International Institute for Applied Systems Analysis
IIASA www.iiasa.ac.at

Address: IIASA, Schlossplatz 1, A-2361 Laxenburg, Austria
Email: repository@iiasa.ac.at **Telephone:** +43 (0)2236 807 342

YSSP Report
Young Scientists Summer Program

Long-term energy storage assessment to adapt to climate change: study case of Brazil

Natalia de Assis Brasil Weber - weber.nati@gmail.com

Approved by

Supervisor: Julian David Hunt and Behnam Zakeri
Program: ENE
[30th of September 2021]

This report represents the work completed by the author during the IIASA Young Scientists Summer Program (YSSP) with approval from the YSSP supervisor.

It was finished by Natália de Assis Brasil Weber and has not been altered or revised since.

This research was funded by IIASA and its National Member Organizations in Africa, the Americas, Asia, and Europe.

Sumário

Abstract

Brazil has one of the most renewable energy matrices in the world, consequently, is exposed to energy variability and availability modifications. An efficient solution to overcome renewable energy variability is to increase its energy storage capacity with different technologies and sources. This type of measure can be characterized as an adaptation strategy to rise above climate change impacts. Electricity system adaptation requires adequate information on uncertainties and vulnerabilities in order to identify needs and appropriate adaptation options to sustain availability and increase reliability. Thus, this study intends to close some research gaps by developing an integrated modeling framework of the electricity system associated with forward-looking information on climate change to determine a least-cost electricity portfolio adapted to future climate conditions. To this end, is proposed a methodology that links an energy system optimization model – MESSAGEix - to regional climate model simulations. Also, Seasonal Pump Hydropower Storage (SPHS) technologies are added as an adaptation strategy to support renewable energy production. Results compute the variability indicators of wind power, solar power, and hydropower potential for each grid cell of the Brazilian territory for different scenarios of global climate change proposed by the IPCC (climate variables data extracted from CORDEX experiment). Variability indicators are obtained by comparing the yearly mean data values of the historical period (1971-2005) with mean data values of future projections (2006-2100). The variability results are used to estimate the future capacity factors of wind power and solar power, and to determine the future water natural inflow of the hydropower. In sequence, these new values were set as an input to the MESSAGEix model of the Brazilian electrical system for each RCP scenario. In wind power potential case was projected to have higher variability than solar power potential. Although, in some regions, such as in the Northeast, there is a tendency for growth in the potential for wind energy production. Solar power potential had lower variability in all scenarios, which means it is expected to be a stable source of energy. MESSAGEix-Br model main results show a complementarity between wind power and hydropower. In the wet period in which there is a more natural inflow of water there is an increase in wind power generation. The model, also, points out that is better to invest in SPHS in a scenario with more water availability, which is the RCP 2.6 scenario. In the other cases, RCP 4.5 and 8.5, the model shows it is more feasible to invest in wind power generation than investing in SPHS.

Keywords: Renewable Energy; Climate Change; Energy Variability; Seasonal Pump Hydropower Storage; Energy System Optimization.

Acknowledgments

I would like to thank my IIASA supervisors Julian David Hunt and Behanm Zakery for their support and guidance along this period. Also, would like to thank all the MESSAGE team for their help and support with the coding. I am also very grateful to the welcoming environment that the ECE (Energy, Climate, and Environment Program) team provided at IIASA supporting me to participate in-person and allowing me to participate in many inspiring meetings. I would also like to thank the YSSP organizing team and in particular Tanja, Pat, Brian and Aleks who put a lot of effort into creating ways for us YSSPers to meet each other virtually or in-person to have a great time together during these summer months. I am also grateful for the support of my home university supervisor Dr. Paulo Smith Schneider for giving me the possibility to participate in such a summer program as well as colleagues at the Universidade Federal do Rio Grande do Sul, especially Augusto Marques that kinded helped me with python. Financial support to my YSSP was greatly appreciated from IIASA and the National Council for Scientific and Technological Development (CNPq).

About the authors

Natália de Assis Brasil Weber is currently a third-year PhD student at the Post-Graduate Program in Mechanical Engineer (PROMEC) at the Federal University of Rio Grande do Sul (Brazil), working on the determination of long-term climate-change impacts in renewable energy production and evaluating the role of energy storage in the Brazilian energy system. Natália holds a MSc degree in Energy Planning from the Institute of Energy and Environment of the University of São Paulo (2017) and a BA in Energy Engineer from UERGS (2015). She has experience with machine learning and her main interests are climate change, energy optimization, and data science. (Contact: weber.nati@gmail.com)

Dr. Julian David Hunt Julian Hunt is a research scholar in the Sustainable Service Systems (S3) Research Group of the IIASA Energy, Climate, and Environment Program where he focuses on implementing daily and seasonal storage energy technologies in MESSAGE models and analyzing the impact of these technologies on long-term energy planning. His research interests include analysis of energy systems, water-energy-land interfaces, climate change risks, energy security, and energy storage. (Contact: hunt@iiasa.ac.at)

Dr. Behnam Zakery is currently a research scholar with the Energy, Climate, and Environment (ECE) Program. He has a master's degree in Energy Technology (Modeling of Energy Systems) from Lappeenranta University of Technology, and a PhD in Energy Technology (Energy Systems Analysis) from Aalto University, Finland. Prior to joining IIASA, he was affiliated with Aalborg University, Denmark, as an Assistant Professor with the Sustainable Energy Planning Research Group. (Contact: zakeri@iiasa.ac.at)

1 Introduction

Renewable energy production can be affected by climate change in a number of ways, such as changes in the efficiency of power plants, changes in wind regimes, and hydrological cycles [1]–[5]. Table 1 resumes the main climate change effect and impacts over the renewable energy supply. On top of this, is the long-life span of renewable energy infrastructure - e.g., between 50-100 years for hydropower plants, and from 20 to 25 years for solar photovoltaic panels and wind turbines - giving this component a longer exposure to the effects of climate change and requiring more planning efforts. Therefore, the consequences of climate change stress on the renewable sources reflect on the availability and reliability of the electricity supply.

Table 1 - Implications of climate change on renewable sources - Adapted from [1], [6], [7]

Source	Climate effect	Impacts	Impacts on the energy sector
Hydropower	Changes in river flow, coastal/inland flooding Inter-seasonal variation in river flow Water availability	Quantity (+/-) Water resource variability Increased uncertainty of expected energy output	Reduced firm energy Increased variability Increased uncertainty Revision of system reliability Revision of transmission needs
Wind power	Alteration in wind speed frequency distribution Changes in seasonal wind pattern	Changes in density Wind speed Increased uncertainty of Energy output	Increased uncertainty on energy output
Solar power	Increasing ambient temperature Changes to insolation (or cloud cover)	Quantity (+/-) Solar cell efficiency reduced by higher temperatures	Reduced firm energy Reduced energy generated Increased uncertainty

Additionally, renewable energy plays a key role to mitigate GHG emissions in future plans to reduce the increasing effect of climate change on the environment. This was already identified by [7] as a paradox, in which climate-dependent energy sources are susceptible to climate change, and at the same time essential to minimize its effect. For example, with the decrease in the availability of renewable sources and the increase in its reliability, additional electricity supply will be necessary. To overcome the uncertainties and reduce cost, the most likely supply to be added is a baseload power plant fueled by fossil fuels, such as natural gas [8]. As a consequence, GHG emissions will increase, which also contributes to the climate change process. In this sense, an adaptation measure has also a mitigation potential for allowing a greater percentage of renewable energy into the grid. In a simplified way, Figure 1 summarizes the interactions and synergies between climate change, climate drivers, climate impacts, socio-economic development, mitigation, and adaptation.

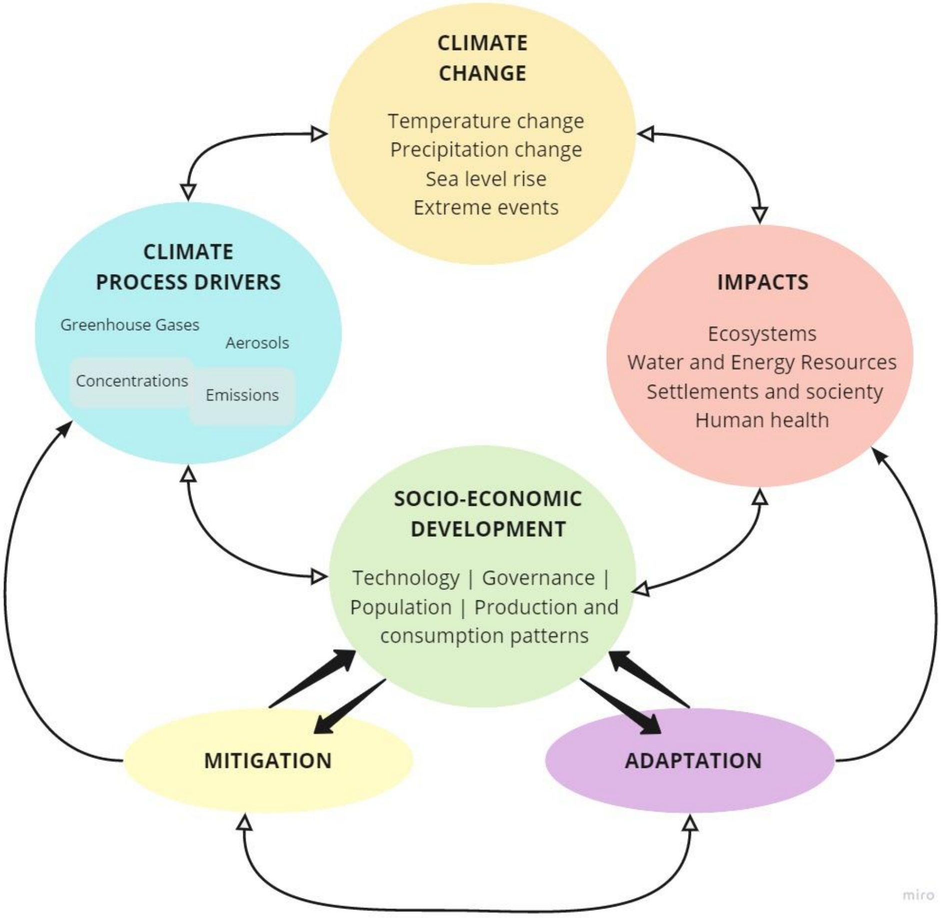


Figure 1 - Interactions and synergies between climate change, climate drivers, climate impacts, socio-economic development and mitigation and adaptation Adapted from: [9]

Brazil is a country which relies on renewable energies with highlighting the water source that accounts for 65.2% of the internal offer and renewable sources represented 84.8% of the domestic electricity supply in Brazil [10]. As one of the countries with the most renewable energy matrices in the world, Figure 2, is also one of the countries with the highest potential to be overwhelmed by climate change impacts. Results from a report developed by Schaeffer et al., 2008, affirm that the Brazilian energy system is vulnerable to climate change. The main climate change effect on the Brazilian renewable electricity supply is the decrease in availability, both driven by reducing energy resources and reducing efficiency, and the increase in the variability [11].

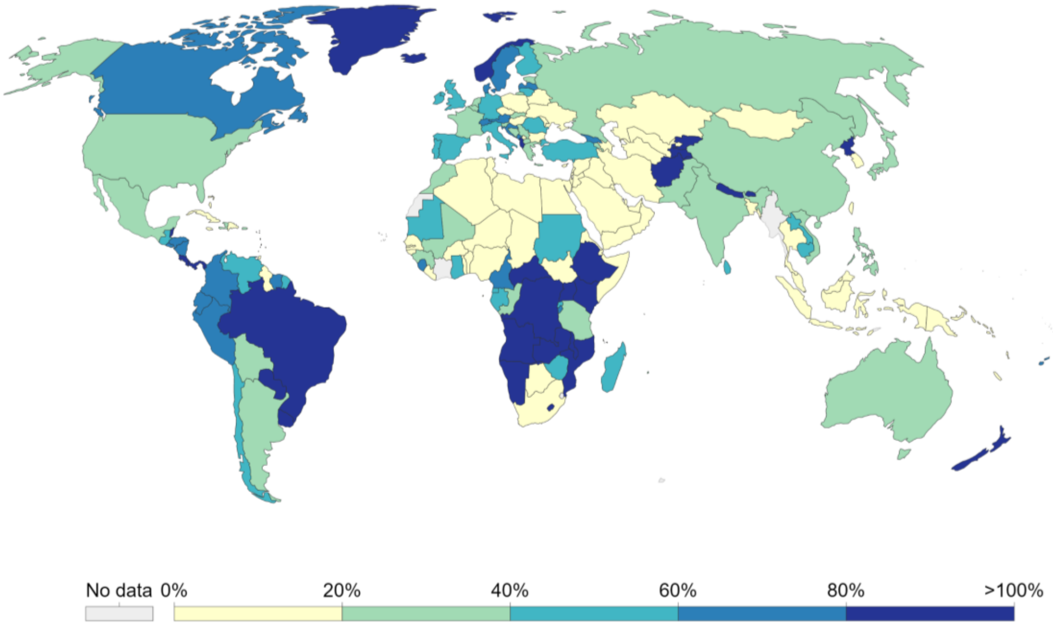
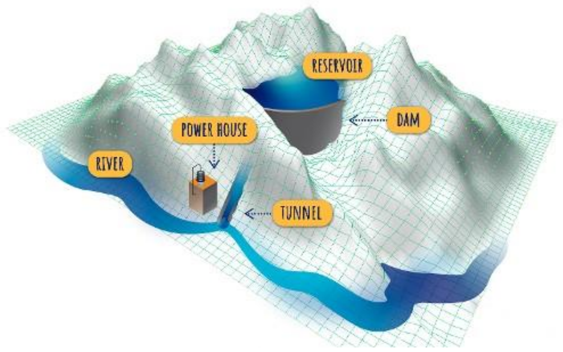
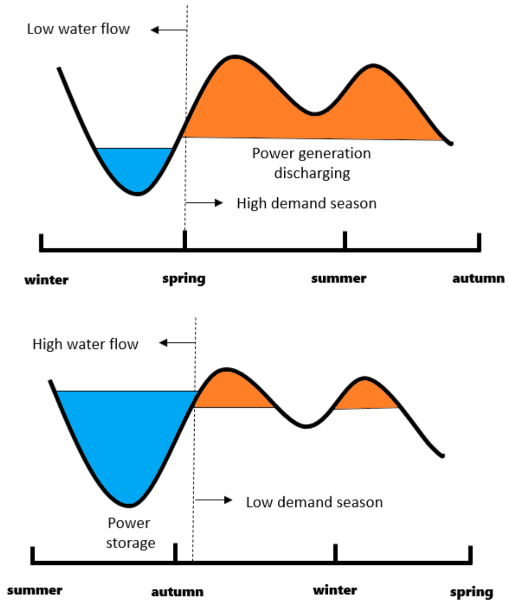


Figure 2 - Share of renewable and non-renewables in total electricity production in the world [12].

Brazil has a very seasonal generation which requires significant energy storage reservoirs. Existing potential for hydropower storage is already explored. However, there is an untapped potential for seasonal pumped hydropower storage (SPHS) which can be used to resolve seasonal fluctuations in electricity supply. These plants store large amounts of water and energy during the wet season for long periods providing long-term energy storage at a relatively low-cost [13]. The main benefits of the SPHS in comparison with conventional reservoir dams are small flooded areas and evaporative losses [14]. In sum, SPHS corresponds of a storage reservoir parallel to a main river, with an existing lower reservoir. The SPHS plant pumps water to the upper reservoir to store water and energy for a daily, week, month, or a season, as shown in **Erro! Fonte de referência não encontrada.**a. The SPHS can be used in two different profiles – if there is an excess of electricity in the system it can used the pump water back to the upper reservoir, or in case of water scarcity it can generate electricity with the stored water. **Erro! Fonte de referência não encontrada.**b shows a representation of these two p rofiles of the SPHS.



(a)



(b)

Figure 3 – SPHS representation (a), source: [15]*; Two main profiles of SPHS (b), source: adapted from:* [16].

Climate models, also known as general circulation models or GCMs, project climate into the future which can be used to estimate the changes in renewable energy generation. Climate models, unlike weather forecasts, are probabilistic and used to indicate areas with higher chances to be warmer or cooler and wetter or drier than usual [17]. The long-term projections of climate forcing by GCM are set to change according to different scenarios [18]. Long-term variability estimation is often used to explore climate change impacts of future production of renewable energy sources [5], [19], [20]. Emphasizing that understand the impacts of climate variability and change over the decades on electricity systems is eminent for operators preparing for weather-related disruptions, policymakers deciding on future directions of energy policies [21]. So, relate climate change variability along the decades with weather-dependent energy sources such as renewable energy is an important advantage for the long-term energy sector planning.

For analyzing long-term climate change impacts on energy systems, energy-system optimization models are frequently used. Such models generate consistent scenarios taking into account the complex inter-temporal, inter-sectoral and inter-regional relationships and allow improving our understanding of the energy system. As such, the objective of these models is to minimize the total system cost for the provision of different energy demands. There are several models already used with the purpose of introducing the climate change impacts on the energy system, such as ADAGE, COPPE-COFFEE, GCAM, IMAGE, MESSAGE-Brazil, Phoenix_LA, TIAM-ECN, POLES, and MARKAL/TIMES [8], [22]–[24]. For example, [23] applied an adapted POLES to analyze the impacts of climate change in heating and cooling demand, and in the supply side, such as: changes in the efficiency of thermal power plants, and changes in hydro, wind (both on- and off-shore) and solar PV electricity output. Main findings include: demand side impacts are larger than supply side impacts; and impacts are larger in Southern Europe than in Northern Europe.

In its turn, MESSAGEix is designed to develop and assess alternative energy supply strategies consonant with the user-defined constraints, for instance: limits on new investment, fuel availability, and trade, environmental regulations and policies as well as diffusion rates of new technologies [25]. MESSAGEix optimized output can choose among different operating technologies to obtain the least-cost portfolio to meet its needs, such as: peaking plants, electric storage technologies, demand-side options; or can choose between renewable and non-renewable generation sources options depending on the cost, availability, and the flexibility they provide or require. This framework allows direct and accurate representation of energy systems technologies, such as hydropower, which is crucial for modelling the Brazilian energy sector. For example, [26] developed a MESSAGEix model to simulate Malé´s cooling and water services demand and optimize the renewable energy supply. Main results shows that additional generation capacity will be supplied by solar panels backed up by batteries, and the current diesel generator will provide base load generation until 2040 [26].

This paper contributes to the future by developing the first long-term energy model that combine hydropower storage with long-term renewable energy production projections under climate change constraints. This report is divided into three main sections. The first section presents the methodology, within the hydropower representation and the MESSAGEix modelling assumptions and description. The second section discuss the results of the MESSAGEix model. Finally, the third section is the conclusion of the report.

2 Methodology

This section describes the methods which encompass the methodology used in this research. The foundation methods addressed are those related to simulations of future energy supply and demand (MESSAGEix) and climate change projections (RCM). These methods are combined in a particular way to tackle the impact of climate change in the Brazilian electricity sector. Figure 4 shows the building blocks of the proposed framework to assess the impact of climate changes on the Brazilian electricity.

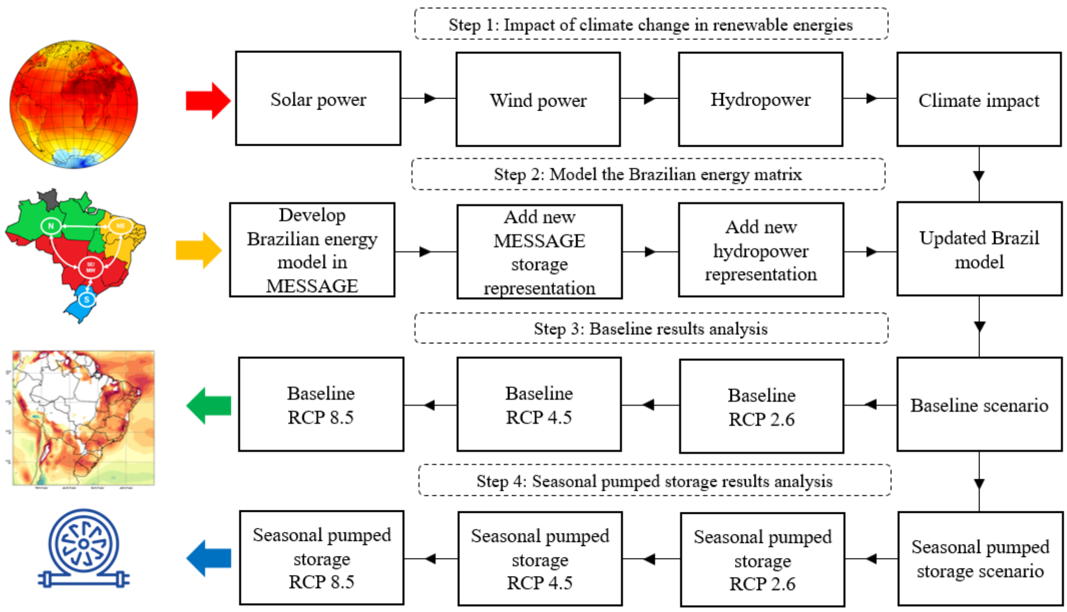


Figure 4 – Methodology framework

2.1 Step 1: Impact of climate change in renewable energy sources

The step 1 encompasses the methods used to transform the climate projections into inputs to the MESSAGEix model of the Brazilian electrical system. These steps were dived into three subsections. The first subsection presents the climate model used to project the climate change into the future. The second section introduces the scenarios chosen to be modeled. The third subsection shows the long-term variability, which is a statistically approach to estimate the variation in the mean state of the climate persisting for an extended period.

2.1.1 Regional Climate Models (GCM-driven)

A GCM can provide reliable prediction information on scales of around 1000 by 1000km. Although, the impacts of a changing climate, and the adaptation strategies required to deal with them, will occur more frequently on smaller scales as regional levels. This is where Regional Climate Downscaling (RCD) applied to GCM has an important role to play by providing projections with much greater detail. Then, Regional Climate Models (RCM) applied over a limited area driven by GCMs can provide information supporting more detailed impact and adaptation assessment and planning. With the growing demand for high-resolution information about regional climate change and its impact all over the world, the CORDEX project (Coordinated Regional Climate Downscaling Experiment) was created [27]. CORDEX aims at contributing to the IPCC report and providing this information for all major inhabited areas of the world.

In sum, the boundary conditions of the RCMs are marked out by the GCMs that are part of the Coupled Model Intercomparison Project Phase 5 (CMIP5)[1]. The periods of time used are divided into historical (20th century) and projections (21st century). The recommended scenarios are associated with future scenarios Representative Concentration Pathways (RCPs) [28]. In this study it was used RCM data downscaled through RCA4 model developed by the Swedish Meteorological and Hydrological Institute (SMHI). The driven global model was the MOHC-HadGEM2-ES developed by the Met Office Hadley Centre (MOHC). This chosen RCM model has a horizontal resolution of 0.44° (about 50 km) over the South America CORDEX domain (SAM44i). The analyzed period is between the years 1961 to 2099 (wherein the period 1961-2005 corresponds to the historical data and from 2006 to 2099 corresponds to the future projections).

