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# Seasonal pumped hydropower storage role in responding to climate change impacts on the Brazilian electrical sector

Natália de Assis Brasil Weber [a], Julian David Hunt [b,c,*], Behnam Zakeri [c], Paulo Smith Schneider [a], Fernando Sérgio Asfor Parente [d], Augusto Delavald Marques [e], Amaro Olímpio Pereira Junior [d]

[a] *Universidade Federal do Rio Grande do Sul (UFRGS), Porto Alegre, Brazil*
[b] *King Abdullah University of Science and Technology (KAUST), Thuwal, Saudi Arabia*
[c] *International Institute for Applied System Analysis (IIASA/ASA), Laxenburg, Austria*
[d] *Universidade Federal de Rio de Janeiro (UFRJ), Rio de Janeiro, Brazil*
[e] *University of Central Florida (UCF), FL, United States of America*

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ABSTRACT

Since Brazil's major energy resources are renewable and directly related to climate factors, it is among the countries most likely of being affected by climate change. Given Brazil's high hydropower storage capacity and the strong seasonal patterns of its renewable resources, introducing Seasonal Pumped Hydropower Storage (SPHS) can help mitigate these challenges. To this end, a methodology is proposed that links the dynamic system-optimization model – MESSAGEix - to regional climate model simulations, called the Brazilian Electricity System MESSAGEix Model (BESMM). This model, with its detailed hydropower representation, is capable of integrating data from three climate change scenarios with the country's energy system. Climate change introduces a new dimension to this approach, as there is evidence of increasing the seasonal imbalance of variable renewable resources in Brazil. BESMM results suggest that SPHS can play a fundamental role in achieving a 100 % renewable matrix by 2100 in RCP 2.6 scenario, as well as enhancing the renewable energy endowment in scenarios RCP 4.5 and RCP 8.5. A reduction of up to 68 % of $CO_2$ emissions is predicted in scenarios incorporating SPHS, compared to scenarios without SPHS.

## 1. Introduction

A well-designed energy storage system plays a key role in both mitigating and adapting energy systems to climate change. Effective energy storage solution can help balance energy supply and demand, reduce greenhouse gas emissions, and enhance the use of renewable energy sources [1–5]. One promising technology is Seasonal Pumped Hydropower Storage (SPHS), which has several advantages over other types of large-scale storage systems [6–8]. SPHS operates by using excess energy generated during periods of low demand to pump water to an elevated reservoir [9]. This process allows for the storage of energy on a seasonal basis, which is particularly useful for renewable energy sources that have strong seasonal patterns, such as hydropower.

The Brazilian power sector, vulnerable to the impacts of climate change [10–12], is an ideal candidate for SPHS technologies. With its significant hydropower storage capacity [13], and renewable resources exhibiting strong seasonal patterns [14]. The country is also facing challenges in balancing the supply and demand for electricity, particularly during droughts that affect the hydroelectric power plants, and introducing SPHS can help overcome these challenges.

This study aims to analyze the effectiveness of SPHS in adapting and mitigating the Brazilian Electric System MESSAGEix Model (BESMM) under climate constraints by incorporating future climate data projections into an optimized energy model. It also investigates the implications of climate change on Brazil's renewable energy, particularly wind, solar, and hydropower. Furthermore, the study delves into the characteristics, benefits, challenges, and opportunities of SPHS technology for the Brazilian electrical sector. Finally, the results will be compared with scenarios without SPHS technologies to assess the potential benefits of SPHS technology for mitigating and adapting to climate change in Brazil.

* Corresponding author at: King Abdullah University of Science and Technology (KAUST), Thuwal, Saudi Arabia.
*E-mail address:* hunt@iiasa.ac.at (J.D. Hunt).

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### 1.1. Seasonal pumped hydropower storage: addressing energy and water storage challenges

[1] defines seasonal storage as “The ability to store energy for days, weeks, or months to compensate for a longer-term supply disruption or seasonal variability on the supply and demand sides of the energy system (e.g., storing heat in the summer to use in the winter via underground thermal energy storage systems)”. The SPHS concept was first proposed by [9], to enhance energy storage by operating a pumped-storage plant on a yearly cycle instead of a daily cycle. SPHS is classified as Long-Duration Energy Storage (LDES) [15]. The main idea is to store potential energy during the wet season when there is excess flow in the river, or when there is excess energy in the grid, by pumping water to an upper reservoir. SPHS corresponds to a storage reservoir parallel to a main river, with an existing lower reservoir, as shown in Fig. 1.

SPHS reservoirs receive water from two sources: tributary river flows due to precipitation and ice melt, or pumping from lower reservoirs [16]. Integrating SPHS with cascading hydroelectric dams can enhance storage efficiency to nearly 90 %, compared to traditional pumped-storage facilities' 75 % efficiency, not accounting for reduced spillage in cascaded dams [17]. This setup allows for adjusting river basin flows for energy storage and generation, with SPHS requiring less land than conventional reservoir dams (CRD) for the same water volume, given equal river water availability. Through the storage process, the water is pushed up, increasing its potential energy, so its energy storage capacity also increases thanks to the SPHS [16].

A study comparing the water-energy-land nexus among existing and proposed CRD and SPHS reservoirs in Brazil conducted by [16] found that there are only a few suitable topographical locations with low socioeconomic and environmental impacts, and that SPHS reservoirs provide water and energy storage while reducing flooded areas and evaporative losses in locations where conventional reservoir dams are not viable. [18] in its turn found out that hybrid systems (wind-hydro) incorporating PHS initially incurs higher costs but demonstrates lower operational expenses. Moreover, both studies concluded that the optimal configuration of the PHS system necessitates a smaller flooded area compared to CRD, resulting in reduced environmental impact [16,18]. Moreover, [19] discovered that Brazil possesses significant potential for weekly, monthly, and seasonal PHS utilizing existing lower reservoirs. They further noted that PHS not only aids in developing fully renewable energy grids but also improves water security in areas where conventional dams are impractical due to difficult terrain, high evaporation rates, and sedimentation problems.

Strategically placing SPHS plants near main rivers can offer environmental benefits, requiring less land while providing similar water management and energy storage advantages as traditional dams [7]. [7], identified potential sites for SPHS plants with this characteristics globally, revealing that viable sites are confined to mountainous areas with ample water and significant hydraulic heads, making them suitable for cost-effective SPHS. Furthermore, [20] identified over 5.1 million potential projects by the SPHS world potential model, all with a 1 GW fixed generation and pumping capacity. The findings in [20] highlight that SPHS projects offer a variety of income-generating services and possess significant potential for competitive storage solutions, rivaling those of natural gas storage. Additionally, [21] emphasizes the low-cost potential for SPHS in the Indus region. Finally, the need for energy and water storage with SPHS plants should be complementary [20,21]. Otherwise, should not be considered as an energy and water storage alternative.

SPHS offers several advantages over other types of large-scale storage. For example, compared with hydrogen storage PHS showed to be superior in two key aspects: efficiency and environmental impact [23]. Compared PHS, hydrogen and compressed air storage and found out that for short-term storage and medium-term storage, PHS is the most cost-effective storage technology, closely followed by compressed air storage, and hydrogen being not cost-competitive in regard to levelized electricity costs. However, according to [24] the situation shifts when utilized for long-duration storage. In this context, PHS emerges as the most expensive form of energy storage, compressed air becomes the most preferred storage technology, with hydrogen storage following closely behind.

SPHS capability to store surplus electricity and supply it during low production periods makes an effective tool for addressing climate variability impacts and contributing to climate change mitigation in various ways: (i) SPHS provides short-term and long-term energy storage services allowing the development of 100 % renewable energy grids [20]. (ii) SPHS also increases water security in regions with unsuitable topography for conventional dams, high evaporation, and sedimentation rates [20]. (iii) The implementation of PHS/SPHS plants avoids the use of fossil fuels and, consequently, reduces greenhouse gas emissions from thermal generation [25]. (iv) The emission of $CO_{2eq}$ in SPHS is lower than CRD due to the smaller size of the reservoirs. In addition, PHS/SPHS installation can use existing reservoirs, whether from traditional hydroelectric plants or other uses [25]. (v) In this way, PHS can assist in GHG emissions mitigation strategies in the Brazilian electricity sector, both directly, due to their production with low levels of

