize hydro reservoir management. Solar power was not installed in S2 and S3 region, nor wind power in W1 and W4 and hydropower in H2. To understand the preference of technologies and regions, it is necessary to take into account Figure 6. For instance, 270 GW of solar power were installed in S4 (reaching the maximum allowed limit), which is strongly complementary to H2, responsible for meeting 36% of annual consumption. H1 also reached the maximum limit of the region (21 GW) and is complementary to H2. Similarly, biomass is complementary to H2 and it had 36 GW installed. Figure 7(b) shows how hydropower generation profile is close to the natural inflow, it is worth mentioning that H1 and H3 represent only 2.8% of the system's storage capacity. Thus, H2, which mostly represents the reservoirs capacity, had a power generation profile very close to the natural inflow profile.

In Figure 8, the complementarity that exists between the sources in the annual cycle is presented. By maximizing complementarity between sources and regions, the need to store hydro energy for annual management was reduced in 70%, representing an annual storage of 6.8 TWh. For instance, in the main region (H2), the variation in reservoir levels was only 2.4%. As in Figure 7(b), there is a large hydro seasonality, however, with the production of wind and biomass (Figure 8), it is possible to smooth the seasonality, as these sources are complementary to hydropower ones (Figure 6).

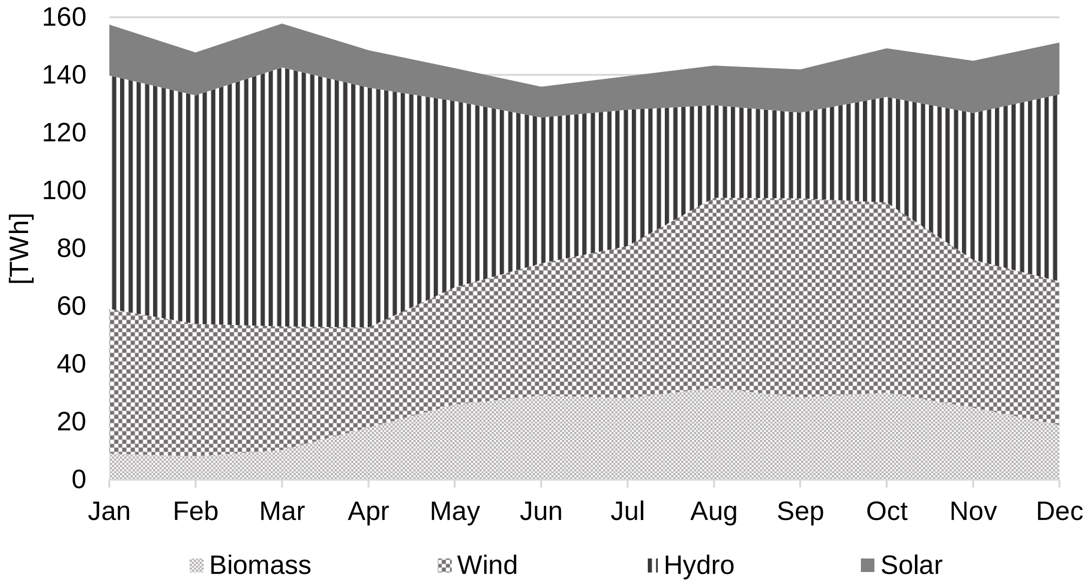


Figure 8. Annual energy generation by technology.

DISCUSSIONS

When the results of the national scenario (national average) are compared with the results of the regional scenario (with the country divided into regions) it is possible to perceive the benefits of using regions. For instance, the use of regions has enabled a 150% growth in solar energy expansion compared to the global scenario and a 70% reduction in the need for energy storage.

In Table 3, the participation rates in the production of electricity from each RES are compared with other studies. As can be seen, in all works hydropower leads the production of electricity, but in this study, it was possible to have the smallest participation of hydropower. This is a good result from the point of view of energy and environmental security, given the recent energy crises that the country has suffered due to dependence on hydro and the environmental impact that the construction of new large hydropower has caused.

Table 3. Annual share in energy production

Technology	Regional	Gils[32]	E[R][16]
Hydro	40%	48%	47%
Wind	35%	26%	25%
Solar	10%	18%	21%
Biomass	15%	7%	7%

CONCLUSIONS

This study presented the importance of characterizing RES by regions in countries with continental dimensions such as Brazil. The use of national average values can suppress the benefits of the complementarity that exists between regions. In the Brazilian case, it was possible to define five solar regions, four wind regions and three hydro regions. This allowed us to verify the complementarity between sources from different regions (-0.97 for H1-H2), between different sources in the same region (-0.86 for W2-W2) and between different sources in different regions (-0.92 for W1-H3). The proposed methodology allowed maximizing complementarity by reducing the distance between the natural inflow profile and the hydropower generation profile.

The demand in 2050 with a 100% renewable system without having to increase the capacity of the reservoirs was proposed. Due to the annual curve of solar radiation having a low variation near the equator, this source showed to be very promising to reduce the need for seasonal storage, representing 40% of the added power. An annual hourly analysis with hydro crisis scenarios should be proposed to present a robust solution.

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