2.1.2 Scenarios

For the projections, three emissions scenarios are included based on the RCPs: RCP 2.6, RCP 4.5, and RCP 8.5. RCPs describe four different 21st century pathways of GHG emissions and atmospheric concentrations, air pollutant emissions and land use; they include a stringent mitigation scenario (RCP 2.6), two intermediate scenarios (RCP 4.5 and RCP 6.0), and one scenario with very high GHG emissions (RCP 8.5) as shown in *Figure 5*.

---

[1] "CMIP5 is meant to provide a framework for coordinated climate change experiments for the next five years and thus includes simulations for assessment in the AR5 as well as others that extend beyond the AR5"[34].

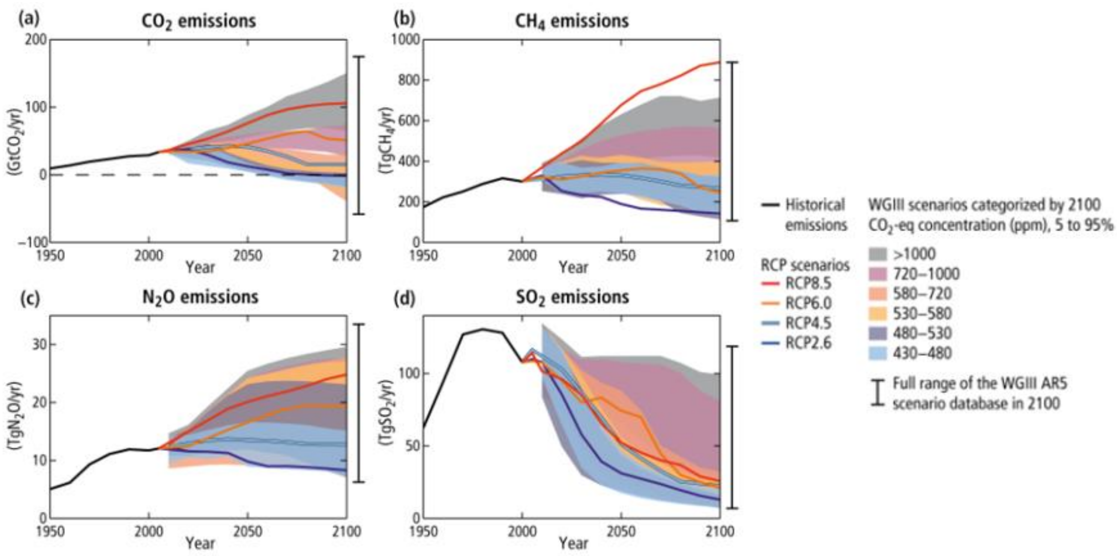


Figure 5 - Emission scenarios and the resulting radiative forcing levels for the Representative Concentration Pathways (RCPs, lines) and the associated scenarios categories used in WGIII. Panels (a) to (d) show the emissions of carbon dioxide (CO2), methane (CH4), nitrous oxide (N2O) and sulfur dioxide (SO2). The vertical lines to the right of the panels (panel a–d) indicate the full range of the WGIII AR5 scenario database [29].

RCP 2.6 is representative of a scenario that aims to keep global warming likely below 2°C above pre-industrial temperatures. This pathway requires that carbon dioxide (CO_2) emissions start declining by 2020 and go to zero by 2100, where radiative forcing[2] peaks at approximately 2.6 W m^{-2} before 2100 and then declines. RCP 4.5 requires that carbon dioxide (CO_2) emissions start declining by approximately 2045 to reach roughly half of the levels of 2050 by 2100, and the possible range of radiative forcing values in 2100 are 4.5 W m^{-2}. In RCP 6.0, emissions peak around 2080, then decline. The RCP 8.5 does not include any specific purpose of mitigation. GHG emissions and concentrations of this scenario significantly increase over time, leading to a radiative forcing of 8.5 W m^{-2} at the end of the century.

2.1.3 Long-term energy variability

Changes in future renewable energy sources were evaluated by comparing, for each grid point, the historical and future energy potential for considered RCPs and time windows. In order to understand the variability of renewable energy sources, the Relative Variability (RV) were calculated. In which, the observed variability of the indicators on yearly and decadal time scales is compared with the variability in the historical and forced climate model simulations. The historical simulation refers to series of each climate variable, ranging from 1971 to 2005, and designates the benchmark or climate normals[3] against which future observations can be compared [30].

The relative variation is expressed by Equation 1:

---

[2] According to IPCC, 2020, "Radiative forcing is the change in the net, downward minus upward, radiative flux (expressed in Watts per square metre; W m-2) at the tropopause or top of atmosphere due to a change in an external driver of climate change, such as, for example, a change in the concentration of carbon dioxide (CO_2) or the output of the Sun".

[3] According to World Meteorological Organization (WMO, 2017) climate normals refers to period averages computed for a uniform and relatively long period comprising at least three consecutive ten-year periods and designate the benchmark against which current observations can be compared, including providing a basis for many anomaly-based climate datasets. They are also widely used, implicitly or explicitly, as a prediction of the conditions most likely to be experienced in a given location.

$$RV = \frac{\sum_{y}^{n} G_{e,y}/n \; - \; \sum_{y}^{n} G_{e,y-1}/n}{\sum_{y}^{n} G_{e,y-1}/n} \; 100 \qquad (1)$$

where, $G_{e,y}$ is the yearly mean energy potential of each grid cell (e) in the decade or multidecade (y), and (n) is total of years considered in the analysis. In this case, the RV indicator was applied for seasonally mean differences along the time frame for the solar power, wind power and hydropower sources. For the solar power the climate variable used was the surface solar radiation (rsds), that can also be known for its long name: surface downwelling shortwave flux in air and its unit is (W m-2). For the wind power it was used the near-surface (10 m) winds (sfcWind), and for the hydropower it was used the precipitation (pr) data.

2.2 Step 2: Model the Brazilian energy matrix on MESSAGEix

The step 2 propose is to represent the Brazilian Electrical System (BES) and the SPHS electricity generation and storage in MESSAGEix. The hydropower representation and SPHS methodologies developed were based on the methodology developed for hydropower representation and SPHS on the Global MESSAGEix. This methodology is divided in main three sections. Section 1 represents the BES model; the section 2 presents the hydropower representation, and Section 3 represents the SPHS plants.

2.2.1 Brazilian electrical system representation

The Brazilian electricity system is a hydro-thermal-wind based system, where the hydroelectric plants are responsible for most of the generation, with more than 60% of the installed capacity. Thanks to the National Interconnected System (SIN), these plants located in 16 hydrographic basins in different regions work in an integrated way to supply electricity where is most needed. Currently, the National Interconnected System, also known by its abbreviation SIN, has 4 subsystems, namely: North, Northeast, Southeast/Midwest, and South. In addition to these, there are also the so-called isolated systems.

In this study it was developed a Brazilian electrical system representation using MESSAGEix as a technology-based model. The interconnection between regions were modeled in a similar way as the electricity is exchange between the subsystems. In which, there is mainly an exchange of energy between the North-Northeast, between the Southeast/Midwest-Northeast, and between the Southeast/Midwest-South [31]. The Figure 6 shows the nodes which represents each subsystem and its interconnection modeled in MESSAGEix.

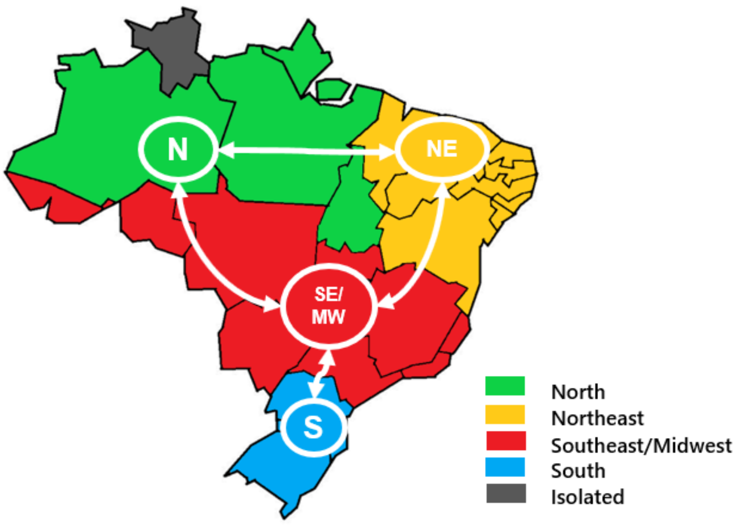


Figure 6 – Brazilian electrical system representation in 4 nodes

The next step of the MESSAGEix representation was to set up the levels, resources and technologies which configure the Brazilian electricity system. In Figure 7 the blocks represent the defined technologies, above them it shows in which level they receive and provide energy.

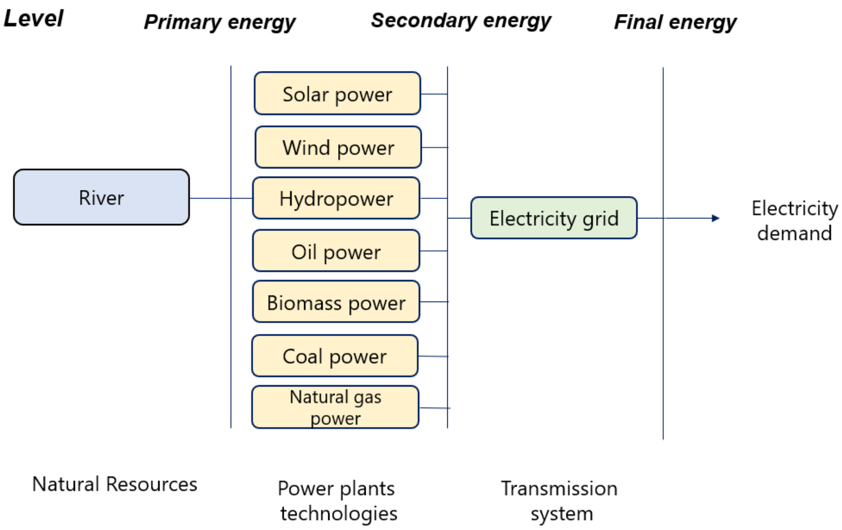


Figure 7 – Brazilian Electrical System MESSAGEix representation

Figure 8 presents the installed capacity values added for each technology and subsystem. Southeast/Midwest has 52% of the total installed capacity of Brazil and at the same time 58% of the total electricity demand of Brazil. The other subsystems demand rate is: 17% in the South region, 16% in the Northeast, and 8% in the North region.

Technology	North [GW]		Northeast [GW]		Southeast/Midwest [GW]		South [GW]	
Hydro	19.8	82%	11.02	34%	63.21	73%	16.99	73%
Termo	3.93	16%	7.33	23%	20.71	24%	4.22	18%
Wind	0.328	1%	12.61	39%	0.03	0%	2.02	9%
Solar	0.05	0%	1.40	4%	0.68	1%	0.04	0%
Nuclear					1.99	2%	-	
Total	24.11	100.0%	32.36	100.0%	86.61	100.0%	23.27	100.0%

Figure 8 – Installed capacity of each subsystem.

2.2.2 Hydropower representation

Considering the importance of the hydropower generation in the Brazilian electrical system and its complexity the hydropower representation on MESSAGEix was made through an aggregation methodology based on different databases, as shown in Figure 9.

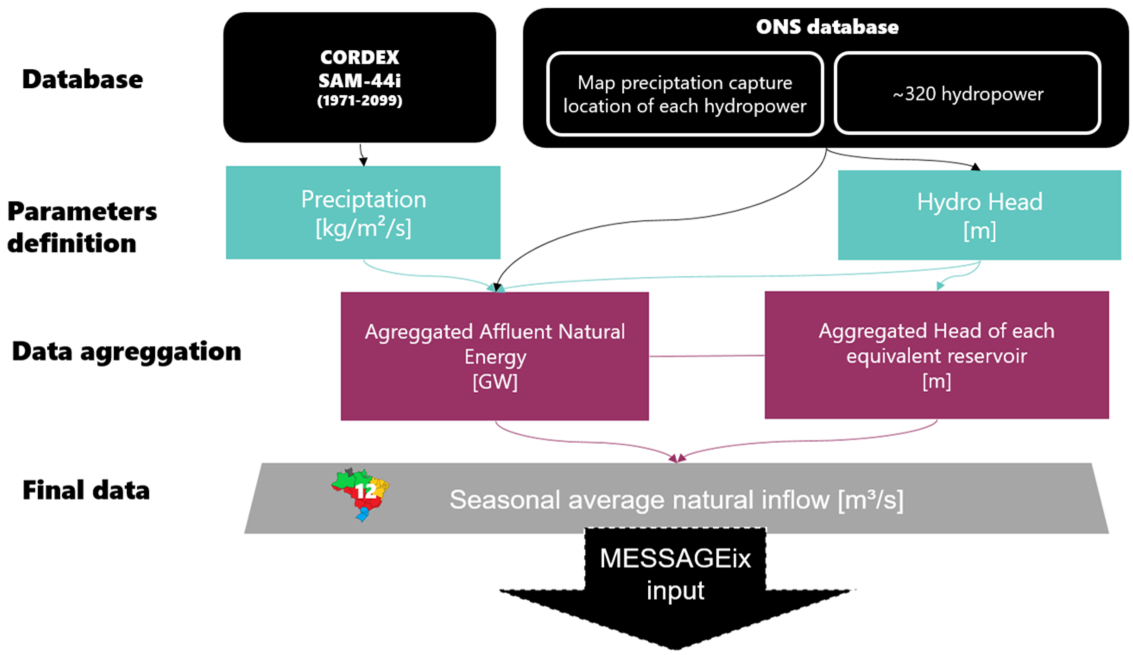


Figure 9 – Hydropower representation methodology framework

This aggregation method consists in assemble the data from almost 320 hydro powerplants into 12 equivalent reservoirs. This approach is used by the National Electric System Operator (ONS) of Brazil to estimate the long-term operation of the Brazilian interconnected system. In which hydro powerplants are aggregated based on their main characteristics. The map, Figure 10, shows the location of each equivalent reservoir and also the region in which they are located. In this methodology the aggregation of the equivalent reservoirs 10, 11 and 5 was module in cascade. And, the others were modeled as if they are one hydropower with equivalent characteristics.

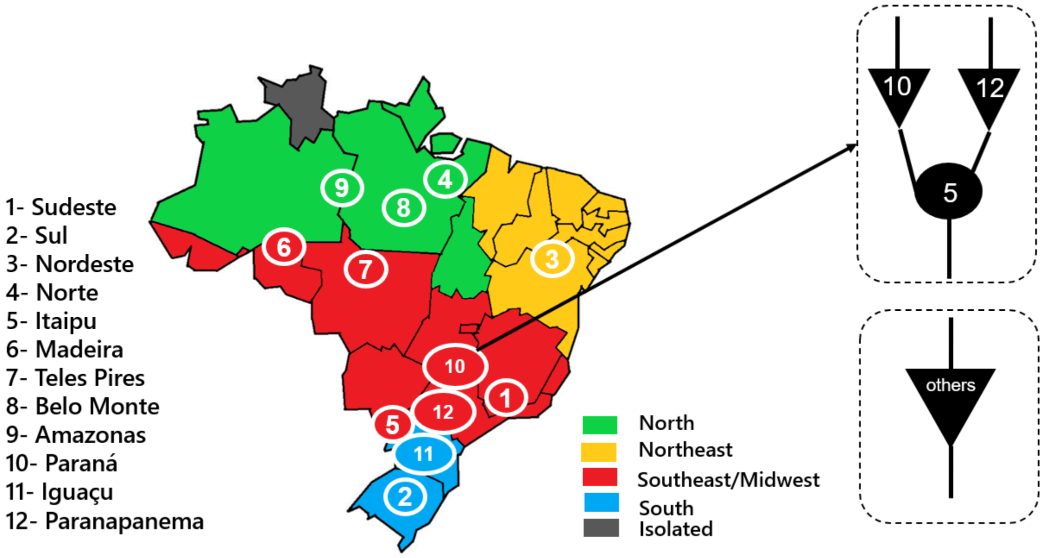


Figure 10 – Hydropower representation in 12 equivalent reservoirs

The main objective of this aggregation process was to obtain the seasonal natural inflow of each equivalent reservoir, which is the input of the technology river on MESSAGEix. This aggregation process was made in two steps. First it was estimated the aggregated affluent natural energy and then the aggregated head of each equivalent reservoir. To determine the affluent natural energy, it was made a link between a map with the potential of the electric energy generation measured by hydropower head (Figure 11a) with the precipitation data from CORDEX (Figure 11b). For example, the map in Figure 11a shows if the precipitation happens in the red area, it would have a great amount of electricity generation, because it has around 600 meters of hydropower head. In its turn, it means in this area it has several dams in cascade and the sum of all cascades is 600 meters. So, to estimate the historical and future affluent natural energy it was used the historical data from CORDEX from 1971 up to 2005 (Figure 11b) and the future data from 2006 up to 2099.

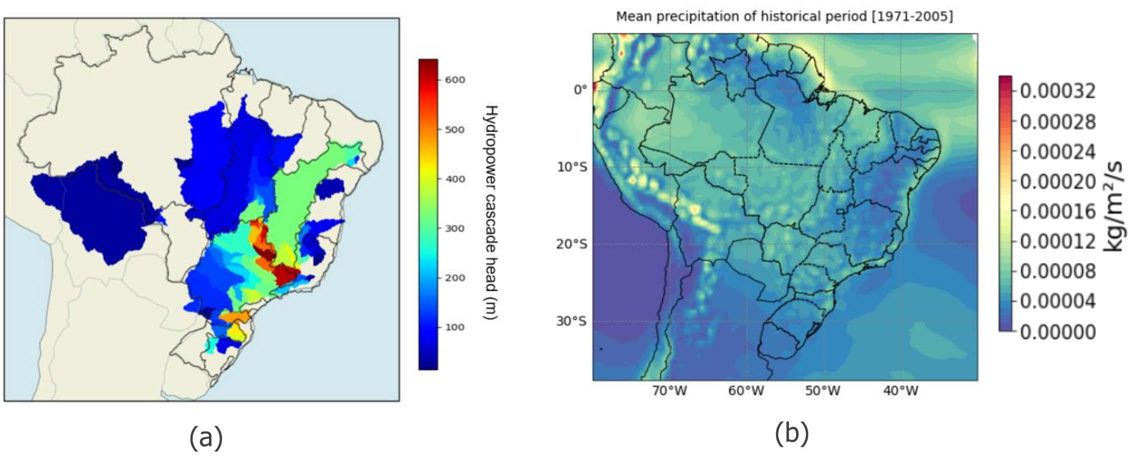


Figure 11 - Hydropower potential in Brazil measured by hydropower cascade head

The second aggregation was to determine the head of each equivalent reservoir. The dam height dictates how much flow will result in hydropower generation. For example, for a head of 117 m, for each 1000 m^3/s can generate close to 1 GWa. In order to representative head of the 320 hydropower into the 12 equivalent reservoir it was made an average between the head considering the storage capacity of the basin with the head that just considers the generation aspect of the head, as if they were all run of the river. In each basin it was analyzed both generation and storage head and it was either take an average of them if they were similar, however if there were very little capacity it was decided to use only the run of the river head. Mainly because the storage head had a small impact on the operation of the dams but would have a huge impact on the representative hydropower head. After it was calculated both heads we used a heurist approach to combine both depending on the characteristics of the basins. In this way we are representing an equivalent reservoir as it was in the middle of the basin representing equally the generation and the storage capacity of the reservoir. This is represented in Figure 12.

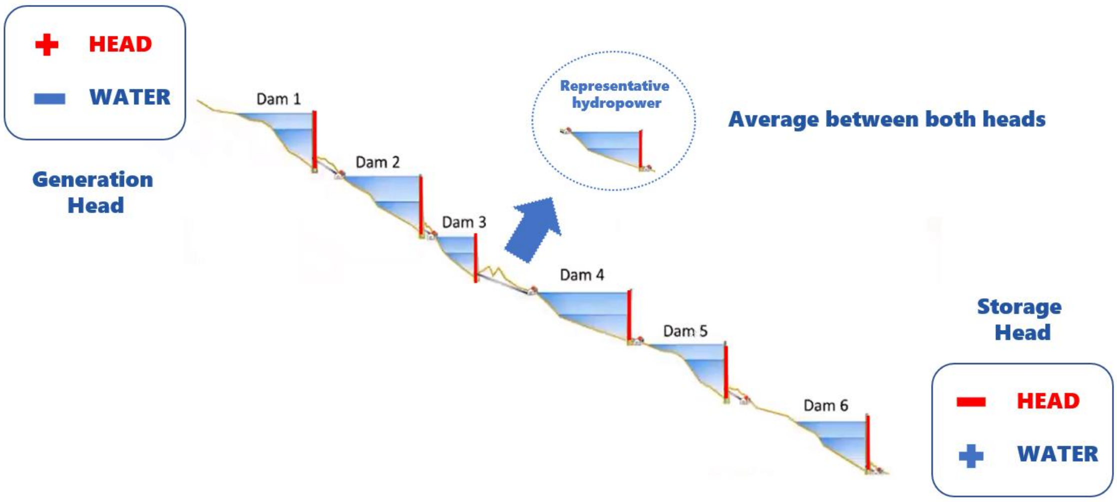


Figure 12 – Aggregation Head methodology of each equivalent reservoir

2.2.3 Seasonal-Pump-Hydropower-Storage representation

SPHS corresponds of a storage reservoir parallel to a main river, with an existing lower reservoir. The SPHS plant pumps water to the upper reservoir to store water and energy for a daily, week, month, or a season. Figure 13 shows a representation of a seasonal pumped power plant with its main components.