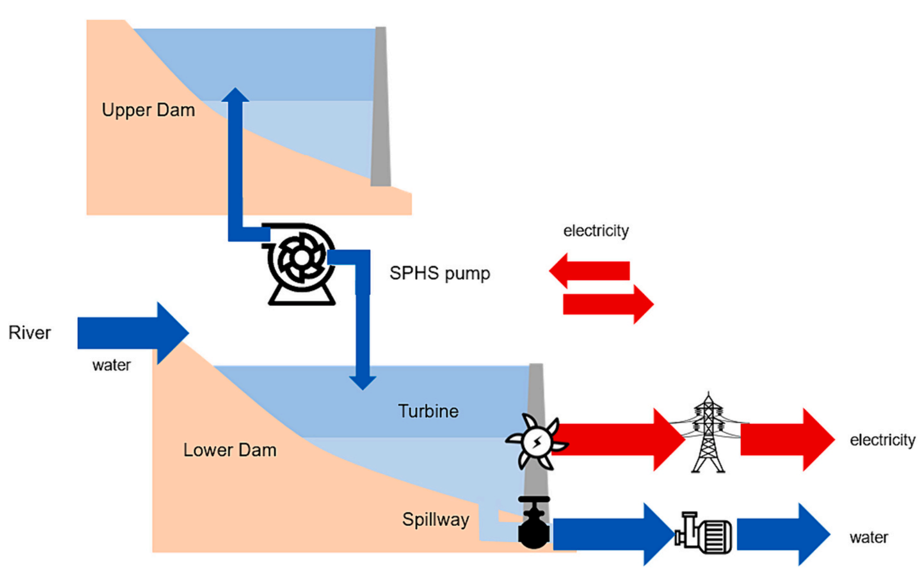


**Fig. 1.** SPHS plant representation with main components.

**Table 1**
Summary of climate change impacts on the Brazilian electrical system.

| | Source | Energy asset | Direction of change | Magnitude of change |
|---|---|---|---|---|
| 1 | Lucena et al. [31] | Hydro and liquid biofuels | Decrease in water availability for North, Northeast and Central regions, in the South-Southeast the impacts are not significant. | By 2100 an increasing vulnerability of the poorest regions, a reduction in biofuel and electricity production in these regions may also suffer [A2 and B2]. |
| 2 | Lucena et al. [32] | Wind | Increase in average wind velocities in the coastal regions in general and in the north/northeast regions. | By 2100 wind power generation potential could have a threefold increase [B2]; and a four-fold increase [A2] as compared to the reference situation of today. |
| 3 | Pereira et al. [33] | Wind | Increase tendency for wind power density in Northeast except for the state of Bahia, and a mild increase in the South region. | By 2100 from +15 % to +30 % in the wind power density in Northeast; and, from +10 % to 20 %, in the South region [A1B]. |
| 4 | Scianni et al. [34] | Hydro | Decrease trend for hydropower production. | By 2040–1.4 % in assured energy [A1B]. |
| 5 | de Queiroz et al. [35] | Hydro | Decrease for hydropower production for all regions except the South region with significant increase. | By 2100 −10.6 % for existing generation system, and −23.6 % for future generation system [A1B] |
| 6 | Invidiata et al. [36] | Demand | Increase in demand for all studied climatic zones (ZB2, ZB3, ZB8). | By 2020 from +19 % to +65 % in annual energy demand; by 2050, from +56 % to 112 %; and, by 2080, from 112 % to 185 % [A2]. |
| 7 | Bierhals et al. [37] | Solar | Decrease in solar radiation potential in most regions. | By 2100 −12 % in the eastern region of the state in the worst case [RCP 8.5]. |
| 8 | de Oliveira et al. [38] | Hydro | Decrease in the mean monthly streamflow for all models and scenarios. | Between 2071 and 2099 −66.1 % for Itutinga hydropower [Eta-HadGEM2-ES RCP 8.5], and −30.7 % of energy production at Funil hydropower plant [ETA-MIROC RCP 4.5]. |
| 9 | Ruffato-Ferreira et al. [30] | Hydro and wind | Decrease in water availability for almost regions and increasing trend in total wind speed. | By 2040 an increasing trend in total wind speed for Northeast, North and South regions. By 2100 water scarcity for almost the entire territory, especially in the central region [RCP 4.5 and 8.5]. |
| 10 | Lucena et al. [12] | Hydro and demand | Decrease for hydropower production and increase for demand for most models. | By 2050 −12 % [RCP 8.5], and −9 % [RCP 4.5] for GFDL; By 2050 −1.5 % [RCP 8.5], and −0.3 % [RCP 4.5] for CESM, of available hydropower generation to meet Brazil's power needs in 2050. |
| 11 | de Jong et al. [39] | Wind and solar | Increase across most regions. | By the 2080s for solar radiation an average of +3.6 % in Northeast and +2.5 % in Southeast; wind speed an average of +7.0 % in Northeast and −0.2 % in South [RCP8.5]. |
| 12 | de Queiroz et al. [29] | Hydro | Decrease in water availability for almost regions. | By 2100 + 35 % South region, and −35 % in North and Northeast region for assured energy [A1B]. |
| 13 | da Silva et al. [40] | Hydro | Decrease in annual naturalized streamflow and Affluent Natural Energy (NEA) | By 2099 up to −10 % of annual streamflow rates and NEA in North and Southeast/Midwest sectors [RCP 4.5 and 8.5]; By 2039 up to +5 % of annual naturalized streamflow and NEA in South sector [RCP 4.5 and 8.5]. |
| 14 | Zuluaga et al. (2022) | Solar | With solar radiation brightening concentrated in the North region and dimming located mainly in the Southeast and Midwest regions. | The regions with the highest annual PPV are NE, CW, and SE (>1400 kWh/m2 year), mainly between July and January (>110 kWh m2 month). |
| 15 | Michels-Brito et al. [41] | Hydro | Streamflow reduction in all sub-basins. For the dry season, precipitation in the basin also diminishes under both RCPs and for both models. RCP 8.5 results in the most extreme reductions in both projections. | By 2099, projections indicate significant reductions in river flow for the Belo Monte hydropower plant. Under the RCP 4.5 scenario, the reductions are estimated at approximately 42 % for Eta-MIROC5 and 27 % for Eta-HadGEM2-ES. In the more extreme RCP 8.5 scenario, these reductions increase to 58 % for Eta-MIROC5 and 64 % for Eta-HadGEM2-ES. Specifically, during the wet season, which is crucial for the Belo Monte HPP's productivity, the reductions can reach up to 34 % in the Eta-MIROC5 projections and 20 % in the Eta-HadGEM2-ES projections. |
| 16 | da Silva et al. [42] | Hydro | The CanESM5 and IPSL-CM6A-LR models, for example, signalled that most reservoirs might present negative trends for all the analyzed subsystems and scenarios, while the MIROC6 and MRI-ESM2–0 models signal positive trends. | Affluent Natural Energy (ANE) results South 20 % increase ANE with the MIROC6 and MRI-ESM2-0 models; Northeast reduction indicated reductions in the average annual anomalies of the ANE of <10 %. Southeast: anomalies below 5 % in both scenarios for near future and 5 and 25 %. to 2090 decade; North: values ranging from 5 to 25 %. |
| 17 | Mello et al. [43] | Hydro | A noticeable reduction in precipitation was identified in the wet season, especially in the 2007–2040 period for RCP4.5 and in the 2071–2099 period for RCP8.5. | Climate Change Impacts on Water Resources of the Largest Hydropower Plant Reservoir in Southeast Brazil. |

emissions, and indirectly, by favoring the use of variable renewable sources, such as wind and solar.

The Brazilian power sector is facing challenges in terms of balancing the supply and demand of electricity, particularly during droughts which affect the hydroelectric power plants, and introducing SPHS can help to mitigate these challenges. The construction of SPHS plant in Brazil has been investigated with a dispatch model (PLEXUS) and showed significant benefits [26]. However, this paper is the first to investigate the impact of SPHS with a long-term energy planning model in Brazil. SPHS stands out as a mature, land-efficient, low-GHG storage solution, cost-effective compared to other long-term storage options, and adept at managing renewable energy's seasonal shifts.

### *1.2. Climate change impact on renewable energy production in Brazil*

Brazil has one of the most renewable energy matrices in the world. In 2022, 87.9 % of the electricity was generated from renewable sources [28]. This makes Brazil particularly susceptible to the impacts of climate change. Studies have shown varying effects on renewable energy sources across different regions (Table 1). Concerning hydropower, most studies project water scarcity for the entire territory, except for the South region, which sees an increase in subsystem assured energy [29,30]. In contrast, wind power shows an increasing trend in wind speed or power density in regions with existing wind power infrastructure, such as the Northeast and South, while other regions see insignificant changes. Climatically driven energy demand is on the rise due to increasing temperatures. Biofuel production is decreasing in the North, Northeast,

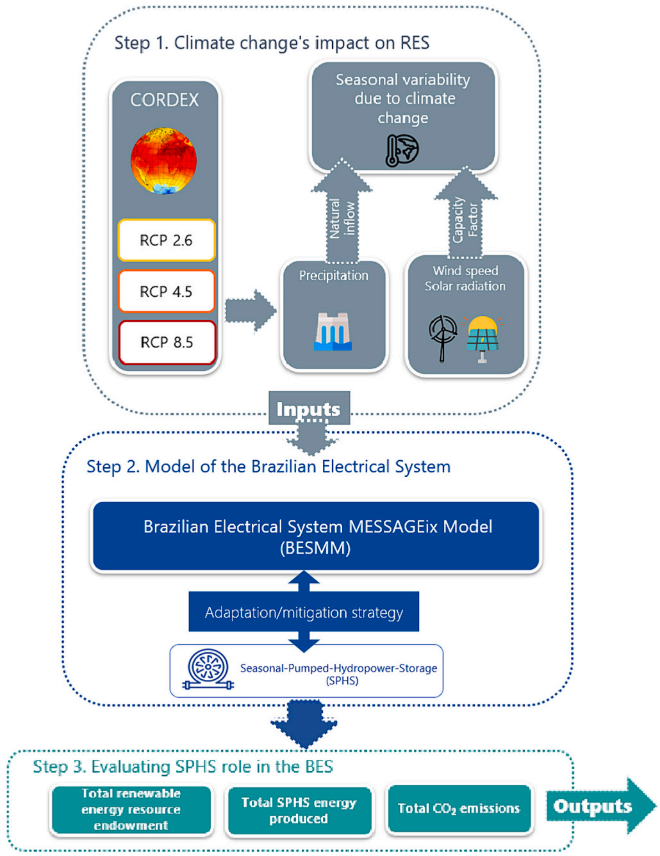


**Fig. 2.** Methodology framework to assess the role of SPHS technology on the Brazilian electricity system due to impact of climate changes.

and Midwest regions, with only one study found in the review. Solar energy, addressed in two studies, shows an increasing trend in surface solar radiation across all Brazilian regions except the South.

Highlighting that the trends and directions should be more emphasized rather than precise results, due to the number of uncertainties of General Circulation Models (GCM) [31,35,44].

## 2. Methodology

The foundation methods addressed are those related to simulations of future energy supply and demand (MESSAGEix) and climate change projections (CORDEX). These methods are combined in a particular way to allow integrating SPHS technologies with the seasonal variability of renewable sources to the Brazilian electrical system model in light of climate change. The novelty of this approach includes the development of an energy system model that optimizes the SPHS technology with the seasonal variability of renewable sources for three climate change scenarios. Additionally, a new detailed hydropower representation was defined for the SPHS implementation on the BESMM. Climate change adds a new dimension to this approach as it has evidence of increasing the seasonal imbalance of variable renewable resources in Brazil. Fig. 2 shows the building blocks of the proposed framework to assess the role of SPHS plants in solving the seasonal imbalance of the Brazilian electricity system under climate change constraints.

### *2.1. Step 1: climate change's impact evaluation on renewable energy sources*

Step 1 involves the methodologies applied to convert climate projections into inputs for the MESSAGEix model of the Brazilian electrical system, incorporating the concept of climate constraints. These constraints are based on updated values for wind and solar power capacity factors, and water inflow, as informed by climate change models, ensuring the model operates within the parameters defined by these climate predictions. This study used Regional Climate Model (RCM) data downscaled through the 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). Then, the CORDEX data was delimited by the Brazilian territory coordinates. The analyzed period is between the years 1971 to 2099 (wherein the period 1971–2005 corresponds to the historical data and from 2006 to 2099 corresponds to the future projections). Three variables from the CORDEX SAM44i were used in this research: precipitation (pr), near-surface (10 m) winds (sfcWind), and surface solar radiation (rsds). Surface solar radiation can also be known for its long name: surface downwelling shortwave flux in air, and its unit is (W $m^{-2}$).

Climate projections consider scenarios related to human activities as well as GHGs emissions, and it involves a number of uncertainties [45]. These projections cannot be taken as a definitive basis for predicting the future, but they are indicatives of a certain lifestyle in the future. Therefore, these projections are considered the most reliable sources of information currently available for developing mitigation and adaptation strategies [46]. In this study three emissions scenarios based on RCM were used to compose four different 21st century pathways of GHG emissions and atmospheric concentrations, air pollutant emissions and land use. RCP 2.6 is a stringent mitigation scenario, RCP 4.5 and RCP 6.0 are intermediate ones and RCP 8.5 is a very high GHG emissions scenario [47].

The overall objective of this step was to prepare the CORDEX

**Fig. 3.** Location of existing wind power plants used to calculate de wind power production [adapted from Aneel, 2022].