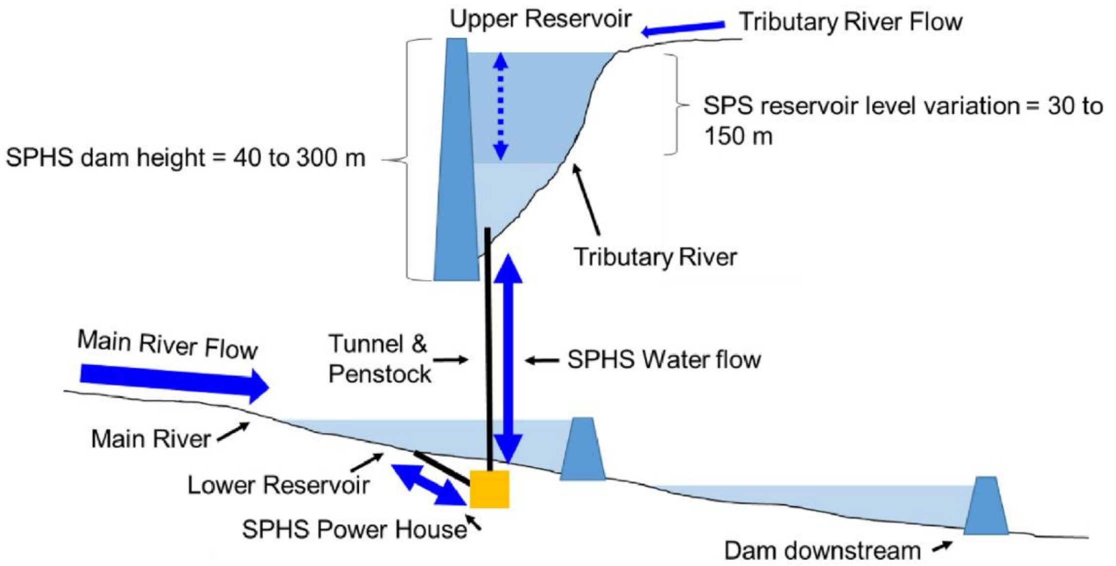


Figure 13 - SPHS plant representation with main components. Source: [32]

To model the SPHS on MESSAGEix it was used the SPHS methodology developed by Behnam Zakery and Julian Hunt for the Global message. Figure 14 shows with detail the technologies, levels and commodities used to model the SPHS in MESSAGEix. In this configuration the water inflow is defined by a technology called river, which doesn't have any costs. River supply the water inflow to the hydro dam (dam_hydro). In this point the model has 4 options – one is to store the water in the dam hydro, in which will depend on the reservoir capacity. Or, can generate electricity in the turbine (hydro). Or, can spilled the water (spillway_hydro), in this case the water can be available to attend other water demands. Lastly the model can pump water from the lower reservoir (dam_sphs) to the upper reservoir (dam_hydro). So, the seasonal pump hydropower turbine (pump_sphs) can be used in two different modes – if there is an excess of electricity in the system it can used the pump water back to the upper reservoir (dam_hydro), or in case of water scarcity it can generate electricity with the stored water (turb_sphs).

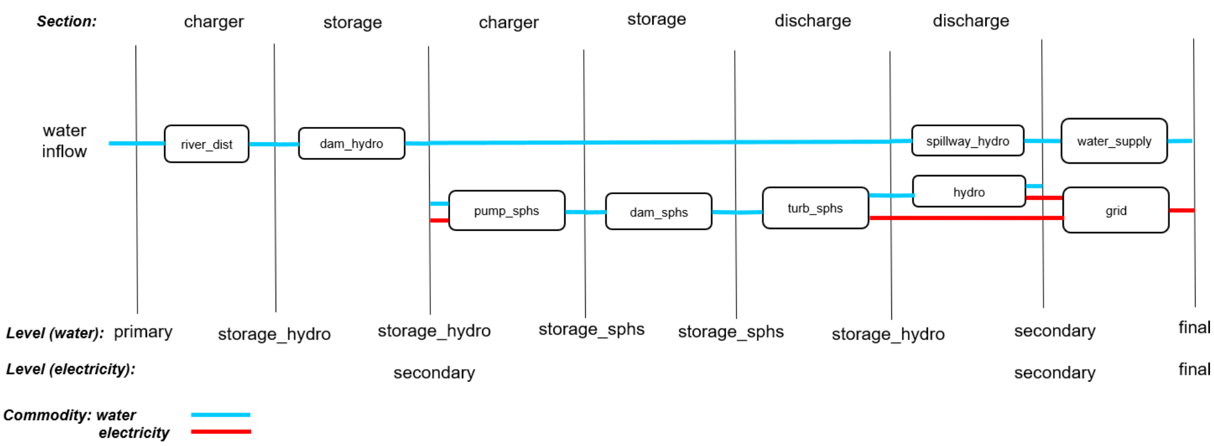


Figure 14 – SPHS representation in MESSAGEix

3 Results

The results will be divided in 4 subsections. The first and second subsections present the results for the solar power and wind power capacity factor variability. In the third subsection it presents the results for the hydropower seasonal natural inflow variability. Finally, the fourth subsection presents the results of the MESSAGEix model.

3.1 Solar power variability and new future capacity factors for each scenario

Solar power potential was calculated from the surface solar radiation (W m^(-2)) variable for each RCP. Figure 15 shows the surface solar radiation historical mean values for each grid cell in Brazil. Northeast region has the highest solar potential, from 225 up to 275 Wm-2, in Brazil in contrast to the coastal area of Southeast that has the lowest potential, approximately 175 Wm-2.

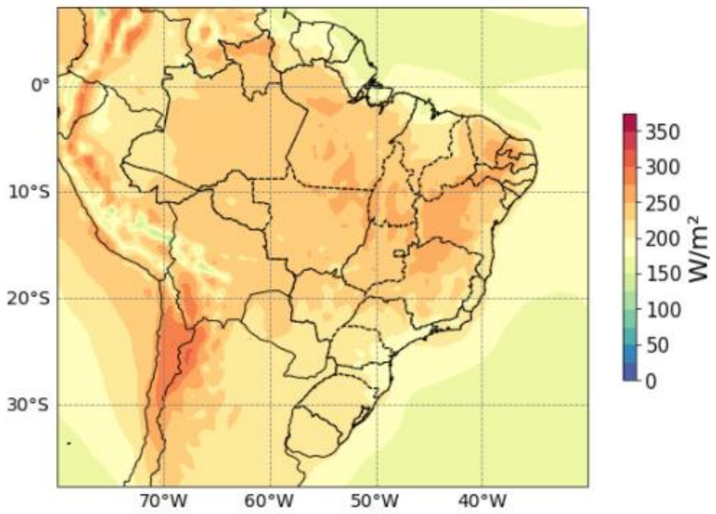
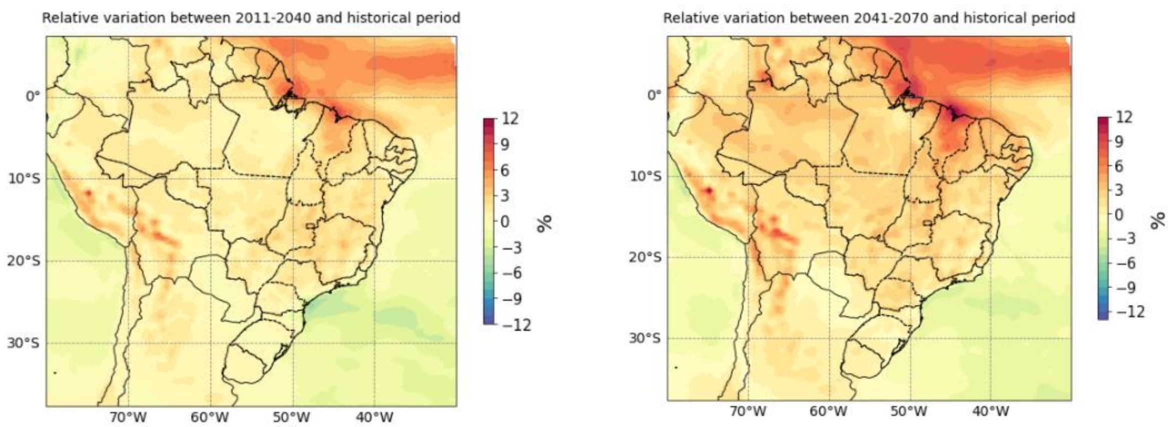


Figure 15 - Surface solar radiation historical mean of Brazil

3.1.1 RCP 2.6

Figure 16 shows the RV of the solar power potential of Brazil between 2011 and 2099 compared to the historical period for the RCP 2.6 scenario, given in percentage (%).



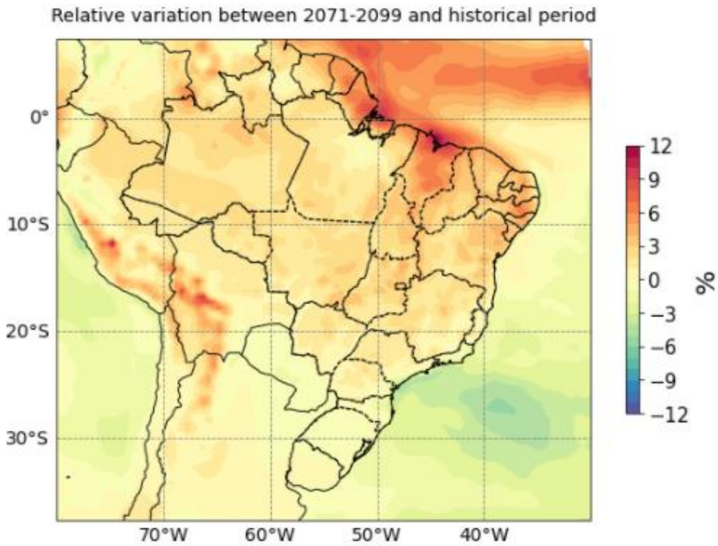


Figure 16 - RV between historical period and future projections (2011-2040, 2041-2070, and 2071-2099) for Brazil and RCP 2.6

RV future projections of surface solar radiation potential, in Brazil, compared to the historical period varied between -3% and +12%, in land area. Majority of Brazilian regions presented an increasing variation in RV, except for most South region. Worth recalling, total solar radiation variation is attenuated by using the means of 10 years without considering seasonality. Seasonal variations are expected to be highly relevant and to affect the availability of solar generation throughout the year. With that aim, it was constructed maps, Figure 17**Erro! Fonte de referência não encontrada.**, of the variations of solar potential from 2071 until 2099 in relation to historical period considering seasonality.

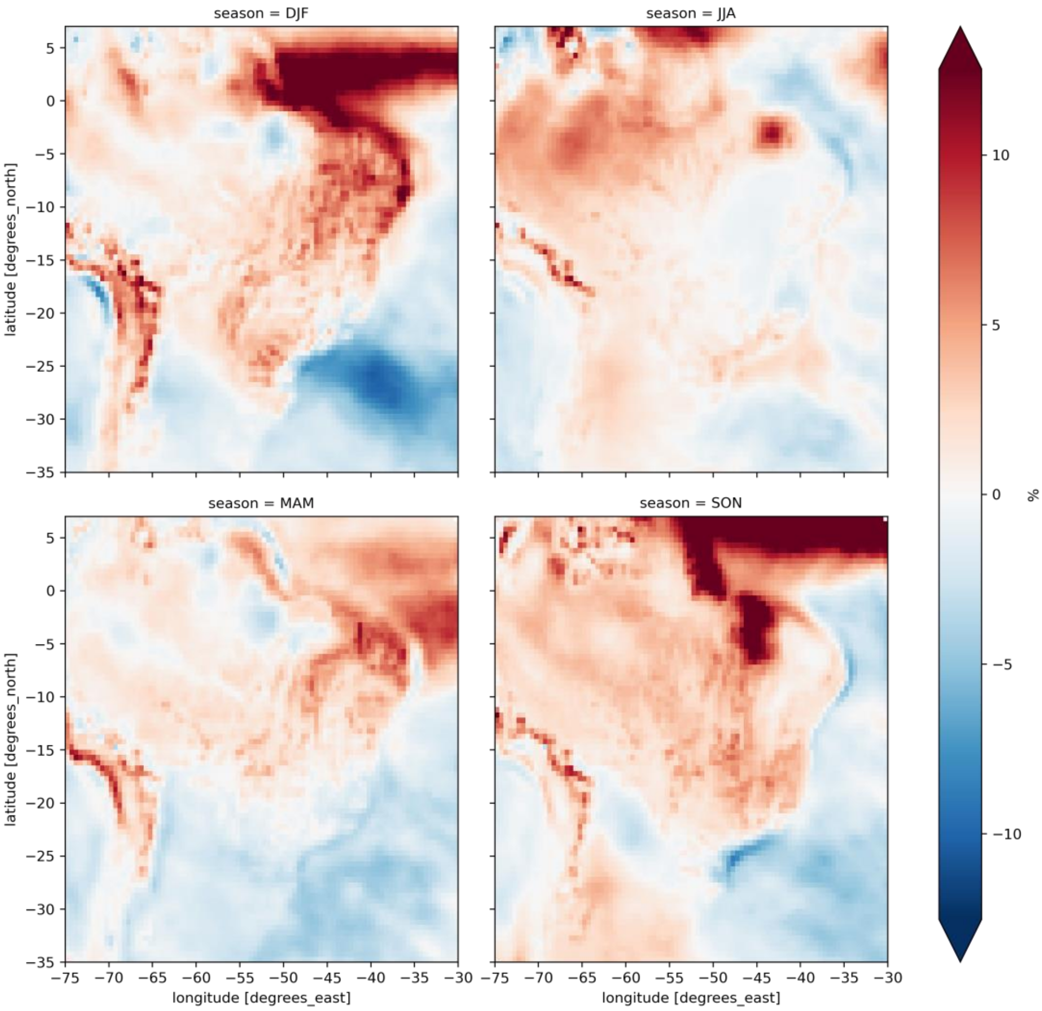


Figure 17 - Seasonal RV between historical period and future projection (2071-2099) for Brazil and RCP 2.6

As mention before, the above seasons maps are categorized in a more simplified way: December, January, and February (DJF) it considered to be summer time; March, April, and May (MAM) its autumn; June, July, and August (JJA) its winter; and, September, October, and November (SON) its spring time. **Erro! Fonte de referência não encontrada.** point out the differences of solar potential RV for each season vary between -15% and +15%. Additionally, in DJF and SON has larger areas with up to +15% of RV compared to the others seasons.

With the RV results the next step was to calculate the new capacity factors of the solar power for each season and for each region. This estimation was made using the capacity factors from 2020 as the baseline and then multiplied by the RV of every decade from 2030 up to 2100. Figure 18 shows the results for each region.

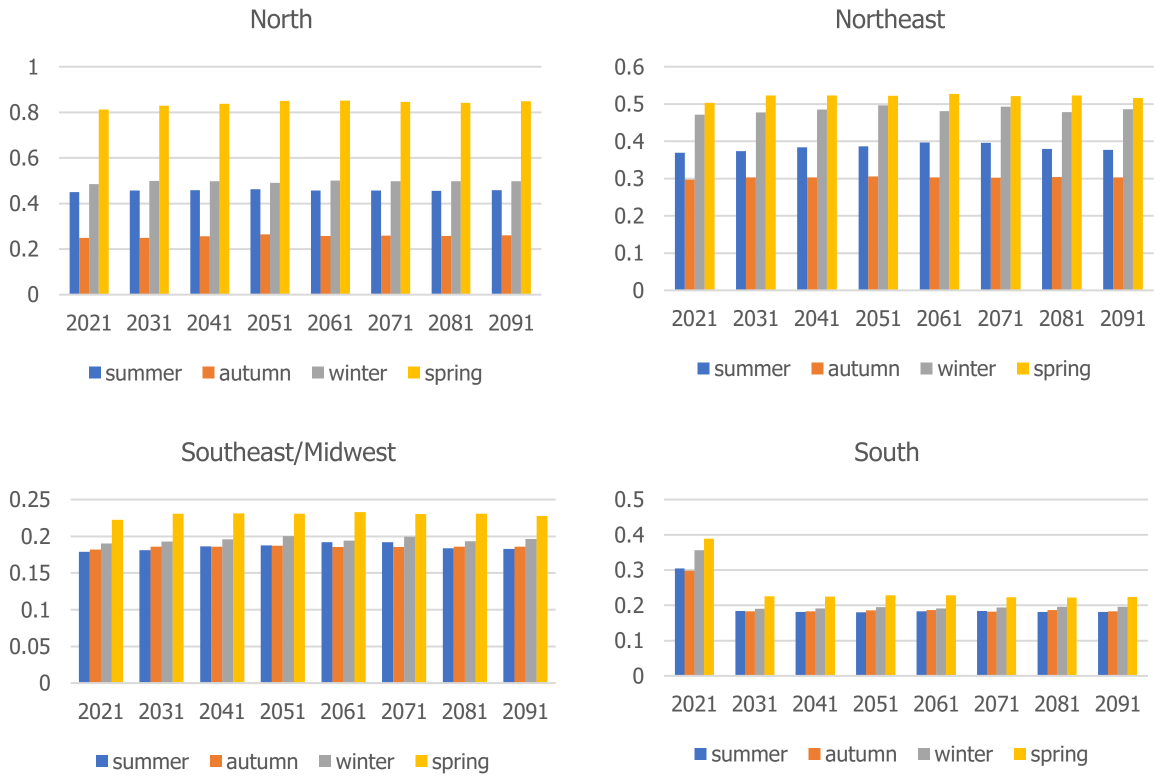
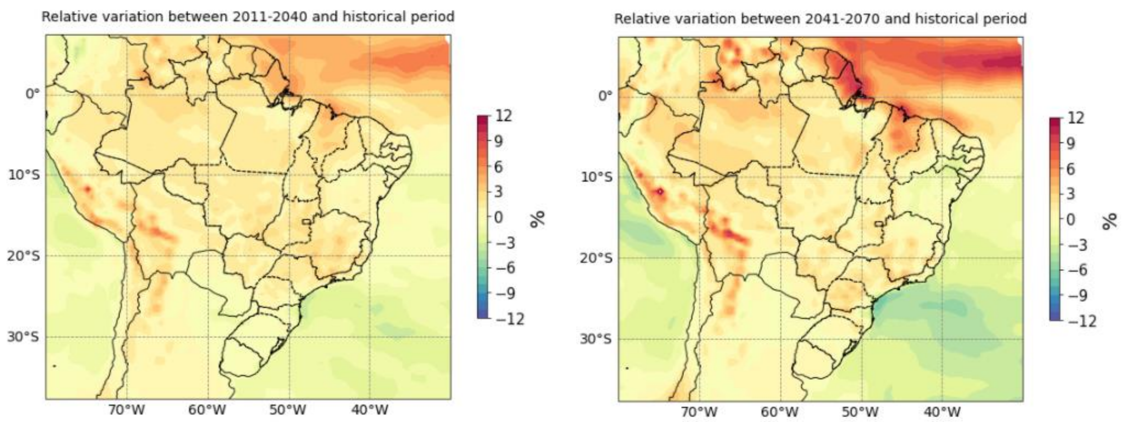


Figure 18 – Historical capacity factor (2020) and new capacity factors from 2030 up to 2100.

3.1.2 RCP 4.5

Figure 19 - RV between historical period and future projections (2011-2040, 2041-2070, and 2071-2099) for Brazil and RCP 4.5

shows the solar power potential of Brazil between 2011 and 2099 compared to the historical period for the RCP 4.5 scenario, given in percentage (%).



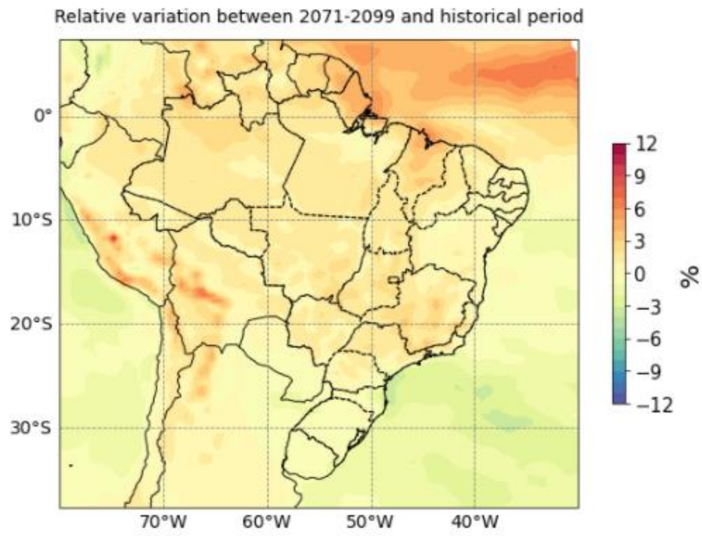


Figure 19 - RV between historical period and future projections (2011-2040, 2041-2070, and 2071-2099) for Brazil and RCP 4.5

RV future projections of surface solar radiation potential, in Brazil, compared to the historical period varied between -6% and +12%. Majority of Brazilian regions presented an increasing variation in RV, except for most South region. Considering that, seasonal variations are expected to be highly relevant and to affect the availability of solar generation throughout the year, it was constructed maps of RV of each season. Figure 20 resume the variations of solar potential from 2071 until 2099 in relation to historical period considering seasonality.

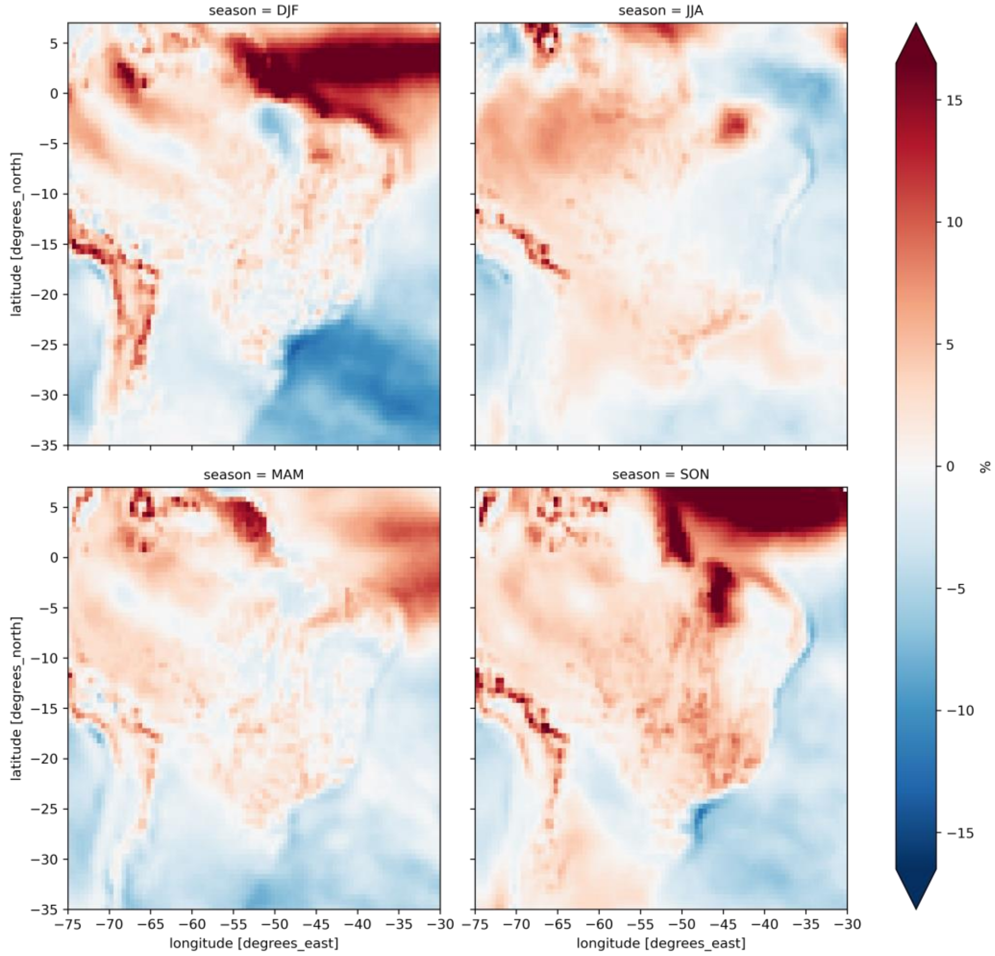
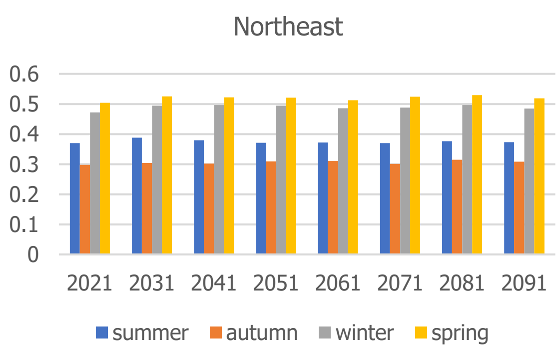
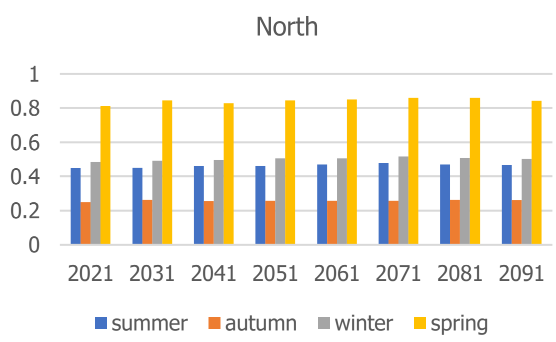


Figure 20 - Seasonal RV between historical period and future projection (2071-2099) for Brazil and RCP 4.5

Solar potential RV for each season vary between -20% and +20%, ±5% more than in RCP 2.6. Also, in Summer (DJF) and Spring (SON) has larger areas with up to +20% of RV compared to the others seasons. As the opposite, Autumn (MAM) and Winter (JJA) showed the lowest variation, up to -20% in large areas of Northeast, Southeast and in the South.