**Table 2**
Selected wind farms to be simulated under climate change scenarios.

| Region | Wind farm locations | Name | Capacity |
|---|---|---|---|
| Northeast onshore | Marcolândia - PI | Chapada Piauí | 205.1 MW |
| Northeast coast | Itarema - CE | Complexo Eólico Pedra Cheirosa | 48.3 MW |
| South | Osório - RS | Complexo Eólico Osório | 375.4 MW |

variables for the wind power, solar power, and hydropower simulation on MESSAGEix. An estimation of solar power and wind power was carried out at specific locations where power generation infrastructure has been established to quantify the change in yield. For hydropower sources, a top-down methodological approach was followed to transform precipitation data into water inflow for 12 equivalent reservoirs. The next subsections detail each approach carried out in this research.

#### *2.1.1. Wind power*

With the Northeast onshore and offshore, and the South as the regions with the greatest potential for wind energy, three specific locations in those regions were selected for future energy production calculations [48,49]. Based on current technologies for using wind turbines positioned at a height of 100 m, the Brazilian onshore wind potential could reach 880.5 GW, of which 522 GW are considered technically feasible and 309 GW for the Northeast Region alone [50]. Overall wind offshore potential in Brazil is 620 GW, for 100 m hub height, in which 370 GW it

**Fig. 4.** Location of existing solar power plants used to calculate solar power production [adapted from Aneel, 2022].

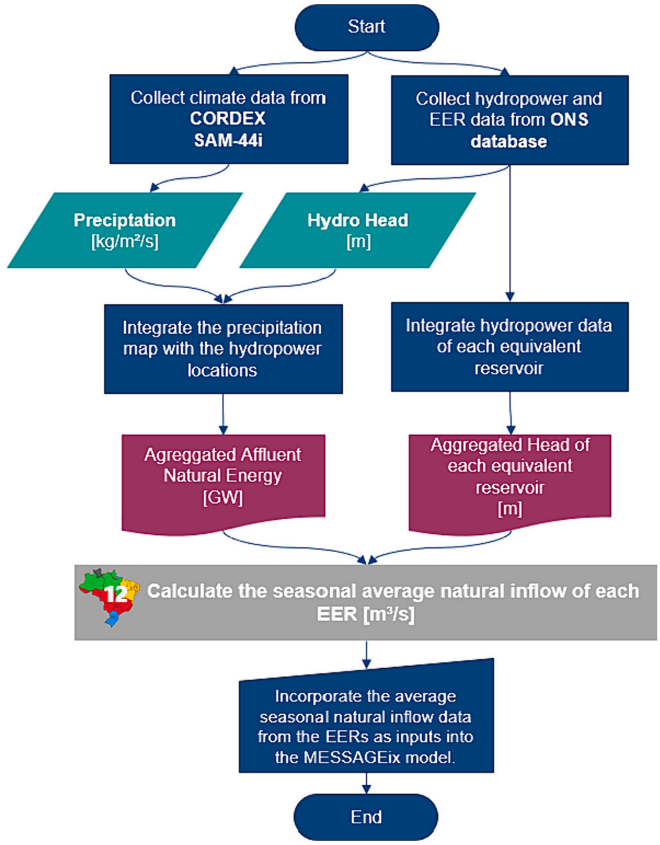


**Fig. 5.** Hydropower representation methodology flowchart.

is located in the Northeast region [48]. South region has also a large wind potential with an onshore installable capacity of 103 GW at 100 m height (in places with speeds averages >7.0 m/s) [51]. Fig. 3 shows the location of the three spots used to simulate wind energy production for different climate change scenarios.

These 3 specific locations were chosen based on three main criteria: location, installed capacity, and the available data regarding energy production. Table 2 details the selected wind farms with the highest installed capacity and at least one year of energy production data.

Wind speed $U$ (m/ s) for 100 m hub height was calculated using CORDEX data of surface wind velocities from 10 m ($z_r$) to the hub height 100 m ($z$) through the power law as presented in Eq. (1):

$$\frac{U(z)}{U(z_r)} = \left(\frac{z}{z_r}\right)^{\alpha} \tag{1}$$

where Alfa ($\alpha$) is the roughness length, and the power-law exponents of 0.2 mm are used in this study, which correlates to a neutral atmosphere on onshore areas [52,53].

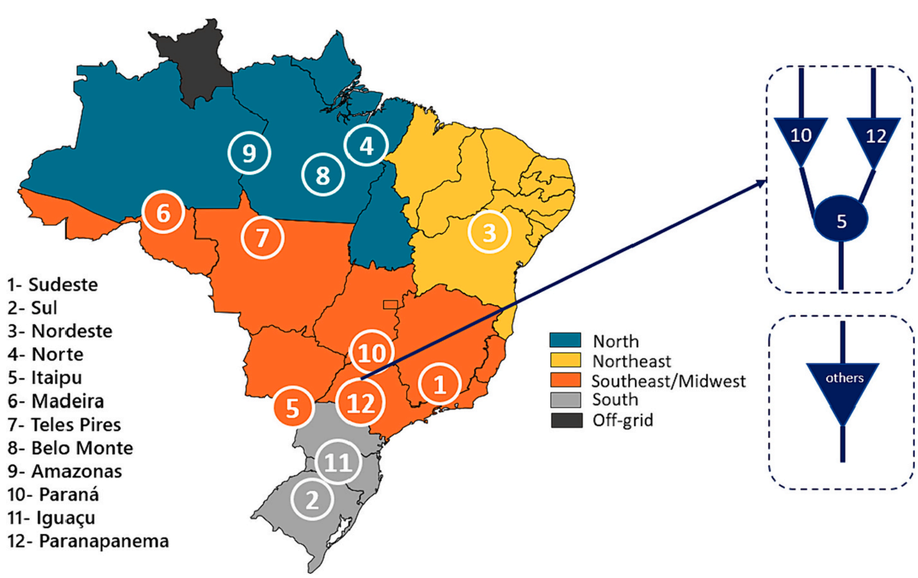


**Fig. 6.** Location of the 12 equivalent reservoirs which aggregates approximately 123 hydropower plants.

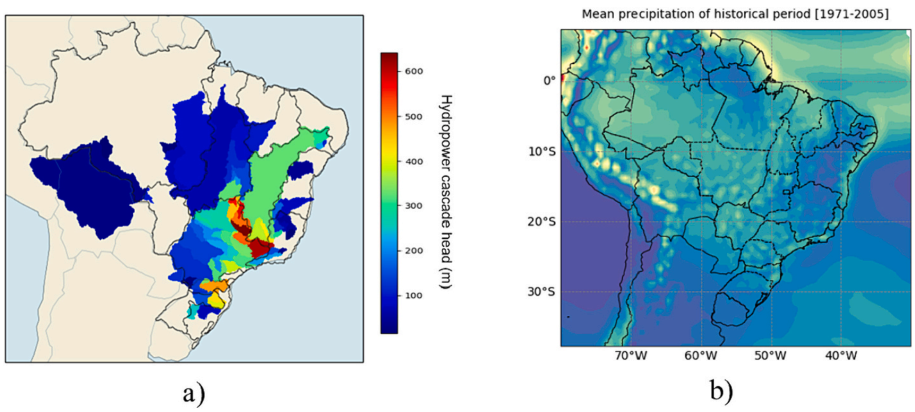


**Fig. 7.** Hydropower potential in Brazil measured by hydropower cascade head.

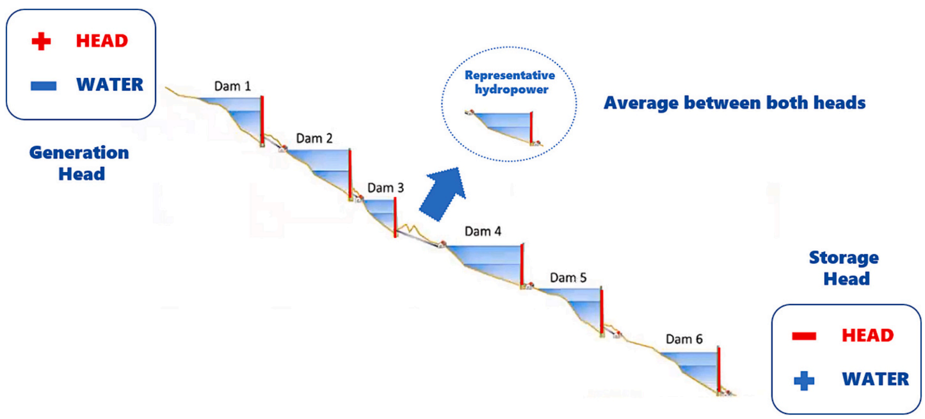


**Fig. 8.** Aggregation head method of each equivalent reservoir.

**Table 3**
EER reservoirs, dam capacity, equivalent head and installed capacity.

| REE | | Reservoirs | Dam capacity [km$^3$] | Equivalent head [m] | Installed capacity [GW] |
|---|---|---|---|---|---|
| 1 | Sudeste | Paraíba do Sul. Doce. Jequitinhonha. Paraguai. Tocantins | 54.8 | 235.3 | 6.4 |
| 2 | Sul | Uruguai. Jacuí | 8.5 | 315.8 | 6.9 |
| 3 | Nordeste | São Francisco | 58.3 | 267.6 | 8.3 |
| 4 | Norte | Tocantins | 39.0 | 72.7 | 9.6 |
| 5 | Itaipu | Paraná | 0 | 117.0 | 14.0 |
| 6 | Madeira | Amazonas | 2.8 | 363.3 | 7.3 |
| 7 | Teles Pires | Amazonas | 2.1 | 94.0 | 3.2 |
| 8 | Belo Monte | Amazonas | 0.4 | 87.2 | 11.0 |
| 9 | Amazonas | Amazonas. Araguari | 10.4 | 84.4 | 1.2 |
| 10 | Paraná | Paranaíba. Grande. Paraná. Tietê | 111.5 | 202.0 | 27.6 |
| 11 | Iguaçu | Iguaçu | 8.6 | 202.1 | 7.3 |
| 12 | Paranapanema | Paranapanema | 11.9 | 112.7 | 2.4 |
| Total | | | 308.4 | | 105.2 |

**Table 4**
IAV variation categories by the range of variation [Adapted from Hofste et al., 2019].

| IAV value | Category |
|---|---|
| <0.25 | Low |
| 0.25–0.50 | Low-medium |
| 0.50–0.75 | Medium-high |
| 0.75–1.00 | High |
| >1.00 | Extremely high |

Energy production was estimated using the Virtual Wind Farm (VWF) model [54] with hourly data from MERRA-2 by means of a linear correlation of the average wind energy production and the average wind speed on monthly basis, due to the lack of hourly available data. Hourly wind speed for the year 2019, considering the hub height of 100 m and the use of the power curve of the wind turbine Vestas (V90) with 2.0 MW of capacity [55].

### *2.1.2. Solar power*

Unlike other energy sources, solar energy has its resource dispersed relatively homogeneously across the national territory and the availability of the primary resource is infinite [56]. Thus, all the Brazilian regions were considered, except the Northwest region as it encompasses several conservation units, indigenous lands, quilombo communities, areas of permanent preservation, among others.

The future solar energy production was calculated using a linear correlation between the monthly average solar energy production and the monthly average solar radiation measured as (W mˆ(−2)), based on hourly data from MERRA-2 and using the Global Solar Energy Estimator (GSEE) [57], as formerly performed to wind energy production. Hourly solar radiation for the year 2019 was employed considering a system loss

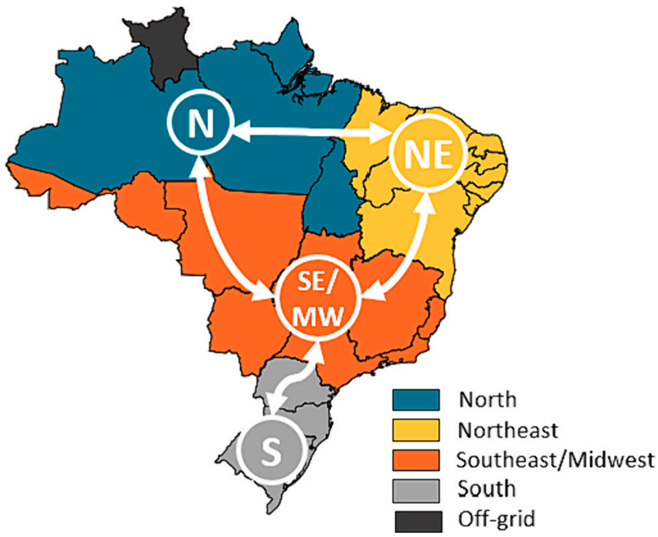


**Fig. 9.** Brazilian electrical system regions representation in 4 nodes: North node (N); Northeast node (NE); Southeast/ Midwest node (SE/MW); South node (S).

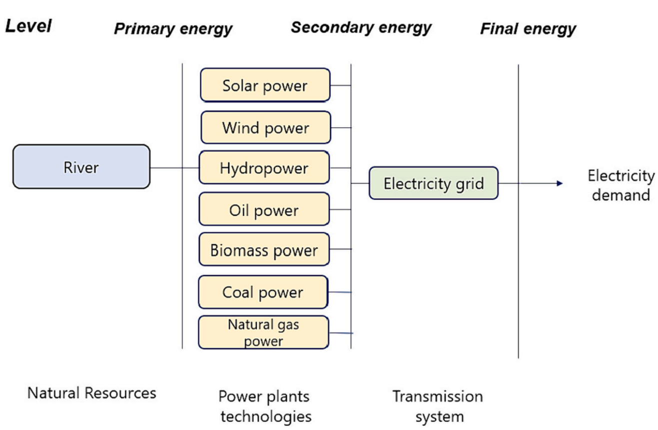


**Fig. 10.** BESMM technologies and levels of energy conversion.

fraction of 0.1, a tracking system with 1 axis (azimuth), the azimuth angle 180°, and the tilt angle specific for each location (see Appendix A[1] for correlations). Fig. 4 shows the location of the four spots used to simulate solar energy production for different climate change scenarios.

### 2.1.3. Hydropower

A top-down approach was followed to estimate climate change impacts on hydropower production, considering the importance and complexity of hydropower generation in the Brazilian electrical system, two main objectives were set for this approach: to prepare the CORDEX data for MESSAGEix hydropower simulation and to make the model available on GitHub[2] to support the development of new research. The novelty of this approach is to use only open-source tools such as python and open-source data. The method involves an aggregation method, which integrates climate data with the mapped location of hydropower plants to determine the seasonal natural inflow, as shown in Fig. 5.

The method aggregates data from 123 active hydropower plants into 12 equivalent reservoirs, a strategy utilized by the ONS for predicting the extended operation of Brazil's interconnected electricity system. Illustrated in Fig. 6, the spatial layout of the 12 equivalent reservoirs is depicted, with reservoirs 10, 12, and 5 specifically modeled in a cascading sequence, in contrast to the others modeled as single units with comparable features..

The aggregation process allowed us to obtain the seasonal natural inflow of each equivalent reservoir, which is the input of the technology river[3] in MESSAGEix, performed in two steps. First, the aggregated Natural Energy Inflow was estimated and then the aggregated head of each equivalent reservoir. To determine the Natural Energy Inflow, it was made a link between a map with the potential of the electric energy generation measured by the hydropower head (Fig. 7a) with the precipitation data from CORDEX (Fig. 7b). For example, the map in Fig. 7a shows if the precipitation happens in the red area, it will have a great amount of electricity generation, because it has around 600 m of hydropower head. This implies that there are several dams in cascade in this area, and the cumulative head of all cascades is 600 m. Therefore, to estimate the historical and future Natural Energy Inflow, historical data from CORDEX from 1971 to 2005 (Fig. 7b) and future data from 2006 to 2099 were utilized.

The second aggregation aimed to identify the head of each equivalent reservoir, crucial for determining hydropower generation based on dam height. For instance, a head of 117 m can generate nearly 1 GWa for every 1000 $m^3s^{-1}$. To accurately represent the 126 hydropower sources within the 12 equivalent reservoirs, we averaged the heads, considering both the storage capacity and generation potential of each basin. When the storage and generation heads were similar, we averaged them; otherwise, we used the run-of-the-river head. This approach was chosen because storage head has minimal impact on dam operations but significantly influenced the representative hydropower head. After calculating both heads, we employed a heuristic method to merge them based on basin characteristics, ensuring a balanced representation of generation and storage capacities within the equivalent reservoirs. This process is illustrated in Fig. 8.

In this approach the storage and installed capacities for each equivalent reservoir are determined by summing up the respective capacities of all hydropower plants within the reservoir (in Table 3 labelled as dam capacity and installed capacity respectively). Table 3 presents the values for three key parameters of the 12 Energy Equivalent Reservoirs (EER), derived from aggregating data across 123 hydropower plants.

The total installed capacity was 105.2 GW for a dam capacity of 308.4 $km^3$. The water inflows were bias corrected by comparing them with historical data, as explained in detail in Appendix C.

### 2.1.4. Selection of year case: inter-annual variability

Our methodology for incorporating climate change effects into the BESMM involved selecting optimal year cases to simulate climate impacts on seasonal renewable energy generation. We identified the year with the highest Inter-Annual Variability (IAV) for each decade from 2020 to 2100. Utilizing IAV allowed us to pinpoint years with marked seasonal energy supply differences, providing a strategic basis for anticipating and preparing for future variability in energy resources. Selecting years with the greatest IAV as our case studies inherently aligns with a precautionary principle aimed at ensuring resilience in the face of climate unpredictability. By focusing on these worst-case scenarios, we underscore the necessity for robust infrastructure capable of withstanding the diverse and dynamic impacts of climate change.

The Inter-Annual Variations IAV is a parameter that allows for identifying fluctuations in climate from year to year, and it can indicate the physical risk of a resource, calculated by Eq. (2).

[1] All appendixes are available at https://github.com/natiweber/BESMM.

[2] All the python documents are available at https://github.com/natiweber/BESMM.

[3] To model a river using MESSAGEix is necessary to create a technology that simulates a river. This technology will provide water to the hydropower system. See Fig. 10 which shows the BESMM representation on MESSAGEix.

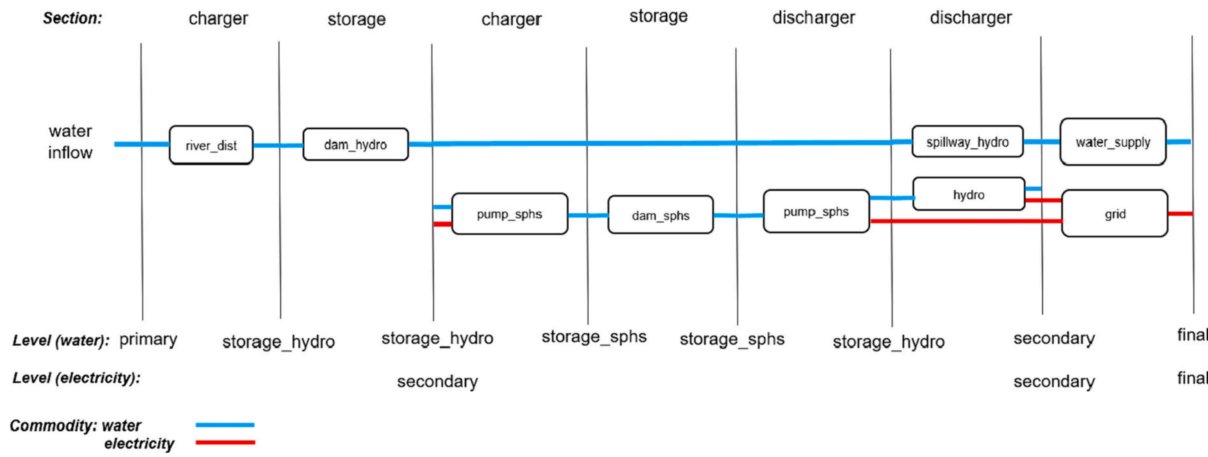


**Fig. 11.** SPHS flow representation indicates the flow of information designed on MESSAGEix. In this representation: the section refers to the different stages of the storage model; the level indicates the exchange levels throughout the storage process until they reach the final level (the consumer); The commodity refers to the commodities involved in this storage model.

$$IAV = \frac{\sigma(G_{e,y})}{\sum_{y}^{h} G_{e,y} \Big/ h} \tag{2}$$

where, $G_{e,y}$ is the yearly mean energy production of each grid cell ($e$) in a year ($y$), $\sigma(G_{e,y})$ is the standard deviation of $G_{e,y}$; and $\sum_{y}^{h} G_{e,y}/h$ is the mean value of $G_{e,y}$ [Hofste et al., 2019]. As higher IAV values are, the wider variations in available supply from year to year can be expected. IAV results can be categorized by the range of variation as described in Table 4, which makes it easier to understand and compare the magnitude of the variability of the analyzed data.

Eq. (2) was applied to calculate the average between-year variability of the wind power, solar power, and hydropower production of all studied locations described in subitem 2.1.3. Further on, a weighted average of the IAV of every location was used to select the year with the highest IAV of each decade. Future projections in the BESMM model are based on 2019 as the historical year and a 10-year horizon from 2020 to 2099. This means that for every decade from 2020 up to 2099, the season capacity factors of wind and solar power, and water inflow, were based on the selected years with the highest IAV. These values were then used as inputs for the BESMM designed using MESSAGEix.

### 2.2. Step 2: model the Brazilian electric system on MESSAGEix

In this study, a BESMM representation was developed using MESSAGEix as a technology-based model, focusing on the integration of SPHS technologies under climate change constraints. The BESMM output includes the least-cost portfolio of technologies to meet future electricity demand from 2019 (the actual system) to 2099, with a 10-year interval. Although 2099 may seem distant, considering the average lifetime of a hydroelectric plant exceeds 50 years, this timeframe is deemed adequate. All BESMM inputs are described in Appendix B.

The Brazilian electrical generation is a hydro-thermal-wind based system, for which the hydroelectric plants are responsible for most of the generation, with >60 % of the installed capacity [28]. These plants are scattered in 16 hydrographic basins in different regions and fully integrated country wide by the SIN system, organized in 4 subsystems, namely: North, Northeast, Southeast/Midwest, and South. BESMM follows the same SIN structure and electricity is exchanged between the subsystems North-Northeast, Southeast/Midwest-Northeast, and Southeast/Midwest-South [58], which constitute the nodes presented in Fig. 9.