After estimating the RV results the next step was to calculate the new capacity factors of the solar power for each season and for each region. This estimation was made using the capacity factors from 2020 as the baseline and then multiplied by the RV of every decade from 2030 up to 2100. Figure 21Figure 18 shows the results for each region.





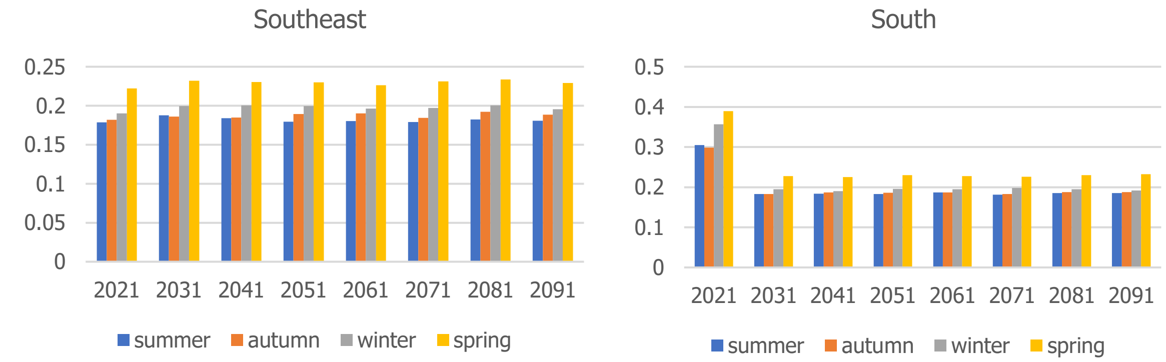


Figure 21 – Historical capacity factor (2020) and new capacity factors from 2030 up to 2100.

3.1.3 RCP 8.5

Figure 22 shows the solar power potential of Brazil between 2011 and 2099 compared to the historical period for the RCP 8.5 scenario, given in percentage (%).

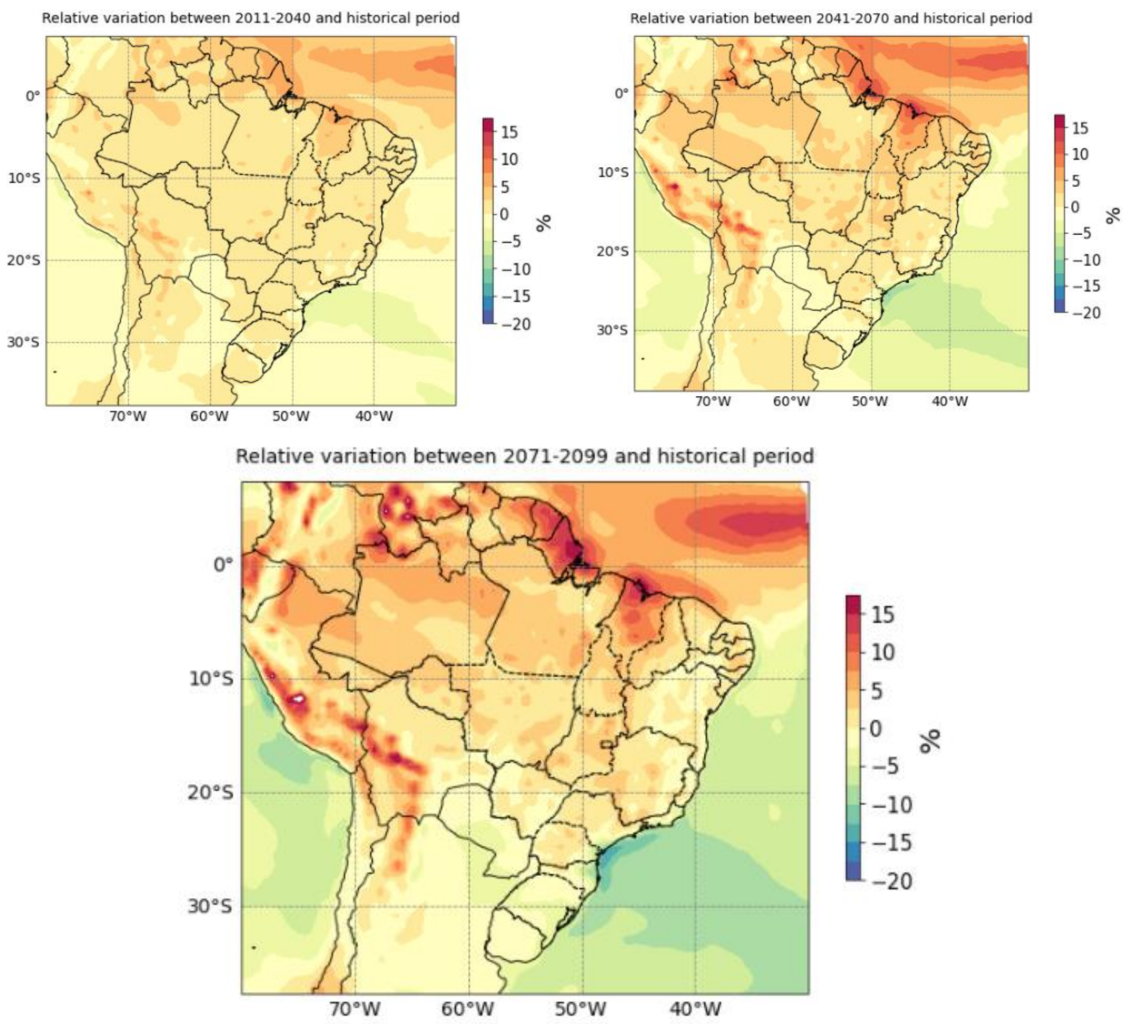


Figure 22 - RV between historical period and future projections (2011-2040, 2041-2070, and 2071-2099) for Brazil and RCP 8.5

Projections of RCP 8.5 of solar potential RV, in Brazil, compared to the historical period varied from -15% up to +17.5%. Majority of Brazilian regions presented an increasing variation in RV from 2011 up to 2070. Only, in 2071-2099 period negative variations were predominant in South, Southeast and parts of Northeast regions. Also, from 2041 the north coast of South region and the south coast of Southeast region are presenting a decrease in solar potential up to -15% in the 2071-2099 period. Add to that, seasonal variations are expected to be highly relevant and to affect the availability of solar generation throughout the year, it was constructed maps of RV of each season. Figure 23 resume the variations of solar potential from 2071 until 2099 in relation to historical period considering seasonality.

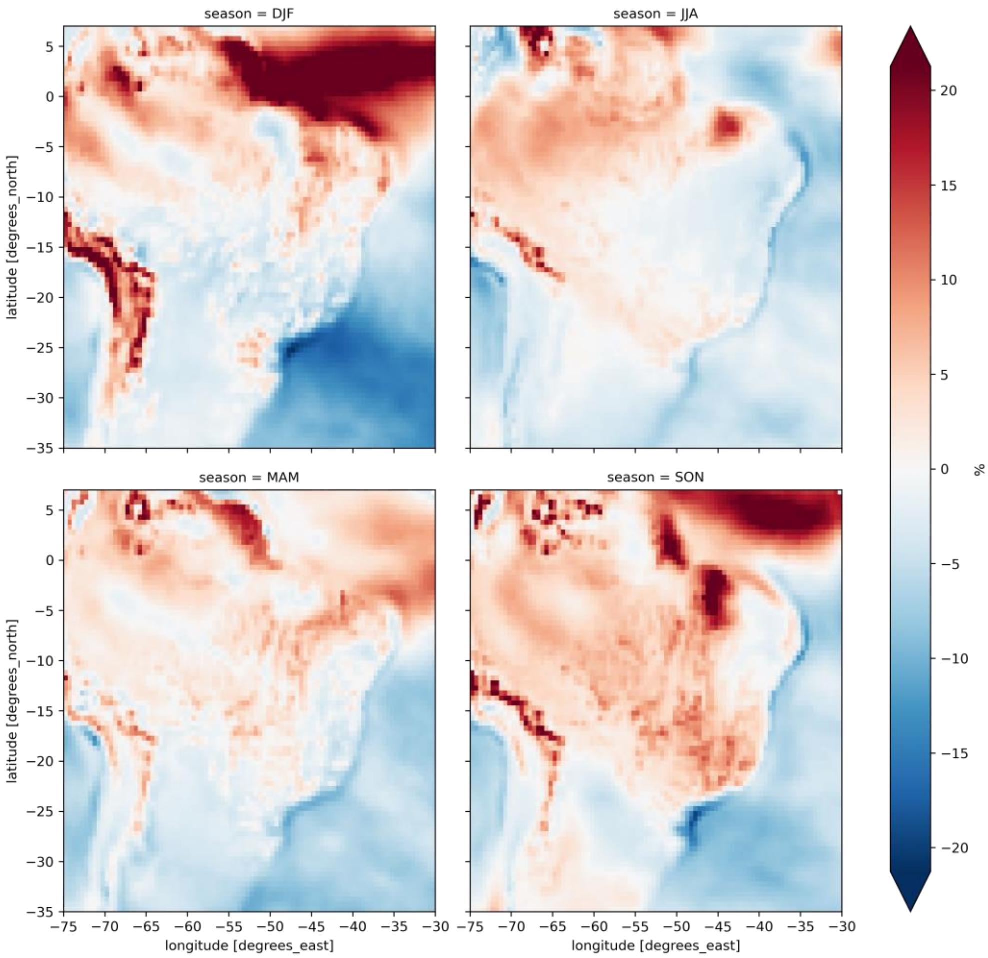


Figure 23 - Seasonal RV between historical period and future projection (2071-2099) for Brazil and RCP 8.5

Solar potential RV for each season vary between -25% and +25%, ±10% more than in RCP 2.6, as show in **Erro! Fonte de referência não encontrada.** and **Erro! Fonte de referência não encontrada.**. In this scenario, DJF and SON has larger areas with up to +20% and at the same time areas with the negative variations up to -25% of RV compared to the others seasons. JJA, winter season, shows the lowest variations, from ±10%.

After estimating the RV results the next step was to calculate the new capacity factors of the solar power for each season and for each region. This estimation was made using the capacity factors from 2020 as the baseline and then multiplied by the RV of every decade from 2030 up to 2100. Figure 24Figure 18 shows the results for each region.

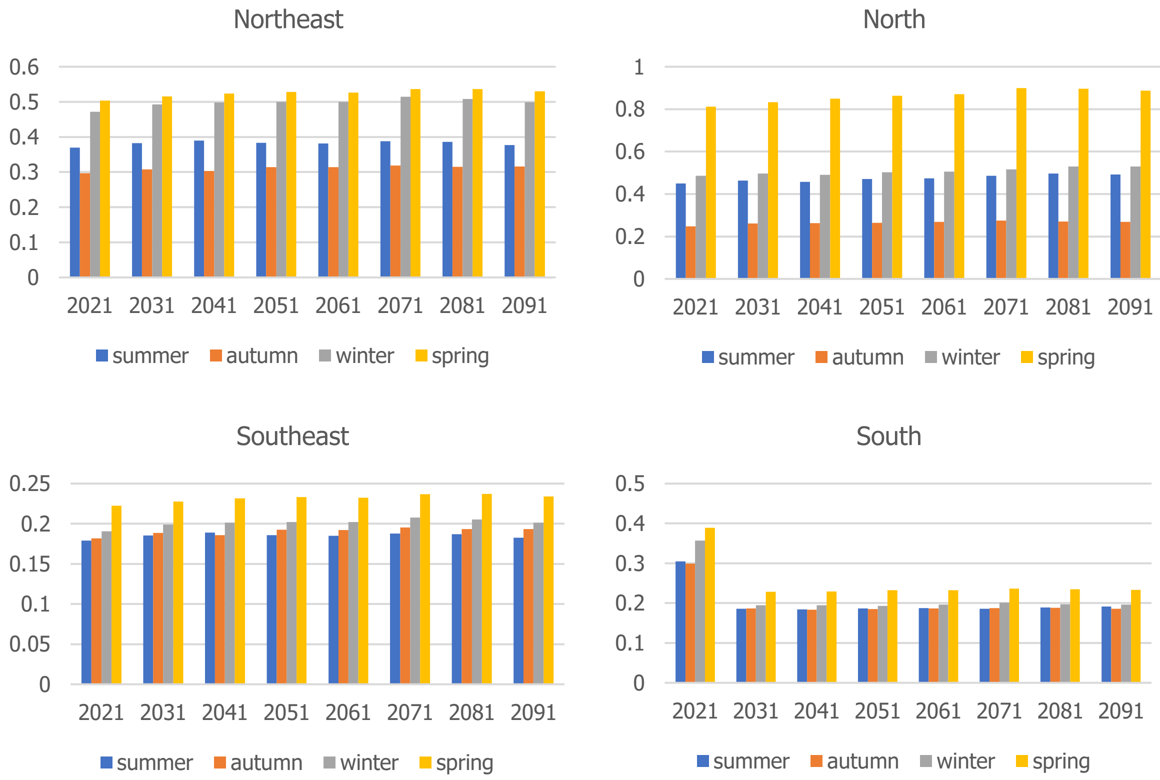


Figure 24 – Historical capacity factor (2020) and new capacity factors from 2030 up to 2100.

3.2 Wind power variability and new future capacity factors for each scenario

The wind power density was calculated from the surface wind speed (m s^(-1)) variable for each RCP. Figure 25 shows the historical mean values of the wind power density. Blanked regions in Figure 25 are those regions that presented wind speed outside the limits of the energy production capacity of the turbines (from 3 to 25 m s^{-1}).

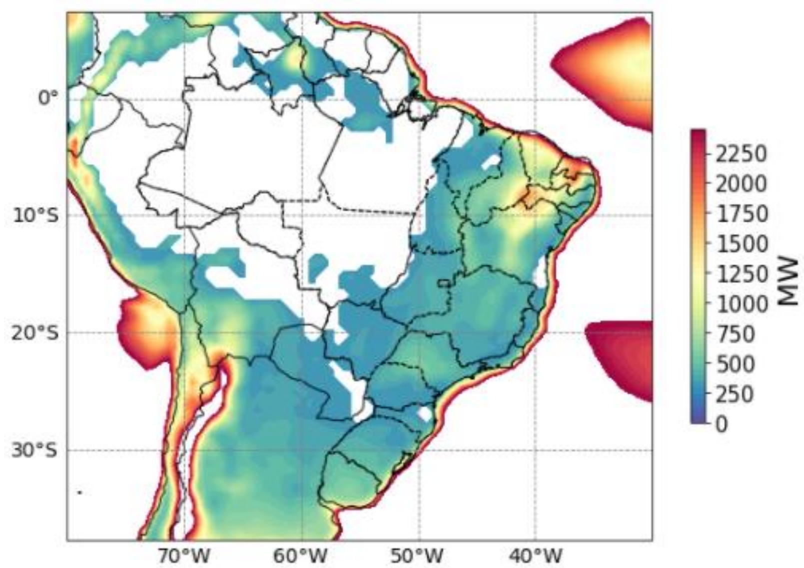


Figure 25 – Wind power density historical mean of Brazil

The regions with the highest wind power density were the northeast region, ranging from 1000 to 2500 MW. More specifically the coastal region of the Northeast region, more specifically the states of Ceará (CE), Rio Grande do Norte (RN), Paraíba (PB), and the countryside of Pernambuco (PE). Besides these, southern tip of the southern region and the countryside of São Paulo have wind power potential, ranging from 500 to 1500 MW.

3.2.1 RCP 2.6

RV given in percentage (%) of the wind power density potential of Brazil from 2011 to 2099 compared to the historical period for the RCP 2.6 scenario are presented in the Figure 52.

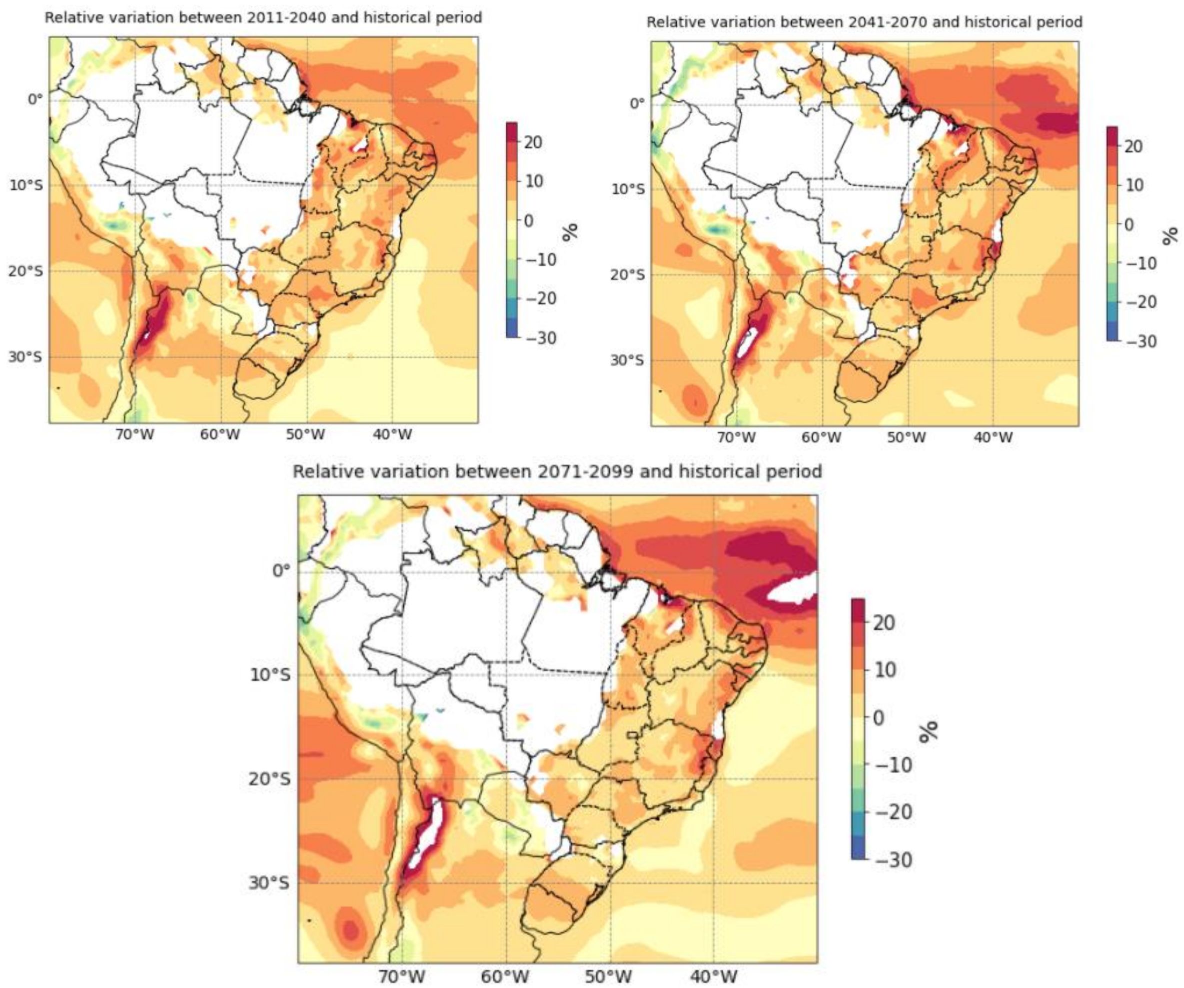


Figure 26 - RV between historical period and future projections (2011-2040, 2041-2070, and 2071-2099) for Brazil and RCP 2.6

In Brazil, future RV projections compared to the historical period varied between -5% and +30%. However, regions that showed reduction in variation were very minimal (small spots can be seen in the countryside of Northeast and Midwest), the majority of regions with wind power potential to be explored presented an increasing variation in RV. Seasonal variations are expected to be highly relevant and to affect the availability of wind generation throughout the year. With that aim, it was constructed maps of the variations of wind power density considering seasonality. Figure 53 shows seasonally relative variation between 2071-2099 and historical period.