The next step of the MESSAGEix representation was to set up the levels, resources and technologies which configure the Brazilian electricity system, as presented in Fig. 10.

The implementation of SPHS in MESSAGEix was built based on the Central Asian energy-water model, as presented by [59], who were the first in introducing the conceptual representation of storage systems in MESSAGEix. This included the mathematical formulation for storage and the structuring and implementation of sub-annual time slices in the model. This study enhances the model by incorporating a detailed, aggregated representation of hydropower, allowing for the equal consideration of both generation capacity and storage capacity for each EER. The existing hydropower and storage potentials are converted into an equivalent head in the BESMM model, as illustrated in Fig. 8. Furthermore, Fig. 11 shows the technologies, levels, and commodities employed to model the SPHS in MESSAGEix.

### 2.3. Step 3: evaluating SPHS role in the BESMM through scenario analysis

This step of the methodology has the objective to assess the impact of SPHS on the seasonal energy availability of the Brazilian electricity system under climate change constraints. To do so, the MESSAGEix portfolio's solution for each Regional Climate Model RCM was analyzed with and without the use of SPHS, based on the total renewable energy resource endowment, total GHG emissions, and total SPHS activity.

## 3. Results

### 3.1. Selection of the year case

An analysis of the IAV (subitem 2.1.4) in energy production from renewable resources was conducted from 2020 to 2099 to identify the year case with the highest IAV for each decade and scenario at the selected locations. The energy production estimates were based on the correlation of hourly values as detailed on Appendix A,[4] utilizing data from CORDEX RCP 4.5. This method was selected to identify the years with the highest IAV, highlighting the annual natural climate variations. Fig. 12 displays the IAV analysis results, with the years selected for each decade marked in red.

Consequently, for each decade spanning from 2020 to 2099, the year exhibiting the highest IAV was chosen as the representative climate value for that period. The final decade (from 2091 to 9099) had the highest IAV at 0.76. Table 5 provides a summary of the years selected for

[4] All appendixes are available at https://github.com/natiweber/BESMM.

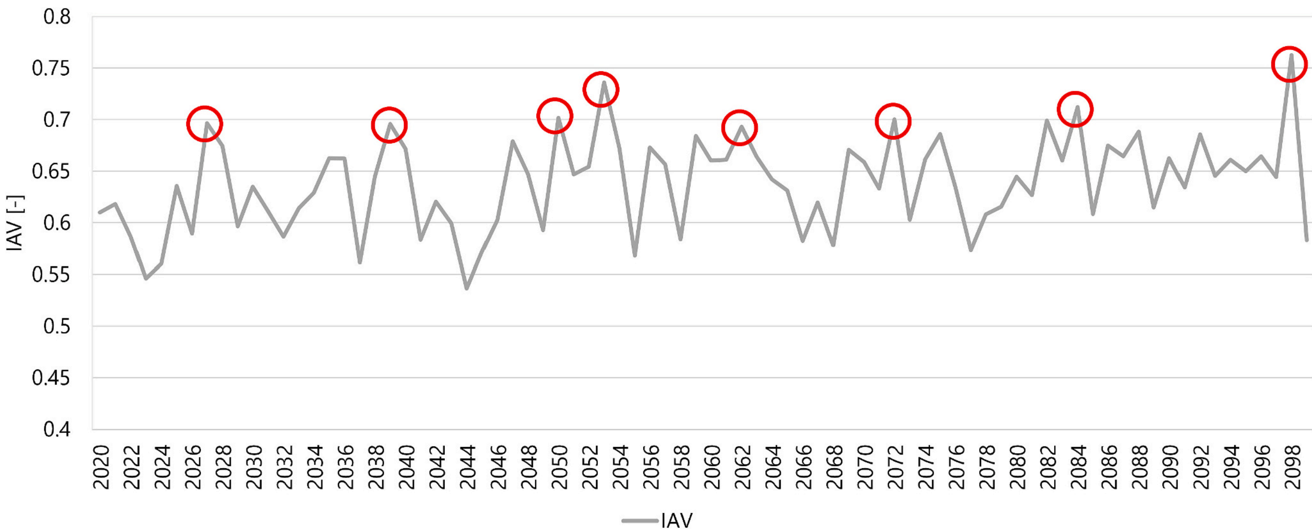


**Fig. 12.** Inter-Annual Variation IAV from 2020 up to 2099 with selected years highlighted.

**Table 5**
Selected years per decade, IAV and IAV category.

| Decade | Selected years | IAV [−] | IAV category |
|---|---|---|---|
| 2021/2030 | 2027 | 0.70 | Medium-high |
| 2031/2040 | 2039 | 0.70 | Medium-high |
| 2041/2050 | 2050 | 0.70 | Medium-high |
| 2051/2060 | 2053 | 0.74 | Medium-high |
| 2061/2070 | 2062 | 0.69 | Medium-high |
| 2071/2080 | 2072 | 0.70 | Medium-high |
| 2081/2090 | 2084 | 0.71 | Medium-high |
| 2091/2099 | 2098 | 0.76 | High |

every decade along with their respective IAV.

These results indicate that the 2050s and 2090s were the decades with the highest IAVs, which means that in those periods there is a higher difference between seasons. Among the selected years, 2098 had the highest IAV. In this year, hydro resources were higher in all seasons, in the Southeast/Midwest region, followed by the lowest wind power resources in the Northeast onshore in all seasons as well, as shown in Appendix D.[5]

### 3.2. BESMM model: scenario comparison

The three future climate change scenarios are RCP 2.6, RCP 4.5, and RCP 8.5[6] were simulated by the BESMM model. MESSAGEix provided the projected future of the electricity supply matrix by means of optimization defined in [60]. Climate variables were incorporated into the BESMM model by using inputs from CORDEX data for solar radiation, wind speed, and precipitation. Subsequently, the values of climate variables were converted into seasonally adjusted capacity factors for solar and wind power for the chosen year, with all results detailed in Appendix D. Results were assessed in respect to the total SPHS activity, the renewable energy endowment and the total GHG emissions. Fig. 13 shows the average of the total SPHS activity of RCP 2.6, 4.5, and 4.5 scenarios for the BESMM. Among these scenarios, RCP 8.5 exhibited the most significant activity throughout the years. Between 2080 and 2100, there was a 4.5-fold rise in SPHS activity within the framework of scenario RCP 8.5.

Fig. 13 illustrates that the trend of SPHS activity from RCP 2.6 to RCP 8.5 does not follow a high-to-low pattern. This irregularity is primarily due to reduced water inflow in the EER Paraná region during RCP 4.5, as detailed in Appendix D (Fig. D-26). The diminished water availability in the EER Paraná, a critical reservoir within the Brazilian energy system, results in decreased SPHS activity, positioning RCP 4.5 as the scenario with the lowest SPHS activity. This outcome underscores the significant influence of selecting years with the highest IAV on the study's findings. By not averaging climate values over decades, the results are not

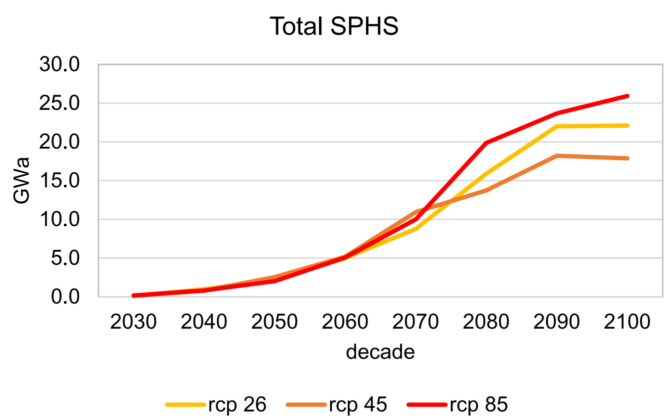


**Fig. 13.** Average of the total SPHS activity of RCP 2.6, 4.5, and 4.5 scenarios for the BESMM.

**Table 6**
SPHS capacity by EER and RCP scenario necessary to adapt the BESMM under climate change constraints.

| Region | EER | RCP 2.6 [GW] | RCP 4.5 [GW] | RCP 8.5 [GW] |
|---|---|---|---|---|
| | SPHS North | 5.0 | 5.0 | 5.0 |
| | SPHS Belo Monte | 5.0 | 5.0 | 5.0 |
| North | SPHS Amazonas | 3.0 | 3.0 | 3.0 |
| Northeast | SPHS Northeast | 10.0 | 10.0 | 10.0 |
| | SPHS Southeast | 10.0 | 10.0 | 10.0 |
| | SPHS Paraná | 15.0 | 15.0 | 15.0 |
| | SPHS Paranapanema | 3.0 | 3.0 | 3.0 |
| | SPHS Madeira | 0.0 | 0.0 | 0.0 |
| Southeast/Midwest | SPHS Teles Pires | 5.0 | 5.0 | 5.0 |
| | SPHS Iguaçu | 10.0 | 10.0 | 10.0 |
| South | SPHS South | 3.7 | 10.0 | 7.35 |

[5] All appendixes are available at https://github.com/natiweber/BESMM.

[6] Detailed results by RCP scenario are on 'Appendix E' available at https://github.com/natiweber/BESMM.

**Table 7**
Order of SPHS development and costs by EER and RCP scenario.

| Order | Region | EER | RCP 2.6 | RCP 4.5 | RCP 8.5 |
|---|---|---|---|---|---|
| | | | [million $/year][a] | | |
| 1 | Northeast | SPHS Northeast | 148 | 148 | 148 |
| 2 | South | SPHS Iguaçu | 148 | 148 | 148 |
| 3 | Southeast/Midwest | SPHS Paraná | 221 | 221 | 221 |
| 4 | South | SPHS South | 55 | 148 | 109 |
| 5 | Southeast/Midwest | SPHS Southeast | 148 | 148 | 148 |
| 6 | North | SPHS Amazonas | 44 | 44 | 44 |
| 7 | Southeast/Midwest | SPHS Teles Pires | 74 | 74 | 74 |
| 8 | North | SPHS North | 74 | 74 | 74 |
| 9 | | SPHS Belo Monte | 74 | 74 | 74 |
| 10 | Southeast/Midwest | SPHS Paranapanema | 44 | 44 | 44 |

[a] The values are the average of 2030–2100.