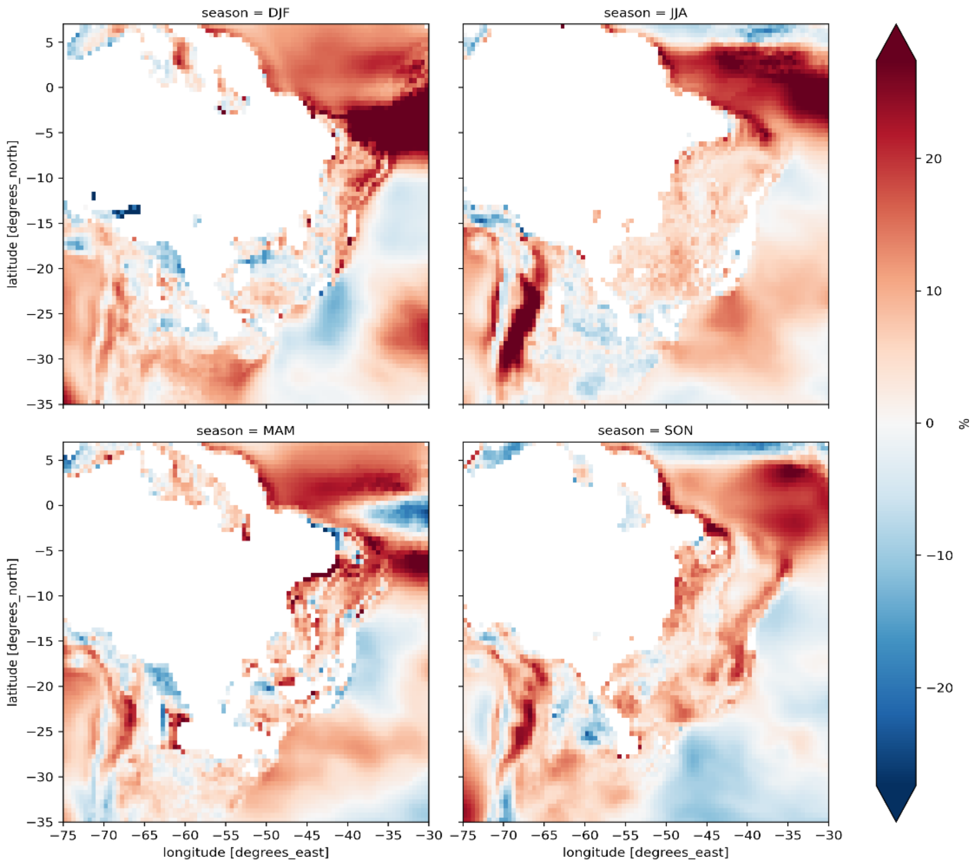
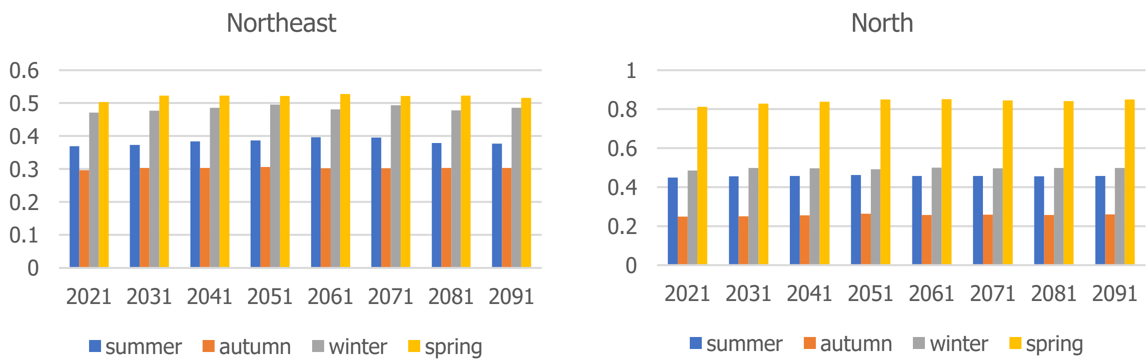


Figure 27 - Seasonal RV between historical period and future projection (2071-2099) for Brazil and RCP 2.6

In above seasonal maps, the seasons are categorized in a more simplified way: December, January, and February (DJF) it considered to be summer time; March, April, and May (MAM) its autumn; June, July, and August (JJA) its winter; and, September, October, and November (SON) its spring time. **Erro! Fonte de referência não encontrada.** highlight the differences of RV for each season, e.g. in summer (DJF) in Southeast region has a large portion of area with negative RV, and an increase variation of more than 20% in the coastal region of Northeast.

After estimating the RV results the next step was to calculate the new capacity factors of the wind power for each season and for each region. This estimation was made using the capacity factors from 2020 as the baseline and then multiplied by the RV of every decade from 2030 up to 2100. Figure 28Figure 18 shows the results.



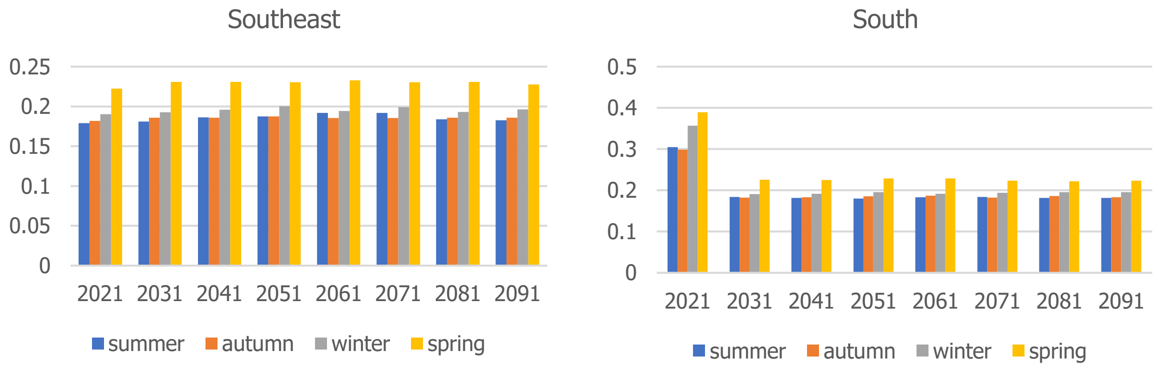


Figure 28 – Historical capacity factor (2020) and new capacity factors from 2030 up to 2100.

3.2.2 RCP 4.5

RV of the wind power potential of Brazil from 2011 to 2099 compared to the historical period for the RCP 4.6 scenario is given in percentage (%) and are presented in the Figure 29.

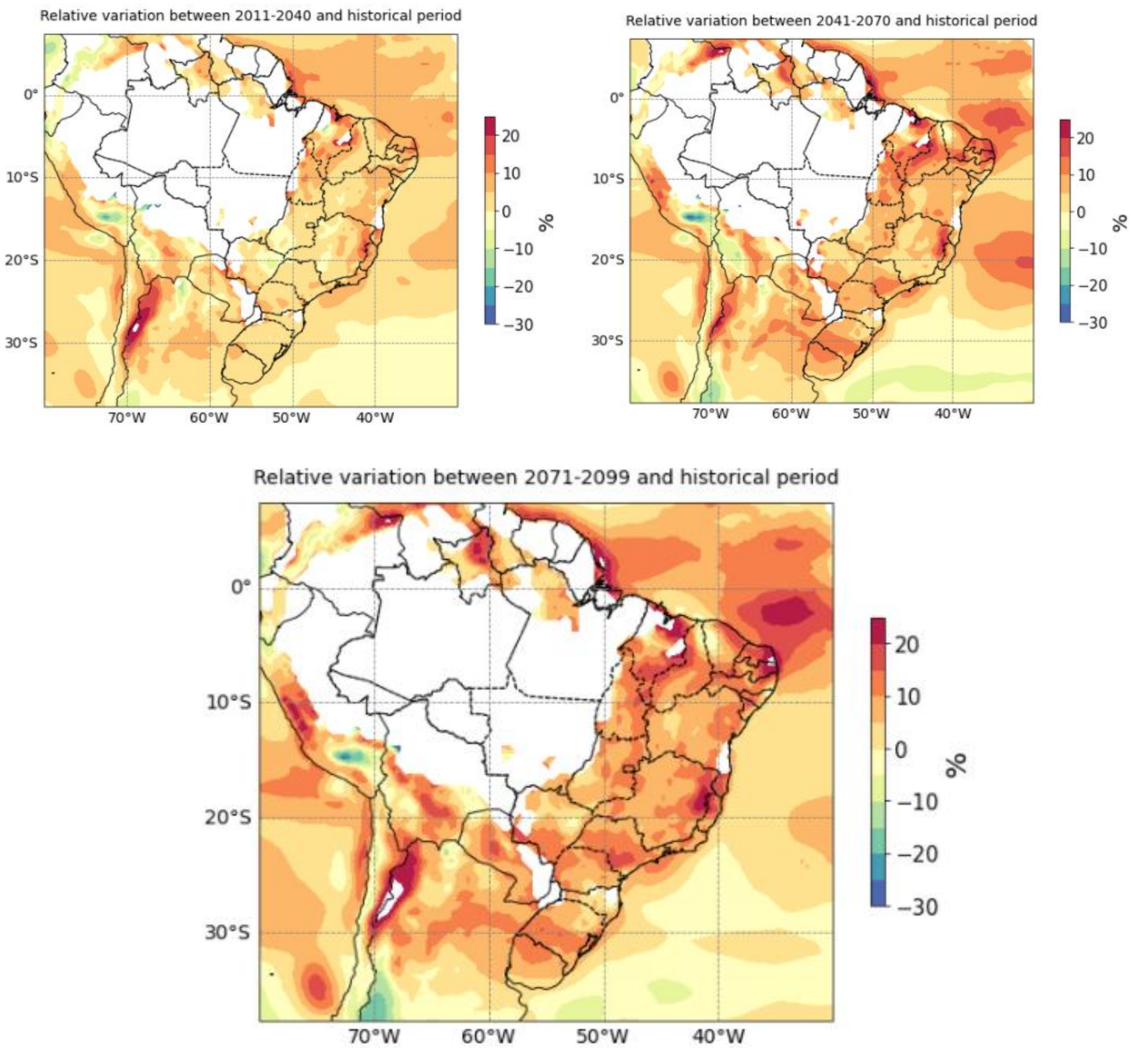


Figure 29 - RV between historical period and future projections (2011-2040, 2041-2070, and 2071-2099) for Brazil and RCP 4.5

In Brazil, for RCP 4.5 projections the RV compared to the historical period varied between -5% and +30%. Mostly in the 2011-2040 projections appeared regions with reduction in variation and they were small and sparse regions. The majority of regions with wind power potential to be explored presented a positive variation in RV over the analyzed periods. Maps of the variations of wind power density considering seasonality were developed to discretize the difference between seasons, Figure 30 shows seasonally relative variation between 2071-2099 and historical period.

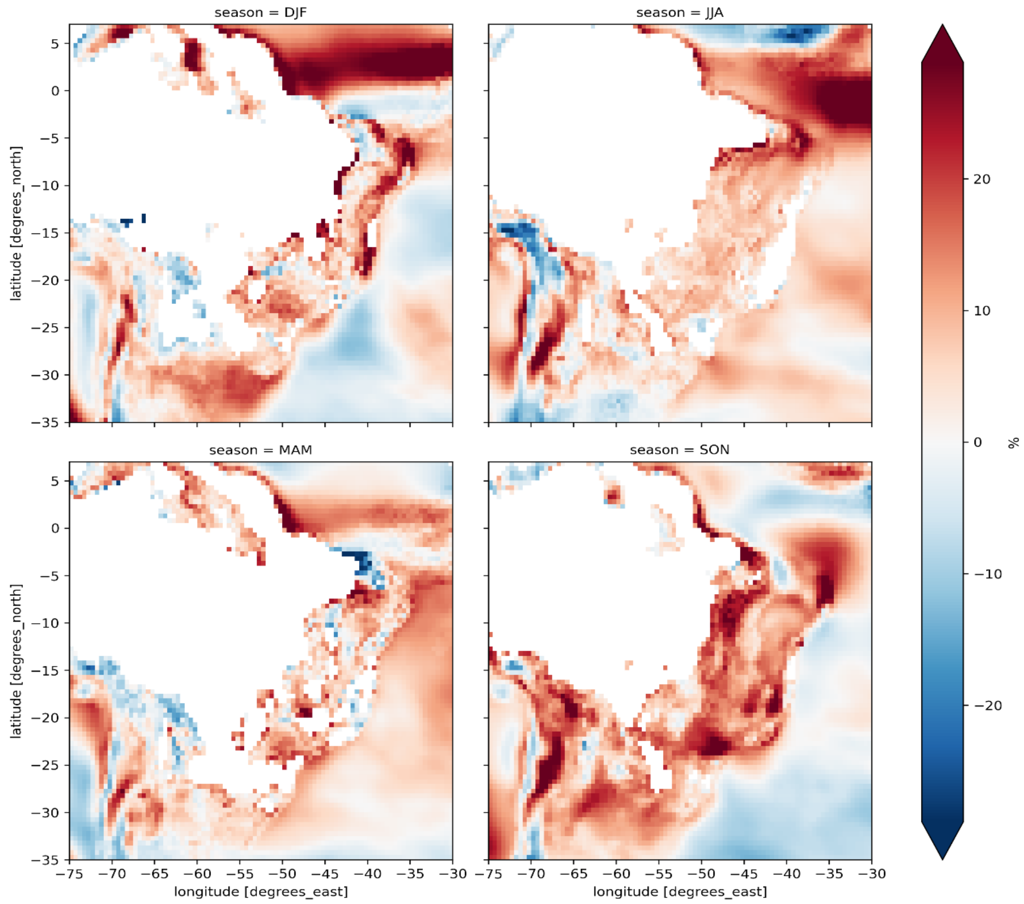


Figure 30 - Seasonally relative variation between 2071-2099 and historical period for RCP 4.5 scenario

In above seasonal maps, Figure 30, can be seen that each season is quite different from another. Autumn (MAM) and Spring (SON) appears to have the highest variation among them. Autumn shows a negative wind power density relative variation up to -20% in north coast of Northeast region and Spring season with a positive relative variation up to +20% in the same area. Besides this, Southeast region showed an increase wind power density variation up to 30% mainly in Summer and Spring; and, in the South region a positive variation up to +30% only in SON.

After estimating the RV results the next step was to calculate the new capacity factors of the wind power for each season and for each region. This estimation was made using the capacity factors from 2020 as the baseline and then multiplied by the RV of every decade from 2030 up to 2100. Figure 18 Figure 31 shows the results.

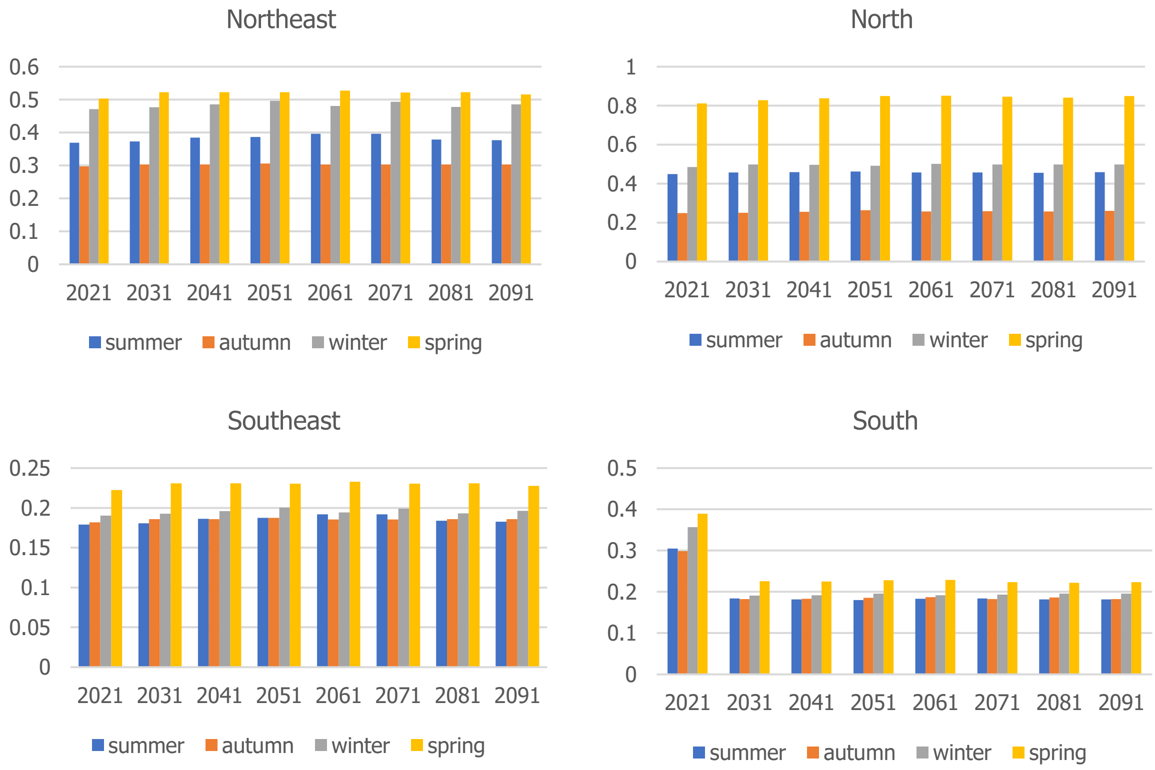
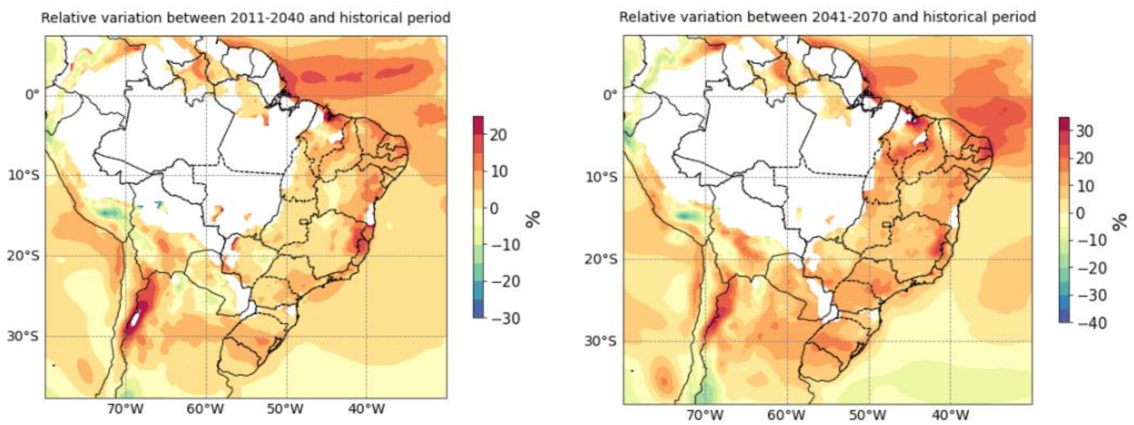


Figure 31 – Historical capacity factor (2020) and new capacity factors from 2030 up to 2100.

3.2.3 RCP 8.5

RV of the wind power potential of Brazil from 2011 to 2099 compared to the historical period for the RCP 8.5 projection is given in percentage (%) and Figure 32 shows the results.



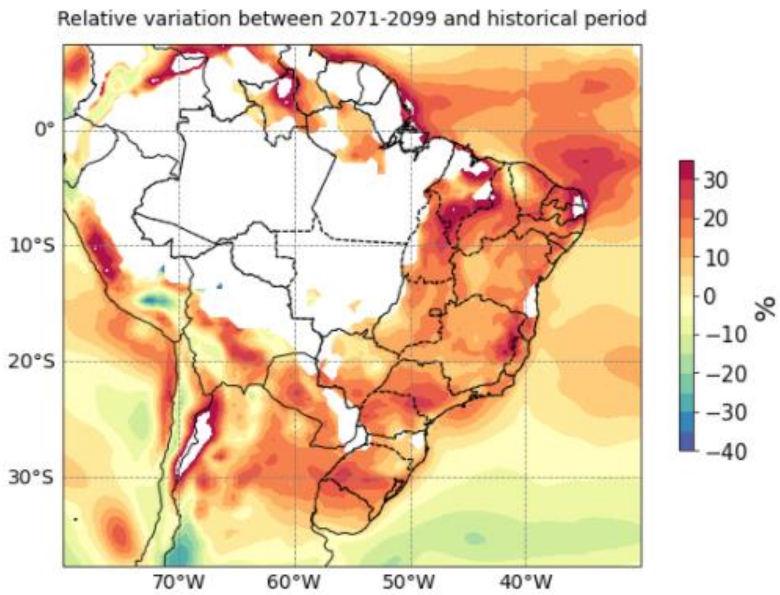


Figure 32 - RV between historical period and future projections (2011-2040, 2041-2070, and 2071-2099) for Brazil and RCP 8.5

In Brazil, for RCP 8.5 projections the RV compared to the historical period varied between -5% and +30%. Mostly in 2011-2040 projections, and in the extreme north coast of Northeast appeared regions with negative variation up to -5%. The majority of regions with wind power potential to be explored presented a positive variation in RV over the analyzed periods. Seasonally relative variation between 2071-2099 and historical period are shown in Figure 33.

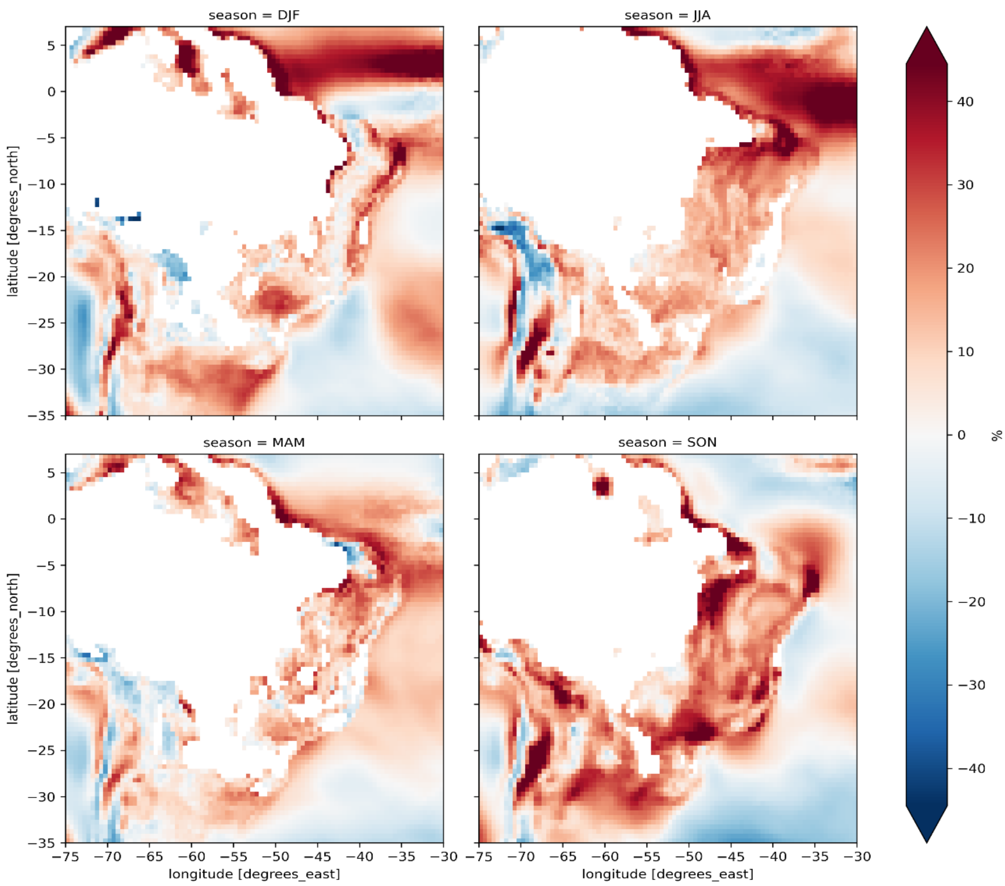


Figure 33 - Seasonally relative variation between 2071-2099 and historical period for RCP 8.5 scenario

In general, variations ranged from -40% up to +50%. Can be highlighted that Spring (SON) will have the most increase variation in wind power density, up to 50%; In Autumn (MAM) there are the lowest variation, up to -40% in the north coast od Northeast region. Besides this, Southeast region showed an increase wind power density variation up to 50% mainly in Spring (SON) season; as well as in the South region a positive variation up to +50% only in Spring (SON).