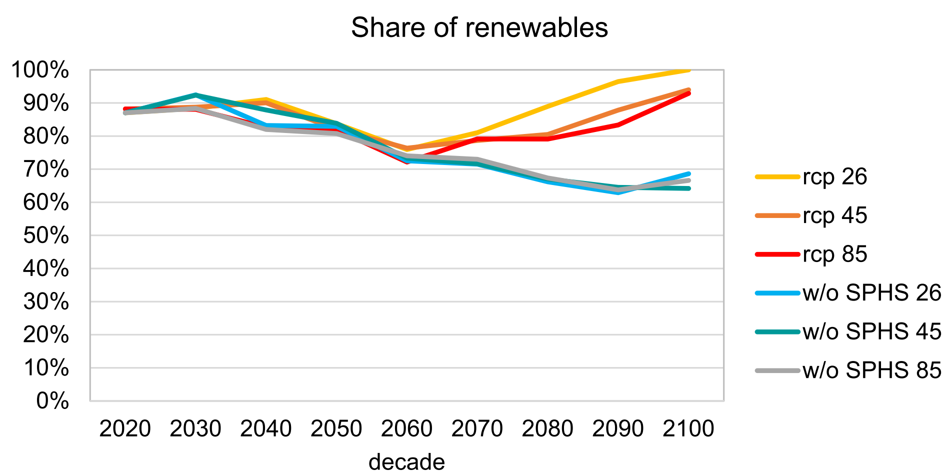


**Fig. 14.** Renewable energy endowment for scenarios with and without SPHS from 2019 up to 2100.

monotonic, highlighting how different factors affect the BESMM.

The comprehensive data in Table 6 summarize the SPHS capacities across all regions and within each EER for every RCP scenario. These findings provide valuable insights into the requisite SPHS infrastructure to effectively adapt the BESMM under diverse climate change scenarios. These results can be used to inform policy decisions related to SPHS investments and resources. In essence, the insights derived from Table 6 provide a nuanced understanding of the spatial and scenario-specific requirements for SPHS, empowering decision-makers to formulate policies that align with the evolving needs of the energy landscape. The highest SPHS capacity needed among all scenarios and regions is in the Southeast/Midwest region for RCP 8.5 scenario, 33GW in total. The scenario with the highest need for adaptation was RCP 4.5, 76.0 GW.

Based on the BESMM findings, the sequence of development should adhere to the order presented in Table 7. The most critical project is the SPHS in the Northeast, essential for storing wind power during periods of low demand and high production, typically occurring in the winter and spring seasons. In addition, Table 7 details the installation costs for each planned SPHS, broken down by EER and RCP scenarios. The SPHS development with the highest cost is at SPHS Paraná, which not only boasts the largest dam capacity in Brazil but also has the potential to install up to 15 GW of SPHS.

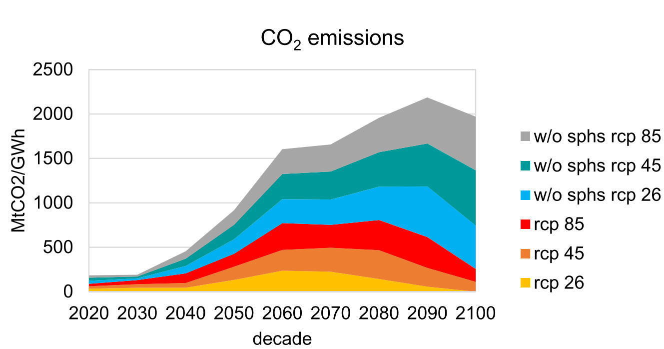


**Fig. 15.** Total GHS emissions of all scenarios from the year 2019 (historical) and projected years from 2020 up to 2100.

Furthermore, each scenario had a different share of renewable energy, and Fig. 14 compares the renewable energy endowment of the scenarios with and without SPHS.

The scenarios with and without SPHS presented similar shares of renewable penetration up to 2050. From 2060 onwards, the scenarios with SPHS increased up to 100 % of renewable endowment in 2100. In the opposite direction, the scenarios without SPHS decreased their share up to 64 %, which is 24 % lower than the historical share, 87 %. As the demand increases, more renewable energy is necessary to be installed. At the same time, more storage solutions are needed to balance the seasonality of renewable sources. The SPHS is a key technology for the Brazilian electricity system to achieve a 100 % renewable energy matrix by 2100.

At the end of the century, each scenario showed different shares of activity by source. RCP 2.6 was the only scenario in which 100 % of renewable energy generation would be achievable. The difference between RCP 2.6 scenario and the other ones is the higher share of wind power generation. One can notice that RCP 2.6 presented lower seasonality differences from wind capacities results (Appendix D[7]). Even though scenarios RCP 4.5 and RCP 8.5 presented higher capacity factors

[7] All appendixes are available at https://github.com/natiweber/BESMM.

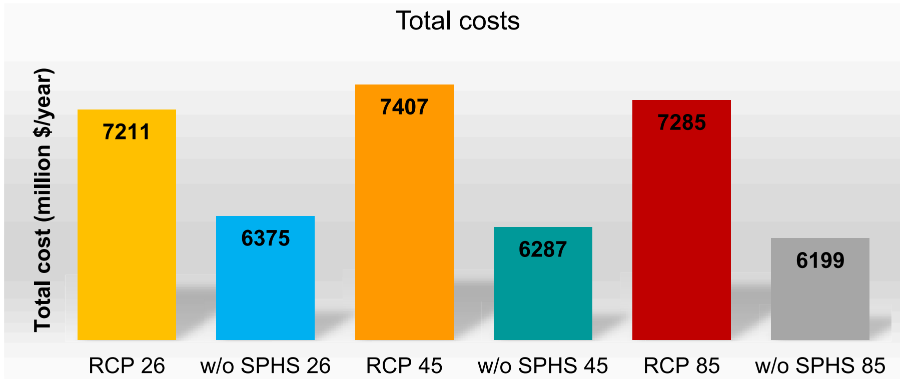


**Fig. 16.** Changes in the total cost of the Brazilian energy system. The results compare the three climate change scenarios, RCP 2.6, 4.5, and 8.5, with and without seasonal pumped hydro storage (SPHS). The values are the average of 2030–2100.

**Table 8**
Share of activity by source in 2100 comparison.

| | Scenarios | | |
|---|---|---|---|
| | RCP 26 | RCP 45 | RCP 85 |
| Natural gas | 0.0 % | 6.0 % | 6.9 % |
| Biomass | 0.0 % | 1.3 % | 0.0 % |
| Hydropower | 13.3 % | 13.4 % | 11.9 % |
| SPHS | 3.9 % | 3.1 % | 4.0 % |
| Oil | 0.0 % | 0.0 % | 0.2 % |
| Solar PV | 16.7 % | 16.4 % | 14.2 % |
| Wind onshore | 18.7 % | 12.8 % | 24.2 % |
| Wind offshore | 47.3 % | 47.0 % | 38.6 % |
| Nuclear | 0.0 % | 0.0 % | 0.0 % |

during the high windy seasons, at the same time, they also presented lower capacity factors during the low peak seasons. From a financial point of view, seasonality increases the financial risk, as well as the need for more seasonal storage capacity. Therefore, the BESMM model indicates that thermoelectric power plants are more cost-effective in those cases.

With different shares of renewable sources endowment and activity, each scenario also had different $CO_2$ emissions. Fig. 15 illustrates the total $CO_2$ emissions from the year 2019 (historical) through the projected years from 2020 to 2100 for all scenarios.

The upward trajectory of GHG emissions becomes evident from 2060 onwards in scenarios characterized by lower renewable energy penetration and the absence of SPHS, such as w/o SPHS RCP 2.6, w/o SPHS RCP 4.5, and w/o SPHS RCP 8.5. The results unequivocally highlight the effectiveness of SPHS as a crucial mitigation tool, countering the rising GHG emissions associated with scenarios lacking sufficient renewable energy integration. SPHS not only acts as a reliable energy storage solution but also contributes significantly to reducing the overall carbon footprint of the energy system. The capacity of SPHS to store excess energy during periods of high renewable generation and release it when demand is elevated serves as a linchpin in fostering a low-emission energy system.

In light of these findings, it becomes imperative to emphasize the role of SPHS technologies in climate change mitigation policies. Furthermore, the use of SPHS can offer economic benefits for the entire region [8], and also provides a variety of income-generating opportunities [20], but it will require significant additional investment costs, which will increase the overall cost of BESMM (Fig. 16). Thus, striking a balance between the economic benefits and the necessary financial commitments is pivotal to ensuring the long-term sustainability and viability of SPHS within the broader energy infrastructure.

Overall, scenarios with the insertion of SPHS technologies presented the highest total costs within the BESMM scenarios. The scenarios without SPHS integration exhibited a total cost approximately 16 % lower on average compared to scenarios incorporating SPHS. Moreover, Fig. 16 do not show a predictable trend from RCP 2.6 to RCP 8.5. The discrepancy mainly stems from RCP 4.5's higher SPHS capacity, as (Table 6 shows, particularly in the South region with 2.65 GW more SPHS installed than in RCP 8.5. This leads to significantly higher costs for RCP 4.5. Moreover, as illustrated in Table 8, the onshore wind activity for RCP 4.5 ranks lowest among all scenarios, with Appendix E further revealing that the capacity factors for onshore wind in the northeast slightly lower. Given MESSAGEix's least-cost optimization framework, it opts for minimal investment in northeastern onshore wind power, preferring instead to enhance SPHS capacity in the South. This decision aligns with the consistent increase in water inflow in the South across all scenarios. It is crucial to note the significant impact of the timing of these differences, particularly as the lower capacity factors for onshore wind power occur in the final four decades of the study period—a time of heightened electricity demand.

## 4. Discussion

The role of SPHS in responding to climate change impacts on the Brazilian electrical sector is multifaceted, as evidenced by several key observations. Initially, in the pursuit of achieving a 100 % renewable matrix by 2100, SPHS emerged as a fundamental player in scenario RCP 2.6. Additionally, SPHS played a pivotal role in scenarios RCP 4.5 and RCP 8.5, contributing to an increased renewables endowment, as depicted in Fig. 14. Another contribution of SPHS lies in its facilitation of offshore wind power integration within the BESMM matrix. This is particularly significant considering the high capacity of offshore wind power, coupled with one of the highest seasonality indices among renewable sources.

Furthermore, scenarios incorporating SPHS demonstrated a reduction of up to 68 % in $CO_2$ emissions compared to scenarios without SPHS, underscoring the environmental benefits of this technology (see Fig. 15). Regionally, specific EERs showcased heightened SPHS activity. In scenario RCP 2.6, the EER Paraná took the lead, while in RCP 8.5, both Paraná and Northeast displayed substantial SPHS involvement. The EER Southeast consistently ranked third in SPHS activity across all scenarios. A crucial insight emerged, revealing a direct correlation between SPHS activity and water inflow seasonality. Higher seasonality levels corresponded to increased SPHS activity. Dryer summers served as triggers for heightened SPHS activity, aligning with increased electricity demand.

Despite the evident economic benefits associated with SPHS, such as emissions reduction and renewable matrix optimization, it is important to acknowledge the substantial additional investment costs involved. This factor is illustrated in Fig. 16, highlighting the impact of these costs on the overall expenses of the BESMM. The juxtaposition of economic benefits and investment challenges underscores the complex decision-making landscape surrounding the integration of SPHS in response to climate change impacts.

Contrary to initial expectations, Figs. 13 and 16 do not present a linear trend from RCP 2.6 to RCP 8.5. These findings highlighted the significant influence of selecting years with the highest IAV on the study's outcomes. Without averaging climate data over decades, the results diverge from a straightforward pattern, illustrating the complex factors influencing the Brazilian electrical system. Additionally, the analysis reveals the critical role of timing, such as the reduced capacity factors for onshore wind power in the study's last four decades—a period marked by increased electricity demand. This timing led to different outcomes than if these changes had occurred sooner. Therefore, it becomes clear that the magnitudes of radiative forcing and their occurrence timings significantly impact the energy system, with shifts in context over time modifying the system's response.

## 5. Conclusion

As the Earth's climate continues to warm, it is causing an increasing variability in energy production, with some sources becoming more intermittent and others becoming more consistent. Brazil is home to a diverse range of energy sources, including hydroelectric, wind, solar, and biomass, which makes it particularly vulnerable to the effects of climate change. As it stands, the business as usual, i.e., generating electricity from fossil fuels in the dry seasons and using hydropower in the wet seasons, does not fully utilize the potential of hydropower resources in the region as well as does not prevent the system from the shocks of increasing climate variability. Droughts in the southeast of the country and head loss in several strategic reservoirs in this region have already prevented an increase in hydropower output even though hydroelectric capacity has increased by nearly 85 % over the past twenty years.

This study pioneers an approach by developing an energy system model that optimizes SPHS technology, considering the seasonal variability of renewable sources across three climate change scenarios. Additionally, a new detailed hydropower representation was defined for the SPHS implementation on the BESMM model. Climate change adds a new dimension to this approach as it has evidence of increasing the seasonal imbalance of variable renewable resources in Brazil. Building upon this innovative foundation, the research aims to investigate the role of SPHS in both adapting to and mitigating the impacts of climate change on the Brazilian electric system.

This objective was pursued through the development of a comprehensive model of the BESMM, integrating the foundational model MESSAGEix and utilizing CORDEX data as key components. These methodologies were intricately combined to incorporate SPHS technologies alongside the seasonal variability of renewable sources into the Brazilian electrical system model, with due consideration given to the effects of climate change. The inclusion of SPHS is paramount due to its maturity as a storage technology, its minimal land requirements, lower greenhouse gas emissions compared to conventional dams, and affordability relative to other long-term storage options. These factors position SPHS as a promising solution for mitigating the seasonal variations in renewable energy production.

BESMM results indicate that SPHS played a fundamental role in achieving a 100 % renewable matrix by 2100 in scenario RCP 2.6, as well as increasing renewable energy endowment in scenarios RCP 4.5 and RCP 8.5. SPHS proved to be a key technology to enable offshore wind power to gain traction within the BESMM matrix, considering that offshore wind power has high capacity but one of the highest seasonality indices. A reduction of up to 68 % of $CO_2$ emissions was achieved in scenarios with SPHS when compared with scenarios without SPHS. Among the factors that triggered SPHS activities were the seasonality of water inflow, higher seasonality, and dryer summers, as well as increased electricity demand. As much as SPHS is considered to have potential economic benefits, it also incurs a substantial amount of additional investment costs, which leads to the cost of the BESMM rising overall.

The research conducted provides important insights into the role of energy storage systems in responding to the impacts of climate change on renewable energy production in Brazil. With increasing variability in energy production due to climate change, the research finds that SPHS technology can play a critical role in enabling Brazil to transition to a more sustainable and resilient energy system. The study highlights the potential benefits of SPHS over conventional hydropower storage, including reduced GHG emissions, inter-basin transfer, and higher energy storage capacity. The study also demonstrates that the integration of SPHS with renewable energy sources can significantly reduce $CO_2$ emissions and contribute to achieving a 100 % renewable matrix by 2100. However, the research also points out that the additional investment costs associated with SPHS technology need to be taken into account when considering its economic viability. These results are important for decision-makers and policymakers to understand the potential role of SPHS in addressing the challenges faced by the power sector in Brazil and other countries in similar situations.

Overall, the study highlights the MESSAGEix model as an adaptable tool for evaluating SPHS technology's benefits within Brazil's energy system, underlining the need for further exploration and investment in energy storage solutions to facilitate a sustainable energy transition in Brazil and beyond. Key limitations include reliance on MESSAGEix and regional climate simulations for SPHS impact forecasts, which may not fully capture the complexity of real-world dynamics due to modelling assumptions and simplifications. Additionally, projections until 2100 are based on current technology levels for SPHS and renewables, not accounting for potential rapid technological advancements that could reshape the energy sector. Future research should focus on refining models, broadening climate scenario analyses, integrating technological progress, and exploring wider economic, policy, and geographical considerations.

## CRediT authorship contribution statement

**Natália de Assis Brasil Weber:** Writing – original draft, Software, Methodology, Data curation, Conceptualization. **Julian David Hunt:** Methodology, Investigation, Formal analysis, Conceptualization. **Behnam Zakeri:** Validation, Supervision, Resources, Methodology. **Paulo Smith Schneider:** Supervision, Project administration, Funding acquisition. **Fernando Sérgio Asfor Parente:** Visualization, Software, Resources, Investigation, Data curation. **Augusto Delavald Marques:** Writing – review & editing, Validation, Resources, Investigation. **Amaro Olímpio Pereira Junior:** Validation, Supervision, Project administration, Formal analysis.

## Declaration of competing interest

All authors have participated in conception and design, or analysis and interpretation of the data, or drafting the article, or revising it critically for important intellectual content, and approved of the final version.

This manuscript has not been submitted to, nor is under review at, another journal or other publishing venue.

The authors have no affiliation with any organization with a direct or indirect financial interest in the subject matter discussed in the manuscript.

The following authors have affiliations with organizations with direct or indirect financial interest in the subject matter discussed in the manuscript.

In other words, there is no conflict of interest involved in this publication.

## Data availability

Data will be made available on request.

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## Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.est.2024.111249.