After estimating the RV results the next step was to calculate the new capacity factors of the wind power for each season and for each region. This estimation was made using the capacity factors from 2020 as the baseline and then multiplied by the RV of every decade from 2030 up to 2100. Figure 34Figure 18 shows the results.

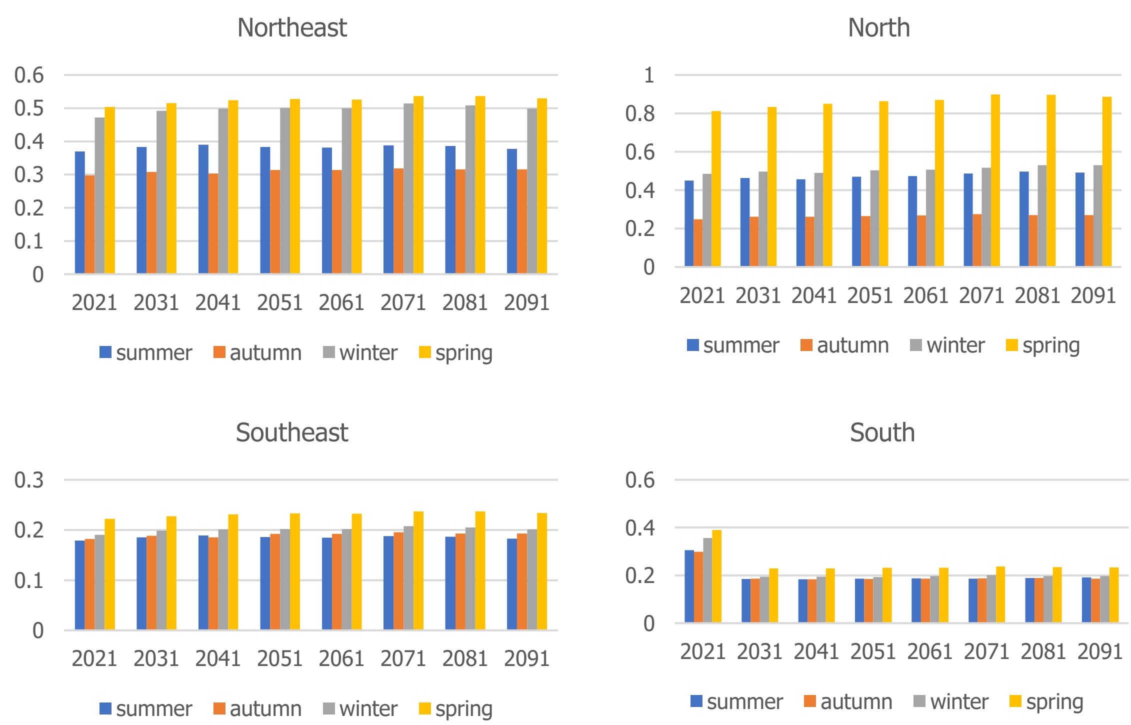


Figure 34 – Historical capacity factor (2020) and new capacity factors from 2030 up to 2100.

3.3 Hydropower variability and new seasonal natural inflow for each scenario

The seasonal natural inflow variability was estimated for each one of the 12-equivalent reservoir for each season and for the 3 RCPs. In total it was generated more than 48 results for each equivalent reservoir. Considering the limitation of presenting all these results in this report it was chosen to show only some examples and present the detailed hydropower analysis within the MESSAGEix results. Thus, Figure 35 and Figure 36 show the estimated seasonal natural inflow from 2011 up to 2100 for the equivalent reservoir 3 (Nordeste) and equivalent reservoir 12 (Paranapanema), respectively.

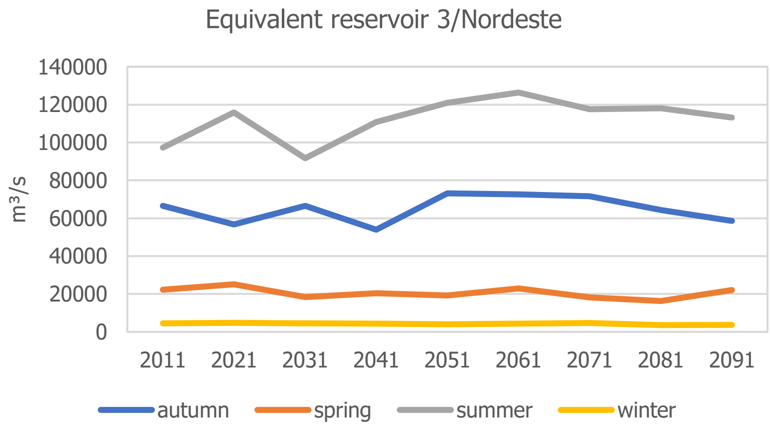


Figure 35 – Seasonal natural inflow of equivalent reservoir 3 from 2011 up to 2100.

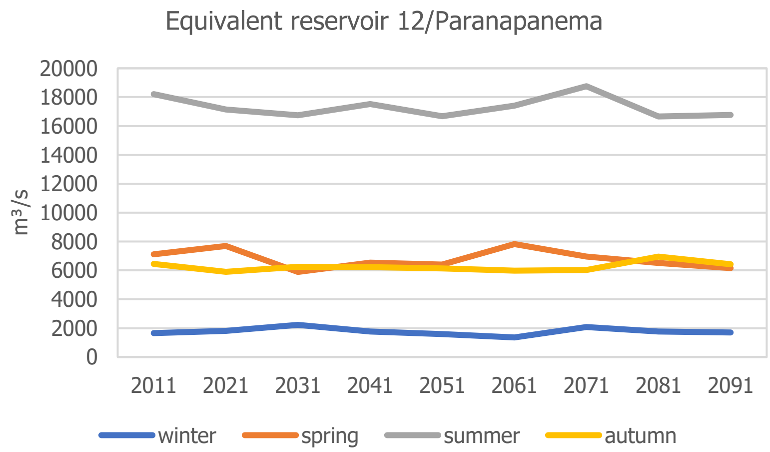


Figure 36 - Seasonal natural inflow of equivalent reservoir 3 from 2011 up to 2100.

3.4 MESSAGEix energy matrix generation and SPHS storage results for each scenario

In this model it was considered the projected average growth rate of the potential consumption of electricity defined by EPE for 2050 [33]. In the baseline scenario it was considered the stagnation scenario, in which it projected an average growth rate of the potential consumption of electricity of 1% per year between 2015 and 2050. Reaching slightly 150 thousand MW average in 2050, as shown in Figure 37.

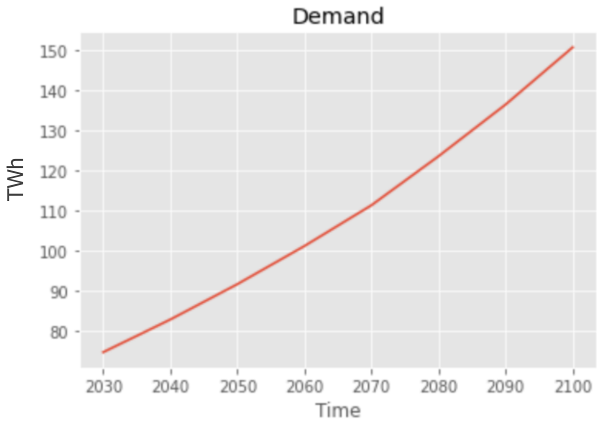


Figure 37 – Demand projection considering a stagnation scenario

For each region and each season, the Brazilian electricity modeled on MESSAGEix, called for short MESSAGEix-Br, defined the least-cost optimization portfolio of energy supply. The Figures 38 – 41 show the optimized solution for the baseline scenario, which does not include any SPHS technology or climate change variability incorporated.

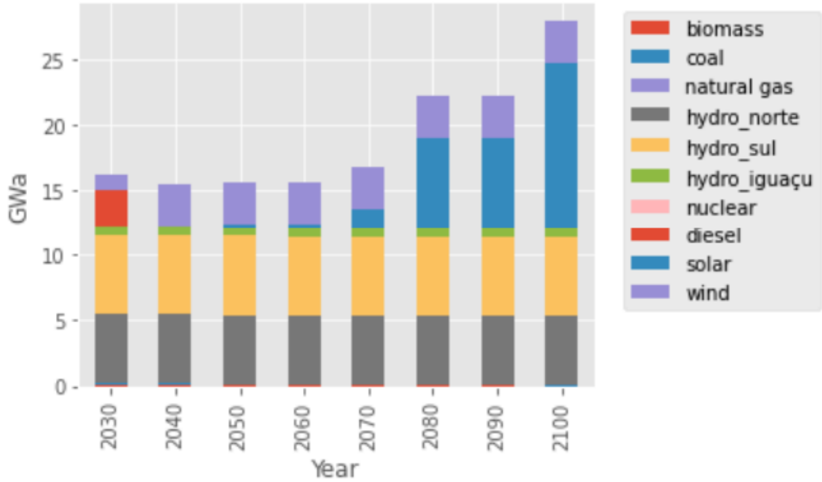


Figure 38 – Final electricity production in the North region by each secondary energy source from 2030 up to 2100

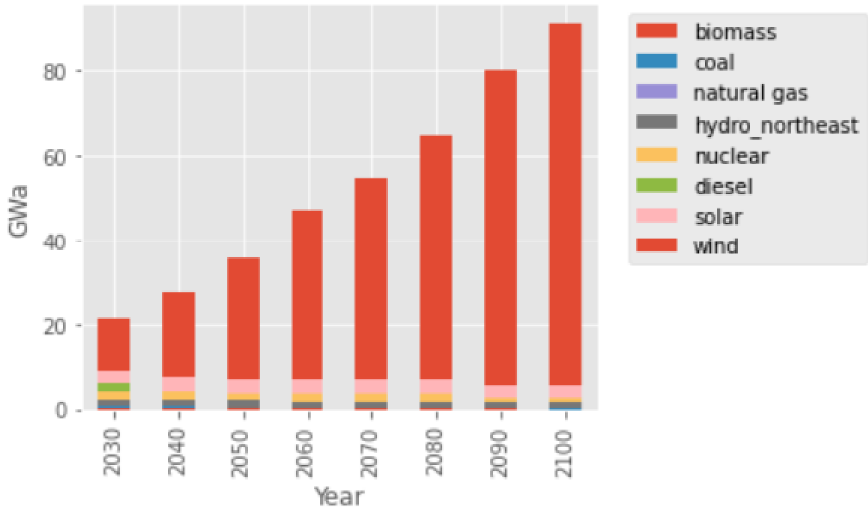


Figure 39 - Final electricity production in the Northeast region by each secondary energy source from 2030 up to 2100

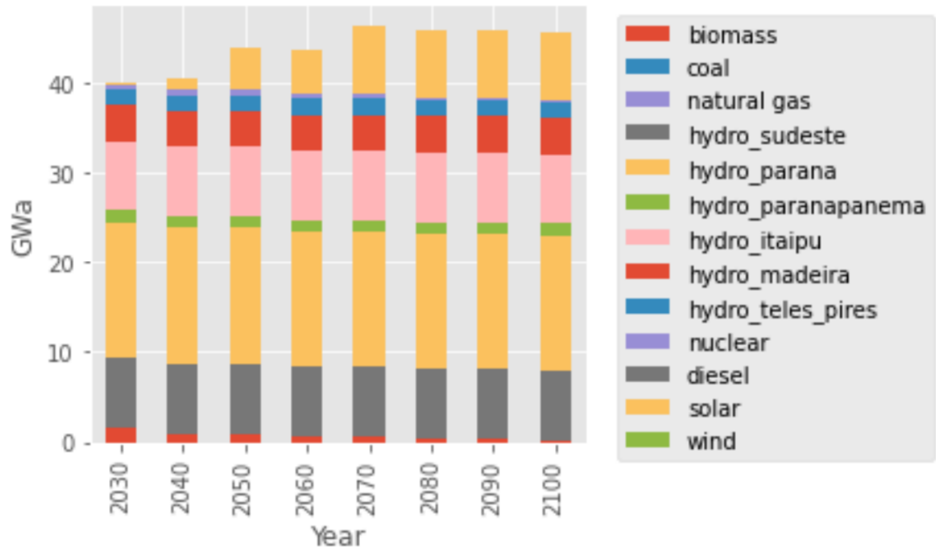


Figure 40 - Final electricity production in the Southeast/Midwest region by each secondary energy source from 2030 up to 2100

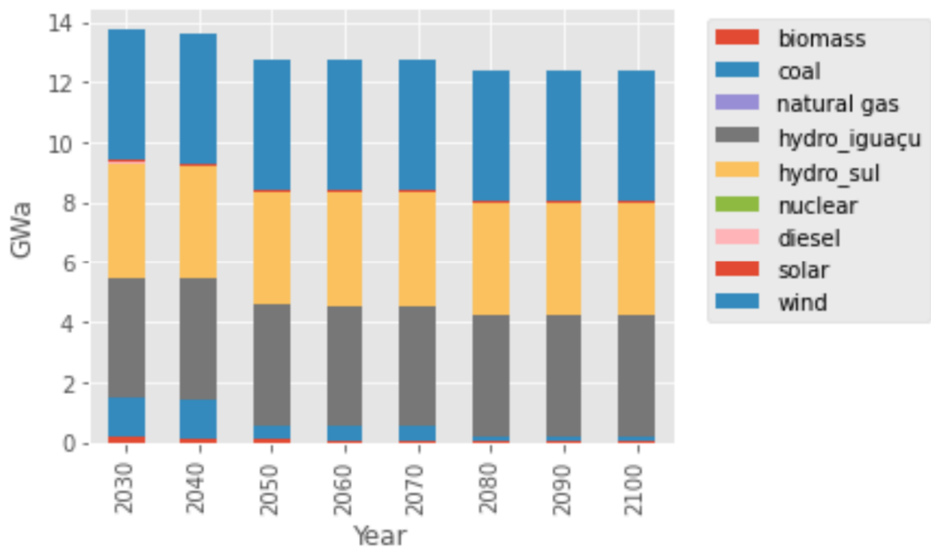


Figure 41 - Final electricity production in the South region by each secondary energy source from 2030 up to 2100

3.4.1 RCP 2.6

The Figures 42 – 44 show the optimized solution for the Brazilian energy matrix for the scenario RCP 2.6. This scenario includes SPHS technology and the climate change variability incorporated on the solar power, wind power and hydropower. These results are related to the electricity generation by each secondary technology in the summer season, which is the season with the highest electricity demand in all regions.

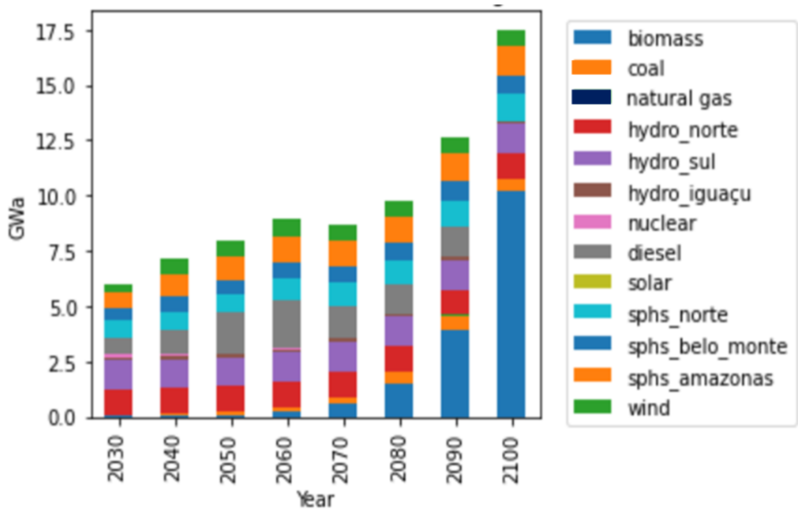


Figure 42 - Final electricity production in the North region by each secondary energy source from 2030 up to 2100 for the summer season

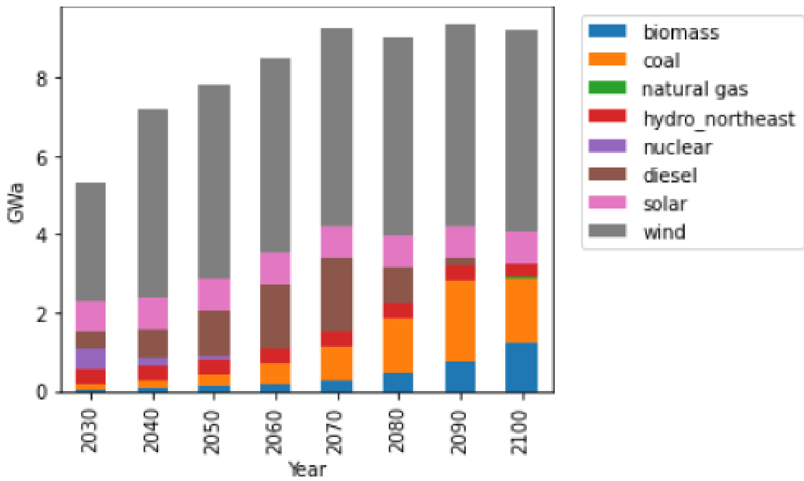


Figure 43 – Final electricity production in the Northeast region by each secondary energy source from 2030 up to 2100 for the summer season

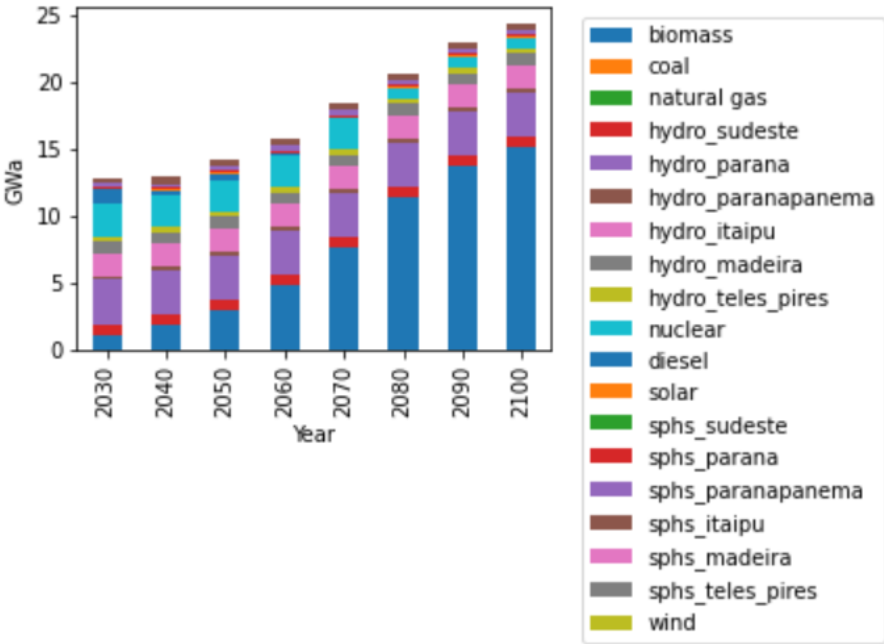


Figure 44 - Final electricity production in the Southeast region by each secondary energy source from 2030 up to 2100 for the summer season

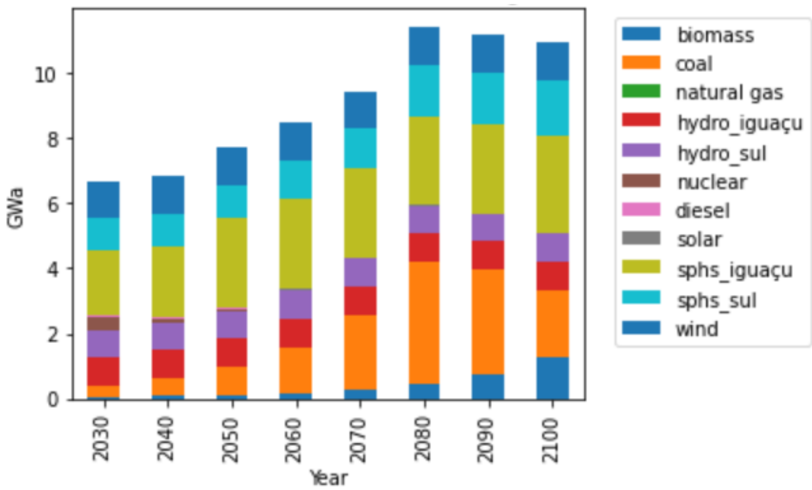
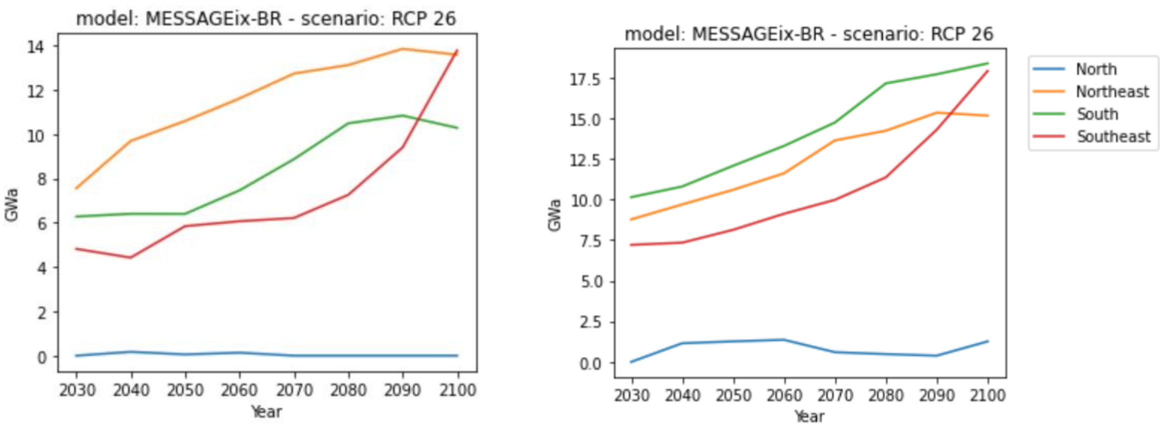


Figure 45 - Final electricity production in the South region by each secondary energy source from 2030 up to 2100 for the summer season

Figure 46 shows how much electricity it was generated by each region during the wet season, Summer, and the dry season, Winter. The wet season is the season in which rains more but at the same time is the season with higher temperature range which leads to a higher demand for electricity. Thus, the dry season is also the season with the lowest demand for electricity in Brazil.



WINTER SUMMER

Figure 46 - Final electricity generation of each Region in winter and in summer from 2030 up to 2100 for RCP 2.6.

Figure 47 shows how much energy was generated by the SPHS turbine in the summer. In other words, it means the amount of energy that was generated from the stored water by the SPHS turbine. Because in this MESSAGEix-Br configuration the SPHS has two different technologies one to pump the water from the lower reservoir to the higher reservoir (pump_sphs) and other to generate electricity with the water that is in the lower reservoir (turb_sphs). So, the pump_sphs technology pumped water back to the higher reserevoir during the spring, winter and autumn and produced electricity in the turb_sphs technology in the summer. These results are related to the amount of energy produced by the turb_sphs technology during the summer season.

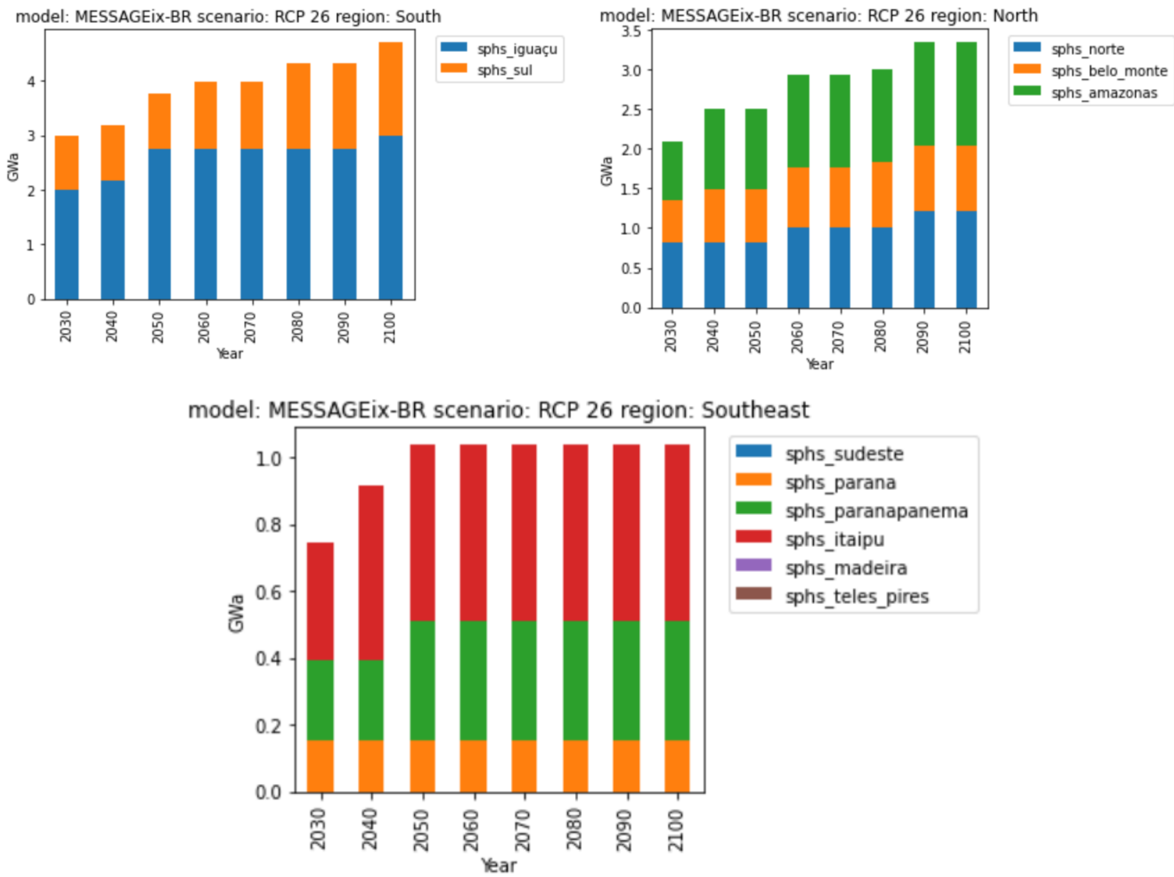


Figure 47 – Final electricity Generation through seasonal pump storage turbine in the regions South, Northeast and Southeast from 2030 up to 2100.

3.4.2 RCP 4.5

The Figures 48 – 51 show the optimized solution for the Brazilian energy matrix for the scenario RCP 4.5. This scenario includes SPHS technology and the climate change variability incorporated on the solar power, wind power and hydropower. These results are related to the electricity generation by each secondary technology in the summer season, which is the season with the highest electricity demand in all regions.

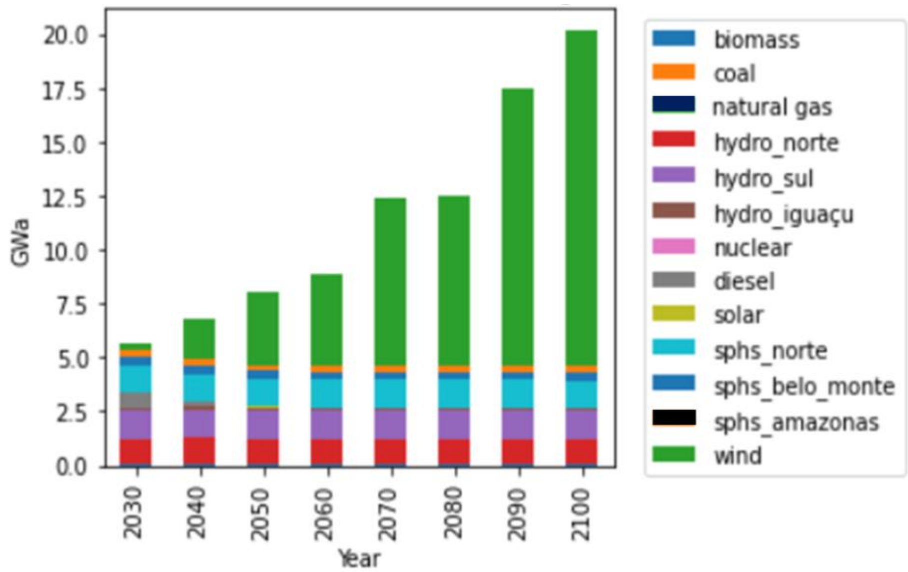


Figure 48 – Final electricity production in the North region by each secondary energy source from 2030 up to 2100 for the summer season

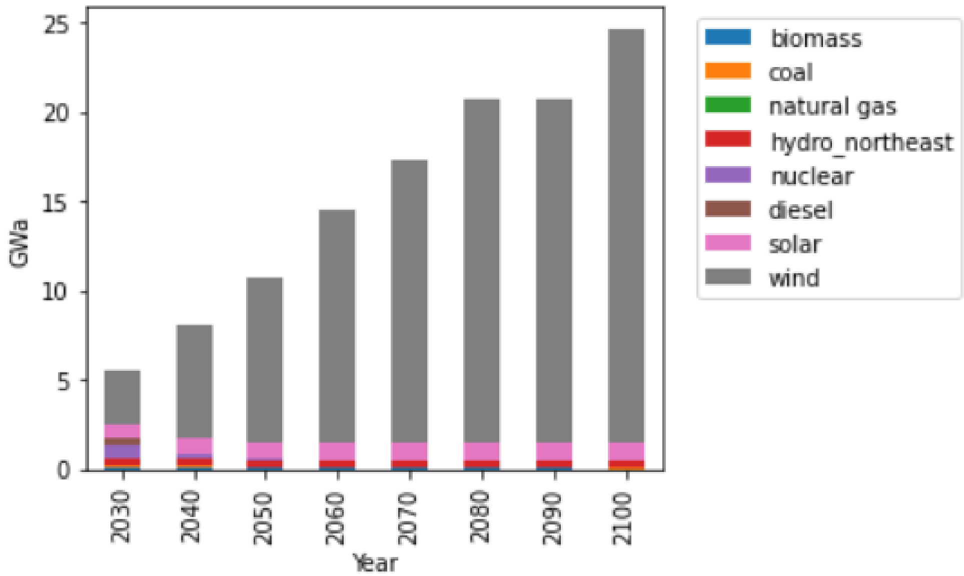


Figure 49 - Final electricity production in the Northeast region by each secondary energy source from 2030 up to 2100 for the summer season

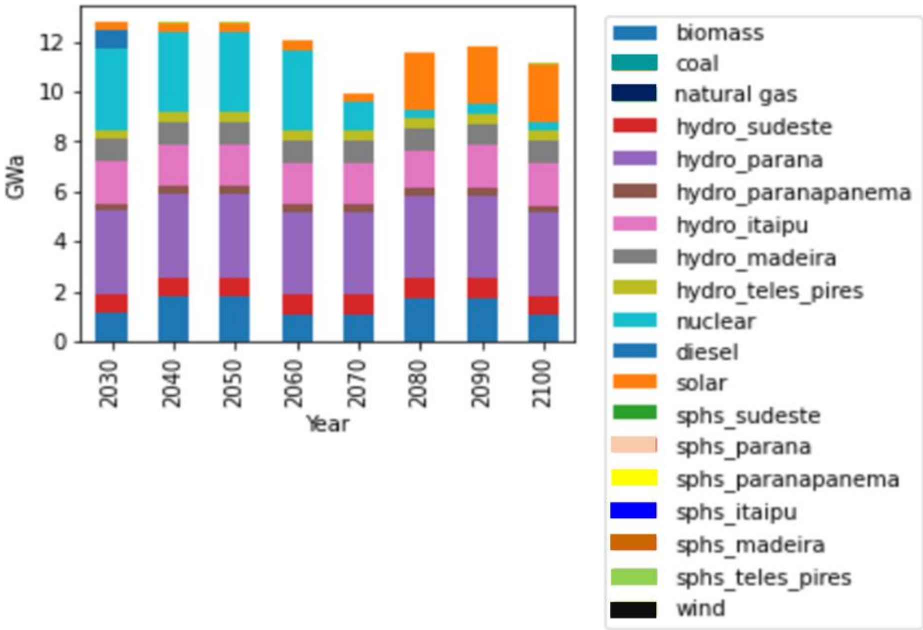


Figure 50 - Final electricity production in the Southeast region by each secondary energy source from 2030 up to 2100 for the summer season

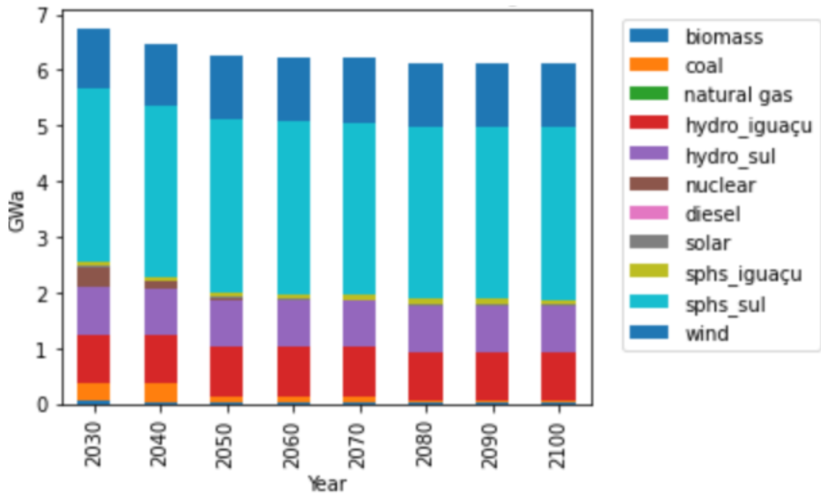
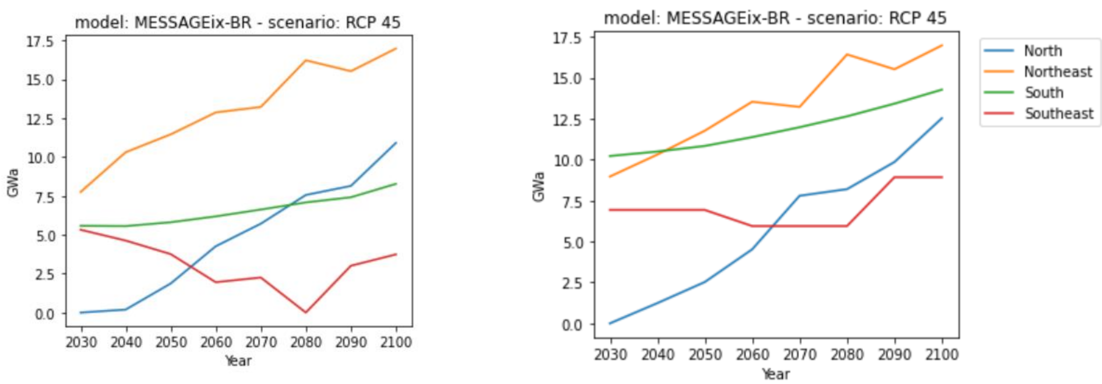


Figure 51 - Final electricity production in the South region by each secondary energy source from 2030 up to 2100 for the summer season

Figure 52 shows how much electricity it was generated by each region during the wet season, Summer, and the dry season, Winter.



WINTER SUMMER

Figure 52 - Final electricity generation of each Region in winter and in summer from 2030 up to 2100 for RCP 4.5.

Figure 53 shows how much energy was generated by the SPHS turbine in the summer. In other words, it means the amount of energy that was generated during the summer from the stored water during the spring, winter, and autumn by the SPHS turbine.

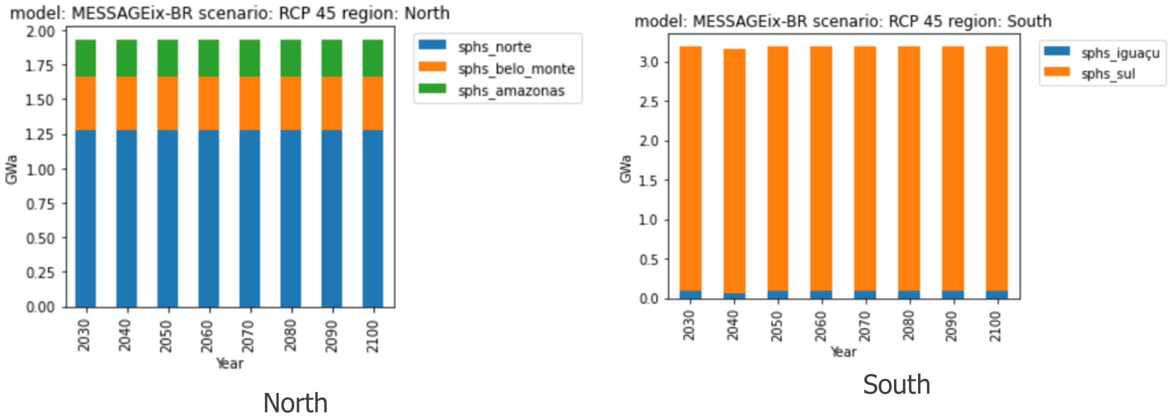


Figure 53 - Final electricity generation through seasonal pump storage turbine in the North and South region in the summer.

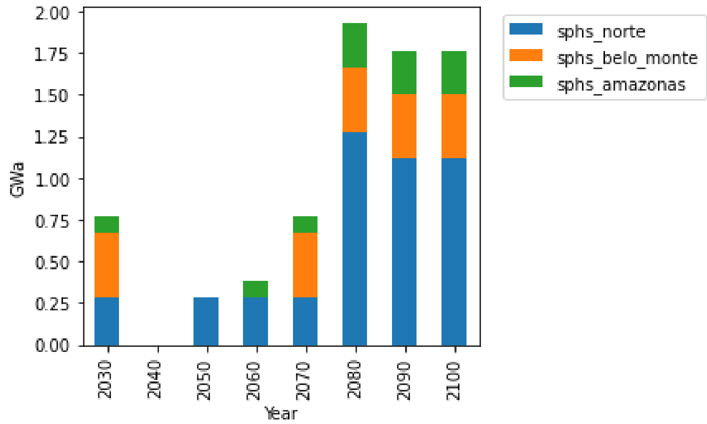


Figure 54 - Final electricity generation through seasonal pump storage turbine in the North region on the winter.

3.4.3 RCP 8.5

The Figures 54 – 57 show the optimized solution for the Brazilian energy matrix for the scenario RCP 8.5. This scenario includes SPHS technology and the climate change variability incorporated on the solar power, wind power and hydropower. These results are related to the electricity generation by each secondary technology in the summer season, which is the season with the highest electricity demand in all regions.

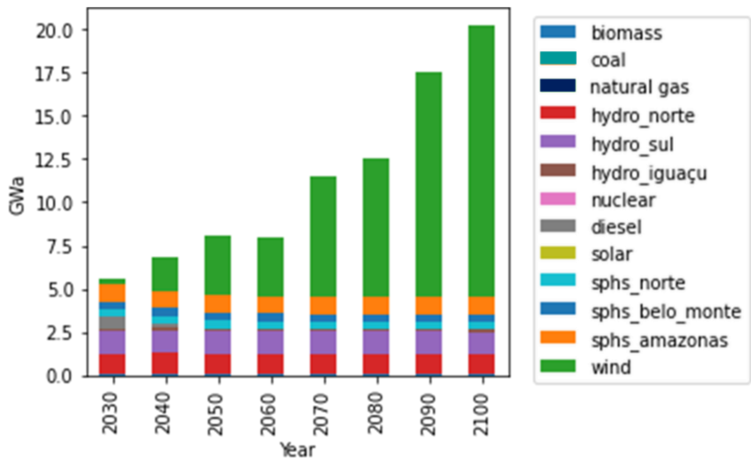


Figure 55 - Final electricity production in the North region by each secondary energy source from 2030 up to 2100 for the summer season

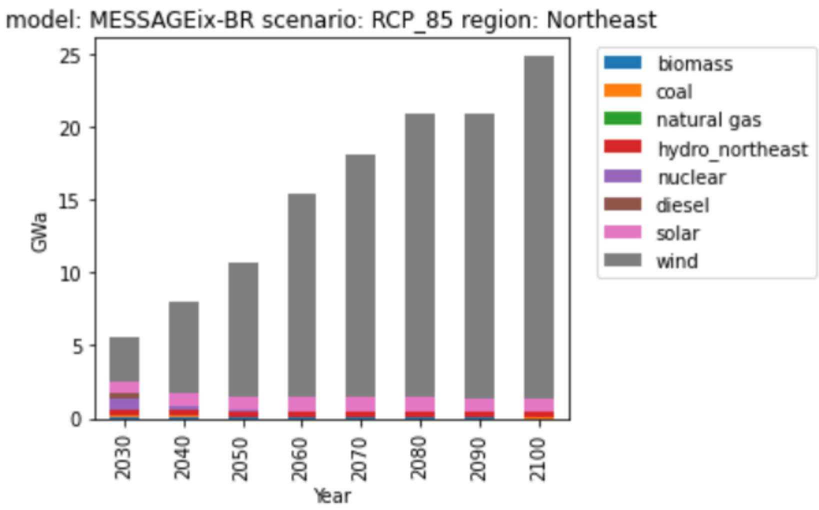


Figure 56 - Final electricity production in the Northeast region by each secondary energy source from 2030 up to 2100 for the summer season

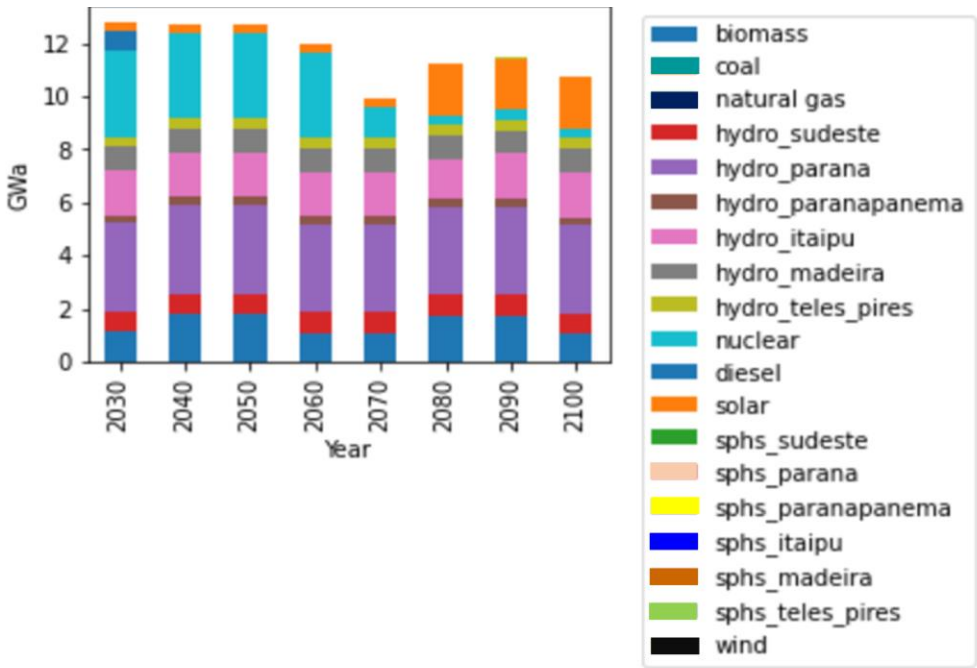


Figure 57 - Final electricity production in the Southeast region by each secondary energy source from 2030 up to 2100 for the summer season

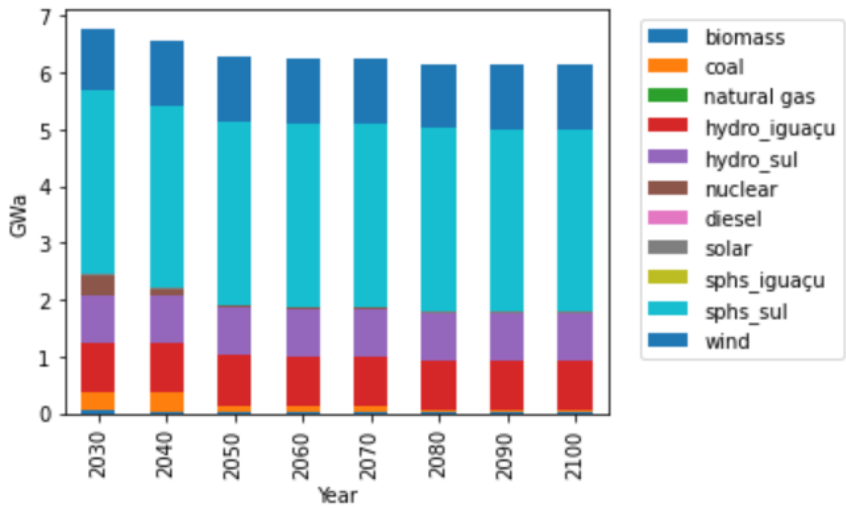


Figure 58 - Final electricity production in the South region by each secondary energy source from 2030 up to 2100 for the summer season

Figure 59 shows how much electricity it was generated by each region during the wet season, Summer, and the dry season, Winter.

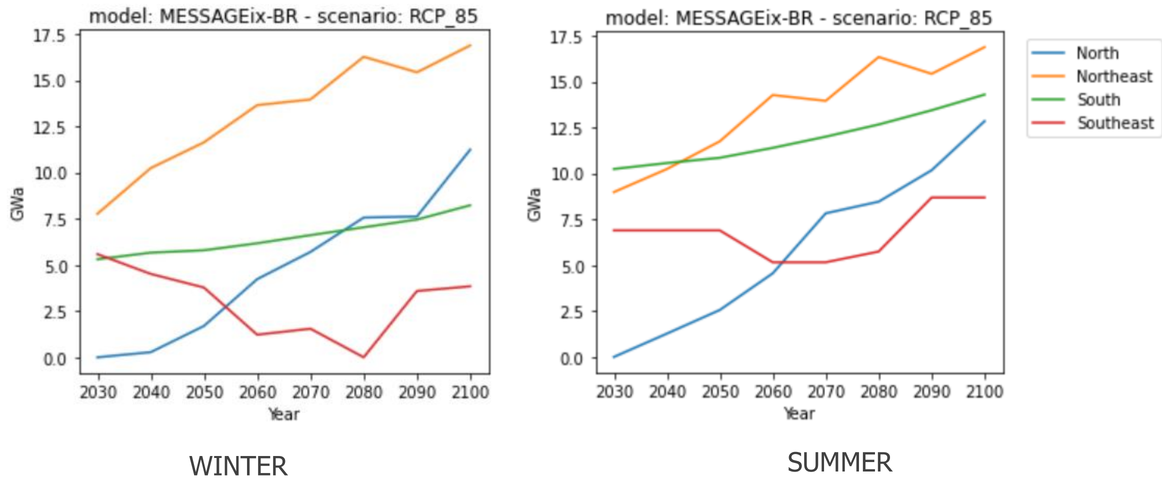


Figure 59 – Final electricity generation of each Region in winter and in summer from 2030 up to 2100 for RCP 8.5.

Figure 60 shows how much energy was generated by the SPHS turbine in the summer. In other words, it means the amount of energy that was generated during the summer from the stored water during the spring, winter, and autumn by the SPHS turbine.

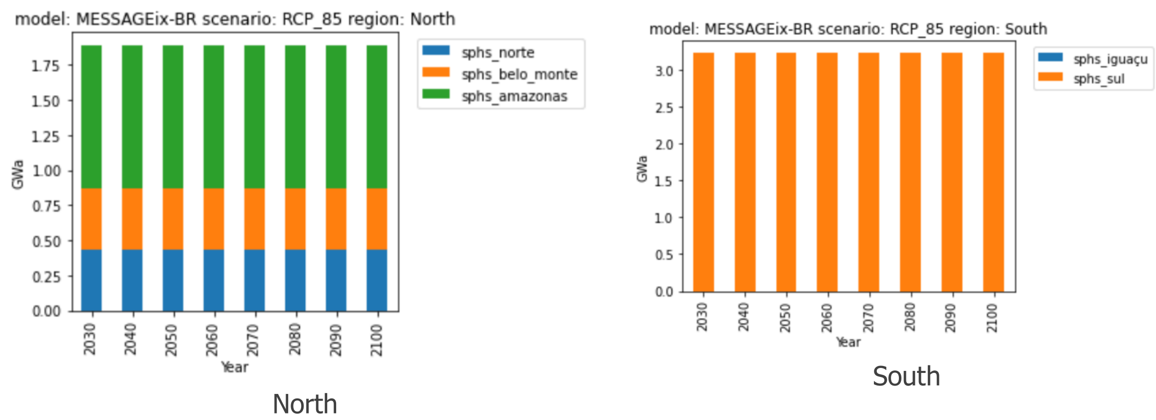


Figure 60 - Final electricity generation through seasonal pump storage turbine in the North and South region in the summer.

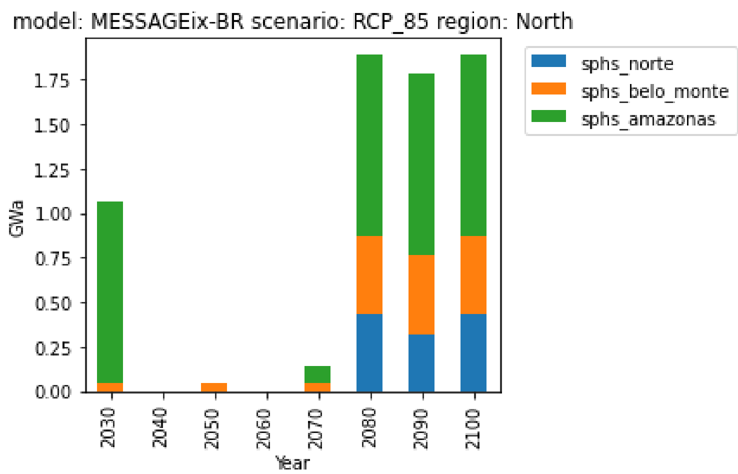


Figure 61 - Final electricity generation through seasonal pump storage turbine in the North region in the winter.

4 Discussion

The seasonal variation in Brazil for hydropower and wind power are complementary. In the wet period in which there is a more natural inflow of water, there is an increase in wind power generation. Figure 62 shows the increase in the wind power generation during the winter (dry season) and the decrease in the SPHS generation in comparison with the SPHS and the wind power generation during the summer (wet season).

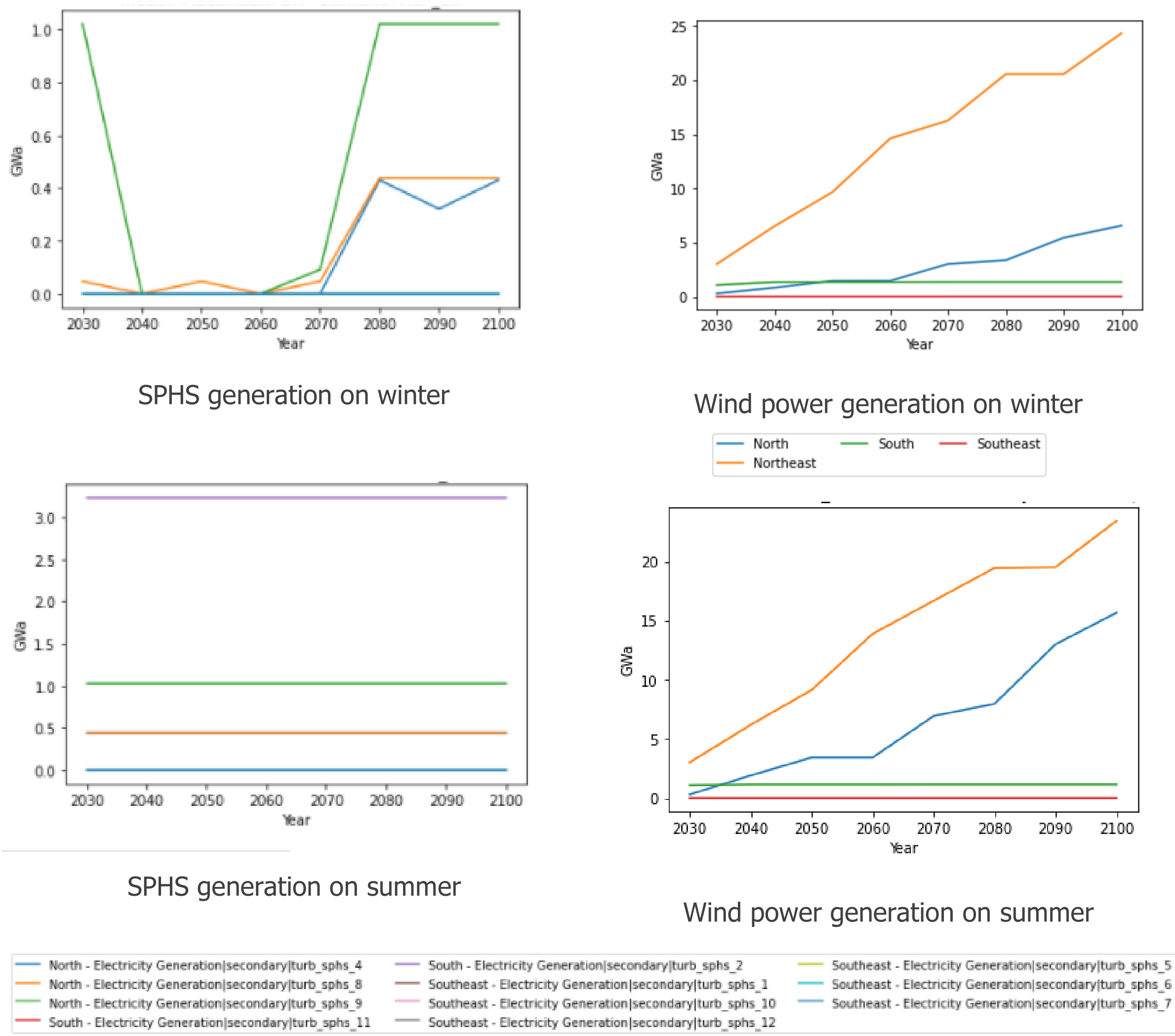


Figure 62 -Comparison between the SPHS and the wind power generation during the winter (dry season) and the summer (wet season) for RCP 8.5.

Also, the results showed that the worst the temperature increase in the atmosphere, scenarios RCP 4.5 and RCP 8.5, the SPHS generation decreased. Figure 63 shows the comparison between the SPHS generation for each RCP scenario. So, the model chooses to invest in wind power instead of investing in SPHS in scenarios with a decrease in the seasonal natural inflow of water, as shown in Figure 64.

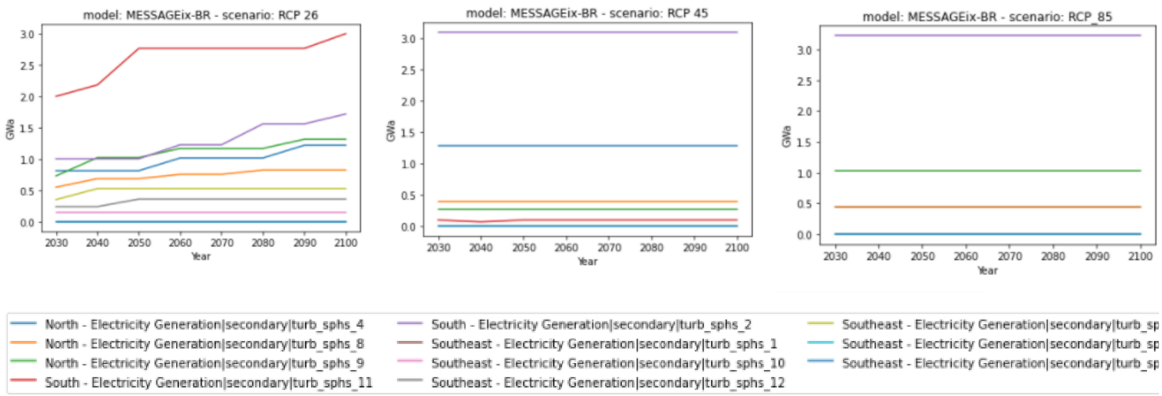


Figure 63 – Comparison of electricity generation in the summer with the SPHS turbine for each RCP scenario.

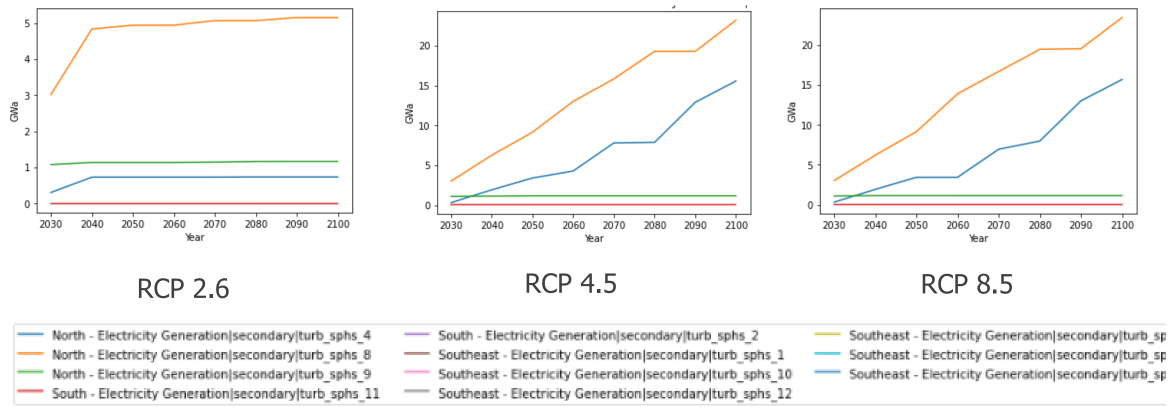


Figure 64 - Comparison of electricity generation in the summer with wind power for each RCP scenario.

The seasonal pump storage showed to be flexible solution which stored energy from the hydropower during the wet period. Although this configuration it was most feasible for the 2.6 RCP scenario which had more natural inflow of water than the other scenarios. For the RCP 4.5 and 8.5 it was more feasible to invest in wind power than in SPHS.

5 Conclusions

Climate has a direct impact on the energy sector, especially on renewable energy production. Brazil has one of the most renewable energy matrices in the world, therefore, can be affected by climate change. Previous studies affirm that Brazil is vulnerable to climate change impacts and its vulnerability is more intense the greater is its dependence on renewable energy sources, especially hydroelectricity. Considering the relevance to address this issue, this research began to explore pathways to long-term energy decision making under climate change to ensure the energy availability and the cost feasibility of the electricity system.

The foundation methods addressed in the methodology are those related to simulations of future energy supply and demand (MESSAGEix) and climate change projections (RCM). Then, to transform climate data from CORDEX projections into renewable energy potential made it possible to estimate the energy variability. In the sequence, climate change constraints are incorporated on different elements - the capacity factor and on the seasonal natural inflow – on the regions and technologies covered in the MESSAGEix model. The final analysis included the determination of how much adaptation is needed by comparing the MESSAGEix portfolio´s solution including climate change constraints with the baseline MESSAGEix portfolio´s solution. Then, evaluate which is the least-cost expansion energy capacity portfolio including SPHS strategies for each scenario.

Variability between the historical period (1961-2005) and future projections from 2006 until 2100 of the wind power, the solar power, and the hydropower potential were evaluated in this chapter. To do so, for each grid cell of the Brazilian territory the technical potential was estimated by the climate variables extracted from CORDEX database for RCP 2.6, RCP 4.5 and RCP 8.5 scenarios. Wind power density RV results, from the historical period (1961-2005) and future projections from 2011 until 2100, indicate a variation between -5% up to +30% for all scenarios. Accentuating those seasonal variations had higher variations from -30 up to +30% for RCP 2.6 and RCP 4.5, and from -40% up to +40% for RCP 8.5. Most affected regions by RV were Northeast and South region. Results point to a decrease in the negative variation and an increase in the positive variation over the scenarios.

Variability indicator results demonstrate that the worse the scenario the greater the impact on the potential for hydropower energy production. In wind power, the potential case was projected to have higher variability than solar power potential. In some regions, as in Northeast showed an increasing trend, so more wind power potential is expected in this region. Solar power potential had lower variability in all scenarios and almost no trend for the Brazilian regions.

MESSAGEix-Br model results showed that there is a complementarity between wind power and hydropower. In the wet period in which there is a more natural inflow of water there is an increase in wind power generation. The model, also, points out that is better to invest in SPHS in a scenario with more water availability, which is the RCP 2.6 scenario. In the other cases, RCP 4.5 and 8.5, the model showed would be more feasible to invest in wind power generation instead of investing in SPHS.

6 References

[1] S. N. Chandramowli and F. A. Felder, "Impact of climate change on electricity systems and markets - A review of models and forecasts," *Sustain. Energy Technol. Assessments*, vol. 5, pp. 62–74, Mar. 2014, doi: 10.1016/j.seta.2013.11.003.

[2] J. C. Ciscar and P. Dowling, "Integrated assessment of climate impacts and adaptation in the energy sector," *Energy Econ.*, vol. 46, pp. 531–538, Nov. 2014, doi: 10.1016/j.eneco.2014.07.003.

[3] V. Eyring *et al.*, "Taking climate model evaluation to the next level," *Nat. Clim. Chang.*, vol. 9, no. 2, pp. 102–110, Feb. 2019, doi: 10.1038/s41558-018-0355-y.

[4] J. Marengo *et al.*, "DANGEROUS CLIMATE CHANGE IN BRAZIL," 2011. Accessed: Aug. 21, 2020. [Online]. Available: www.ccst.inpe.br.

[5] S. C. Pryor and R. J. Barthelmie, "Climate change impacts on wind energy: A review," *Renewable and Sustainable Energy Reviews*, vol. 14, no. 1. Pergamon, pp. 430–437, Jan. 01, 2010, doi: 10.1016/j.rser.2009.07.028.

[6] P. Audinet, J.-C. Amado, and B. Rabb, "Climate Risk Management Approaches in the Electricity Sector: Lessons from Early Adapters," in *Weather Matters for Energy*, Springer New York, 2014, pp. 17–64.

[7] J. Ebinger and W. Vergara, "A World Bank Study: Climate Impacts on Energy Systems," 2011. Accessed: Aug. 21, 2020. [Online]. Available: http://documents1.worldbank.org/curated/en/580481468331850839/pdf/600510PUB0ID181mpacts09780821386972.pdf.

[8] A. F. P. de Lucena *et al.*, "Interactions between climate change mitigation and adaptation: The case of hydropower in Brazil," *Energy*, vol. 164, pp. 1161–1177, Dec. 2018, doi: 10.1016/j.energy.2018.09.005.

[9] IPCC, "IPCC activities," 2007. https://archive.ipcc.ch/activities/activities.shtml.

[10] EPE, "Balanço Energético Nacional 2021," 2021. [Online]. Available: https://www.epe.gov.br/sites-pt/publicacoes-dados-abertos/publicacoes/PublicacoesArquivos/publicacao-601/topico-596/BEN2021.pdf.

[11] BRASIL, "Clima," *Ministério da Ciência, Tecnologia e Inovações*, 2020. https://antigo.mctic.gov.br/mctic/opencms/ciencia/SEPED/clima/textogeral/emissao_corporativos.html (accessed Dec. 22, 2020).

[12] H. Ritchie and M. Roser, "Energy," *Our World Data*, Nov. 2020, Accessed: Sep. 16, 2021. [Online]. Available: https://ourworldindata.org/energy.

[13] J. D. Hunt *et al.*, "Global resource potential of seasonal pumped hydropower storage for energy and water storage," *Nat. Commun. 2020 111*, vol. 11, no. 1, pp. 1–8, Feb. 2020, doi: 10.1038/s41467-020-14555-y.

[14] J. D. Hunt, E. Byers, K. Riahi, and S. Langan, "Comparison between seasonal pumped-storage and conventional reservoir dams from the water, energy and land nexus perspective," *Energy Convers. Manag.*, vol. 166, pp. 385–401, Jun. 2018, doi: 10.1016/j.enconman.2018.04.044.

[15] J. D. Hunt *et al.*, "Global resource potential of seasonal pumped hydropower storage for energy and water storage," *Nat. Commun.*, vol. 11, no. 1, Dec. 2020, doi: 10.1038/S41467-020-14555-Y.

[16] H. Chen, T. N. Cong, W. Yang, C. Tan, Y. Li, and Y. Ding, "Progress in electrical energy storage system: A critical review," *Prog. Nat. Sci.*, vol. 19, no. 3, pp. 291–312, Mar. 2009, doi: 10.1016/J.PNSC.2008.07.014.

[17] NOAA, "Climate Models | NOAA Climate.gov," 2020. https://www.climate.gov/maps-data/primer/climate-models (accessed Aug. 25, 2020).

[18] IPCC, "Summary for Policymakers — IPCC," *SPM.2.1. Key drivers of future climate*, 2014. https://ar5-syr.ipcc.ch/topic_summary.php (accessed Sep. 20, 2021).

[19] H. Hueging, R. Haas, K. Born, D. Jacob, and J. G. Pinto, "Regional changes in wind energy potential over Europe using regional climate model ensemble projections," *J. Appl. Meteorol. Climatol.*, vol. 52, no. 4, pp. 903–917, Apr. 2013, doi: 10.1175/JAMC-D-12-086.1.

[20] C. Viviescas *et al.*, "Contribution of Variable Renewable Energy to increase energy security in Latin America: Complementarity and climate change impacts on wind and solar resources," *Renew. Sustain. Energy Rev.*, vol. 113, p. 109232, Oct. 2019, doi: 10.1016/j.rser.2019.06.039.

[21] M. C. Bonjean Stanton, S. Dessai, and J. Paavola, "A systematic review of the impacts of climate variability and change on electricity systems in Europe," *Energy*, vol. 109. Elsevier Ltd, pp. 1148–1159, Aug. 15, 2016, doi: 10.1016/j.energy.2016.05.015.

[22] K. Poncelet *et al.*, "The Importance of Integrating the Variability of Renewables in Long-term Energy Planning Models." Accessed: Oct. 30, 2020. [Online]. Available: http://www.mech.kuleuven.be/tme/research/1.

[23] P. Dowling, "The impact of climate change on the European energy system," *Energy Policy*, vol. 60, pp. 406–417, Sep. 2013, doi: 10.1016/j.enpol.2013.05.093.

[24] J. Cronin, G. Anandarajah, and O. Dessens, "Climate change impacts on the energy system: a review of trends and gaps," *Clim. Change*, vol. 151, no. 2, pp. 79–93, Nov. 2018, doi: 10.1007/s10584-018-2265-4.

[25] D. Huppmann *et al.*, "The MESSAGEix Integrated Assessment Model and the ix modeling platform (ixmp): An open framework for integrated and cross-cutting analysis of energy, climate, the environment, and sustainable development," *Environ. Model. Softw.*, vol. 112, pp. 143–156, Feb. 2019, doi: 10.1016/j.envsoft.2018.11.012.

[26] J. D. Hunt *et al.*, "Deep seawater cooling and desalination: Combining seawater air conditioning and desalination," *Sustain. Cities Soc.*, vol. 74, p. 103257, Nov. 2021, doi: 10.1016/J.SCS.2021.103257.

[27] CORDEX, "WCRP CORDEX," 2020. https://cordex.org/ (accessed Nov. 13, 2020).

[28] D. P. van Vuuren *et al.*, "The representative concentration pathways: An overview," *Clim. Change*, vol. 109, no. 1, pp. 5–31, Nov. 2011, doi: 10.1007/s10584-011-0148-z.

[29] IPCC, "Climate Change 2014: Synthesis Report," *Contribution of Working Groups I, II and III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change [Core Writing Team, R.K. Pachauri and L.A. Meyer (eds.)]*, 2014. https://ar5-syr.ipcc.ch/topic_futurechanges.php (accessed Nov. 13, 2020).

[30] WMO, "WMO Guidelines on the Calculation of Climate Normals," 2017.

[31] ONS, "Páginas - Histórico da Operação," 2021. http://www.ons.org.br/Paginas/resultados-da-operacao/historico-da-operacao/intercambios_energia.aspx (accessed Sep. 27, 2021).

[32] J. D. Hunt, E. Byers, K. Riahi, and S. Langan, "Comparison between seasonal pumped-storage and conventional reservoir dams from the water, energy and land nexus perspective," *Energy Convers. Manag.*, vol. 166, pp. 385–401, Jun. 2018, doi: 10.1016/J.ENCONMAN.2018.04.044.

[33] BRASIL, "PNE 2050: Plano Nacional de Energia," Brasília, 2020. Accessed: Mar. 27, 2021. [Online]. Available: https://www.epe.gov.br/sites-pt/publicacoes-dados-abertos/publicacoes/PublicacoesArquivos/publicacao-227/topico-563/Relatorio Final do PNE 2050.pdf.

[34] PCMDI, "PCMDI - CMIP5 Overview," *CMIP5 - Coupled Model Intercomparison Project Phase 5 - Overview*. https://pcmdi.llnl.gov/mips/cmip5/ (accessed Nov. 26, 2020).