## References

[1] IEA, Technology Roadmap - Energy Storage – Analysis, IEA, 2014. https://www.iea.org/reports/technology-roadmap-energy-storage. (Accessed 29 October 2022).
[2] S. Rehman, L.M. Al-Hadhrami, M.M. Alam, Pumped hydro energy storage system: a technological review, Renew. Sustain. Energy Rev. 44 (2015) 586–598, https://doi.org/10.1016/J.RSER.2014.12.040.
[3] L. Qiu, L. He, H. Lu, D. Liang, Pumped hydropower storage potential and its contribution to hybrid renewable energy co-development: a case study in the Qinghai-Tibet Plateau, J Energy Storage 51 (2022) 104447, https://doi.org/10.1016/J.EST.2022.104447.
[4] V. Costa, B. Bonatto, A. Zambroni, P. Ribeiro, M. Castilla, L. Arango, Renewables with energy storage: a time-series socioeconomic model for business and welfare analysis, J Energy Storage 47 (2022) 103659, https://doi.org/10.1016/J.EST.2021.103659.
[5] J.D. Ampah, S. Afrane, B. Li, H. Adun, E.B. Agyekum, A.A. Yusuf, O. Bamisile, H. Liu, The overarching role of electric vehicles, power-to-hydrogen, and pumped hydro storage technologies in maximizing renewable energy integration and power generation in Sub-Saharan Africa, J Energy Storage 67 (2023) 107602, https://doi.org/10.1016/J.EST.2023.107602.
[6] J.D. Hunt, D. Stilpen, M.A.V. de Freitas, A review of the causes, impacts and solutions for electricity supply crises in Brazil, Renew. Sustain. Energy Rev. 88 (2018) 208–222, https://doi.org/10.1016/J.RSER.2018.02.030.
[7] J.D. Hunt, B. Zakeri, R. Lopes, P.S.F. Barbosa, A. Nascimento, N.J. de Castro, R. Brandão, P.S. Schneider, Y. Wada, Existing and new arrangements of pumped-hydro storage plants, Renew. Sustain. Energy Rev. 129 (2020) 109914, https://doi.org/10.1016/J.RSER.2020.109914.
[8] J.D. Hunt, B. Zakeri, A. Nascimento, R. Brandão, Pumped hydro storage (PHS), storing energy: with special reference to renewable, Energy Source. (2022) 37–65, https://doi.org/10.1016/B978-0-12-824510-1.00008-8.
[9] J.D. Hunt, M.A.V. Freitas, A.O. Pereira Junior, Enhanced-pumped-storage: combining pumped-storage in a yearly storage cycle with dams in cascade in Brazil, Energy 78 (2014) 513–523, https://doi.org/10.1016/J.ENERGY.2014.10.038.
[10] IPCC, Climate Change 2022: Impacts, Adaptation and Vulnerability | Climate Change 2022: Impacts, Adaptation and Vulnerability. https://www.ipcc.ch/report/ar6/wg2/, 2022. (Accessed 8 October 2022).
[11] R. Schaeffer, A.S. Szklo, A.F.P. de Lucena, R.R. de Souza, B.S.M.C. Borba, I.V.L. da Costa, A.O.P. Júnior, S.H.F. da Cunha, Mudanças climáticas e segurança energética no Brasil, CPTEC, 2008, p. 67. http://mudancasclimaticas.cptec.inpe.br/~rmclima/pdfs/destaques/CLIMA_E_SEGURANCA-EnERGETICA_FINAL.pdf. (Accessed 22 September 2020).
[12] A.F.P. de Lucena, M. Hejazi, E. Vasquez-Arroyo, S. Turner, A.C. Köberle, K. Daenzer, P.R.R. Rochedo, T. Kober, Y. Cai, R.H. Beach, D. Gernaat, D.P. van Vuuren, B. van der Zwaan, Interactions between climate change mitigation and adaptation: the case of hydropower in Brazil, Energy 164 (2018) 1161–1177, https://doi.org/10.1016/j.energy.2018.09.005.
[13] Agência Nacional de Águas - ANA, Capacidade de Armazenamento dos Reservatórios. https://metadados.snirh.gov.br/geonetwork/srv/api/records/67199519-c5f4-497b-baf8-ab00e057e8da, 2021. (Accessed 22 October 2023).
[14] A.R. Silva, F.M. Pimenta, A.T. Assireu, M.H.C. Spyrides, Complementarity of Brazil's hydro and offshore wind power, Renew. Sustain. Energy Rev. 56 (2016) 413–427, https://doi.org/10.1016/j.rser.2015.11.045.
[15] J. Twitchell, K. DeSomber, D. Bhatnagar, Defining long duration energy storage, J Energy Storage 60 (2023) 105787, https://doi.org/10.1016/J.EST.2022.105787.
[16] J.D. Hunt, E. Byers, K. Riahi, S. Langan, Comparison between seasonal pumped-storage and conventional reservoir dams from the water, energy and land nexus perspective, Energ. Conver. Manage. 166 (2018) 385–401, https://doi.org/10.1016/j.enconman.2018.04.044.
[17] J.D. Hunt, M.A.V. de Freitas, A.O. Pereira Junior, A review of seasonal pumped-storage combined with dams in cascade in Brazil, Renew. Sustain. Energy Rev. 70 (2017) 385–398, https://doi.org/10.1016/j.rser.2016.11.255.
[18] F.A. Canales, A. Beluco, C.A.B. Mendes, A comparative study of a wind hydro hybrid system with water storage capacity: conventional reservoir or pumped storage plant? J Energy Storage 4 (2015) 96–105, https://doi.org/10.1016/J.EST.2015.09.007.
[19] J.D. Hunt, B. Lagore, R. Brandão, F.A. Diuana, E. Quaranta, M. de Miranda, A. Lacorte, P.S. Barbosa, M.A.V. de Freitas, B. Zakeri, N.J. Castro, Y. Wada, Mapping the potential for pumped storage using existing lower reservoirs, J Energy Storage 73 (2023) 109047, https://doi.org/10.1016/J.EST.2023.109047.
[20] J.D. Hunt, E. Byers, Y. Wada, S. Parkinson, D.E.H.J. Gernaat, S. Langan, D.P. van Vuuren, K. Riahi, Global resource potential of seasonal pumped hydropower storage for energy and water storage, Nature Communications 11 (1) (2020) 11 (2020) 1–8, https://doi.org/10.1038/s41467-020-14555-y.
[21] J.D. Hunt, G. Falchetta, S. Parkinson, A. Vinca, B. Zakeri, E. Byers, J. Jurasz, E. Quaranta, E. Grenier, A.O. Pereira Junior, P.S.F. Barbosa, R. Brandão, N.J. de Castro, P.S. Schneider, L.W. Vieira, A. Nascimento, Y. Wada, Hydropower and seasonal pumped hydropower storage in the Indus basin:pros and cons, J Energy Storage 41 (2021) 102916, https://doi.org/10.1016/J.EST.2021.102916.
[23] C. de M. Altea, J.I. Yanagihara, Energy, exergy and environmental impacts analyses of pumped hydro storage (PHS) and hydrogen (H2) energy storage processes, J Energy Storage 76 (2024) 109713, https://doi.org/10.1016/J.EST.2023.109713.
[24] F. Klumpp, Comparison of pumped hydro, hydrogen storage and compressed air energy storage for integrating high shares of renewable energies—potential, cost-comparison and ranking, J Energy Storage 8 (2016) 119–128, https://doi.org/10.1016/J.EST.2016.09.012.
[25] EPE, Usinas Hidrelétricas Reversíveis (UHR): Desafios para inserção em mercados de energia elétrica, Rio de Janeiro NT-013, 2021, p. 37. https://www.epe.gov.br/sites-pt/publicacoes-dados-abertos/publicacoes/PublicacoesArquivos/publicacao-561/EPE-DEE-NT-013_2021-r0.pdf.
[26] R. Brandão, N. Castro, J.D. Hunt, A Viabilidade das Usinas Reversíveis no Sistema Interligado Nacional. http://www.gesel.ie.ufrj.br/app/webroot/files/publications/31_livro_uhr_2021_12_16.pdf, 2021.
[28] EPE, BEN: Summary Report 2023. https://www.epe.gov.br/sites-pt/publicacoes-dados-abertos/publicacoes/PublicacoesArquivos/publicacao-748/topico-681/BEN_S%C3%ADntese_2023_EN.pdf, 2023. (Accessed 26 October 2023).
[29] A.R. de Queiroz, V.A.D. Faria, L.M.M. Lima, J.W.M. Lima, Hydropower revenues under the threat of climate change in Brazil, renew, Energy 133 (2019) 873–882, https://doi.org/10.1016/J.RENENE.2018.10.050.
[30] V. Ruffato-Ferreira, R. da Costa Barreto, A. Oscar Júnior, W.L. Silva, D. de Berrêdo Viana, J.A.S. do Nascimento, M.A.V. de Freitas, A foundation for the strategic long-term planning of the renewable energy sector in Brazil: hydroelectricity and wind energy in the face of climate change scenarios, Renew. Sustain. Energy Rev. 72 (2017) 1124–1137, https://doi.org/10.1016/j.rser.2016.10.020.
[31] A.F.P. de Lucena, A.S. Szklo, R. Schaeffer, R.R. de Souza, B.S.M.C. Borba, I.V.L. da Costa, A.O.P. Júnior, S.H.F. da Cunha, The vulnerability of renewable energy to climate change in Brazil, Energy Policy 37 (2009) 879–889, https://doi.org/10.1016/j.enpol.2008.10.029.
[32] A.F.P. de Lucena, R. Schaeffer, A.S. Szklo, Least-cost adaptation options for global climate change impacts on the Brazilian electric power system, Glob. Environ. Chang. 20 (2010) 342–350, https://doi.org/10.1016/j.gloenvcha.2010.01.004.
[33] E.B. Pereira, F.R. Martins, M.P. Pes, E.I. da Cruz Segundo, A. de A. Lyra, The impacts of global climate changes on the wind power density in Brazil, renew, Energy 49 (2013) 107–110, https://doi.org/10.1016/j.renene.2012.01.053.
[34] A.R. de Queiroz, L.M. Marangon Lima, J.W. Marangon Lima, B.C. da Silva, L. A. Scianni, Climate change impacts in the energy supply of the Brazilian hydro-dominant power system, renew, Energy 99 (2016) 379–389, https://doi.org/10.1016/j.renene.2016.07.022.
[35] L.A. Scianni, A.R. Queiroz, L.M.M. Lima, J.W.M. Lima, The influence of climate change on hydro generation in Brazil, in: 2013 IEEE Grenoble conference PowerTech, POWERTECH 2013, 2013, https://doi.org/10.1109/PTC.2013.6652402.
[36] A. Invidiata, E. Ghisi, Impact of climate change on heating and cooling energy demand in houses in Brazil, Energ. Buildings 130 (2016) 20–32, https://doi.org/10.1016/j.enbuild.2016.07.067.
[37] E.E.J. Bierhals, F. Pereira, C. Brazil, E.G. Rossini, Solar radiation projections of Cmip5 models for South of Brazil, Journal of Contemporary Urban Affairs 1 (2017), https://doi.org/10.25034/ijcua.2018.36xx71.
[38] V.A. de Oliveira, C.R. de Mello, M.R. Viola, R. Srinivasan, Assessment of climate change impacts on streamflow and hydropower potential in the headwater region of the Grande river basin, Southeastern Brazil, Int. J. Climatol. 37 (2017) 5005–5023, https://doi.org/10.1002/joc.5138.
[39] P. de Jong, T.B. Barreto, C.A.S. Tanajura, D. Kouloukoui, K.P. Oliveira-Esquerre, A. Kiperstok, E.A. Torres, Estimating the impact of climate change on wind and solar energy in Brazil using a South American regional climate model, renew, Energy 141 (2019) 390–401, https://doi.org/10.1016/j.renene.2019.03.086.
[40] M.V.M. da Silva, C. da S. Silveira, G.K. da Silva, W.H. de V. Pedrosa, A.D. Marcos Júnior, F. de A. Souza Filho, Projections of climate change in streamflow and affluent natural energy in tbrazilian hydroelectric sector of cordex models, Revista Brasileira de Recursos Hidricos 25 (2020) 1–15, https://doi.org/10.1590/2318-0331.252020200020.
[41] A. Michels-Brito, D.A. Rodriguez, W.L. Cruz Junior, J. Nildo de Souza Vianna, The climate change potential effects on the run-of-river plant and the environmental and economic dimensions of sustainability, Renew. Sustain. Energy Rev. 147 (2021) 111238, https://doi.org/10.1016/J.RSER.2021.111238.
[42] M.V.M. Da Silva, C.D.S. Silveira, S.L. Cabral, A.D.M. Junior, G.K. Da Silva, C.E. S. Lima, Naturalized streamflows and affluent natural energy projections for the Brazilian hydropower sector for the SSP2-4.5 and SSP5-8.5 scenarios of the CMIP6,

Journal of Water and Climate Change 13 (2022) 315–336, https://doi.org/10.2166/WCC.2021.352.

[43] C.R. Mello, N.P.A. Vieira, J.A. Guzman, M.R. Viola, S. Beskow, L.A. Alvarenga, Climate change impacts on water resources of the largest hydropower plant reservoir in southeast Brazil, Water 13 (2021), https://doi.org/10.3390/W13111560. Page 1560 13 (2021) 1560.

[44] A.F.P. de Lucena, A.S. Szklo, R. Schaeffer, R.M. Dutra, The vulnerability of wind power to climate change in Brazil, renew, Energy 35 (2010) 904–912, https://doi.org/10.1016/j.renene.2009.10.022.

[45] F. Giorgi, Thirty years of regional climate modeling: where are we and where are we going next? J. Geophys. Res. Atmos. 124 (2019) 5696–5723, https://doi.org/10.1029/2018JD030094.

[46] M.S. Reboita, C.A.C. Kuki, V.H. Marrafon, C.A. de Souza, G.W.S. Ferreira, T. Teodoro, J.W.M. Lima, South America climate change revealed through climate indices projected by GCMs and Eta-RCM ensembles, Climate Dynamics 58 (1) (2021) 58 (2021) 459–485, https://doi.org/10.1007/S00382-021-05918-2.

[47] 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.)]. https://ar5-syr.ipcc.ch/topic_futurechanges.php, 2014. (Accessed 13 November 2020).

[48] EPE, Publicações: Roadmap Eólica Offshore Brasil. https://www.epe.gov.br/pt/publicacoes-dados-abertos/publicacoes/roadmap-eolica-offshore-brasil, 2020 (accessed October 26, 2023).

[49] INPE, Atlas do Potencial Eólico Brasileiro. https://www.observatoriodocarvao.org.br/wp-content/uploads/2020/01/Novo-Atlas-do-Potencial-Eolico-Brasileiro-SIM_2013.pdf, 2017. (Accessed 13 December 2022).

[50] F. Diniz Bezerra, Ano 6 | N$^{o}$ 200 | Dezembro | 2021, Caderno Setorial ETENE, 2021, p. 13. https://www.bnb.gov.br/s482-dspace/handle/123456789/1045. (Accessed 13 December 2022).

[51] SEMA, Atlas Eólico do RS - Sema - Secretaria do Meio Ambiente e Infraestrutura. https://sema.rs.gov.br/atlas-eolico-do-rs, 2014. (Accessed 18 November 2022).

[52] R. Corrêa Da Silva, I. De Marchi Neto, S. Silva Seifert, Electricity supply security and the future role of renewable energy sources in Brazil, Renew. Sustain. Energy Rev. 59 (2016) 328–341, https://doi.org/10.1016/J.RSER.2016.01.001.

[53] H. Hueging, R. Haas, K. Born, D. Jacob, J.G. Pinto, Regional changes in wind energy potential over Europe using regional climate model ensemble projections, J. Appl. Meteorol. Climatol. 52 (2013) 903–917, https://doi.org/10.1175/JAMC-D-12-086.1.

[54] I. Staffell, S. Pfenninger, Using bias-corrected reanalysis to simulate current and future wind power output, Energy 114 (2016) 1224–1239, https://doi.org/10.1016/J.ENERGY.2016.08.068.

[55] Vestas, V90-2.0 MW™. https://www.vestas.com/en/products/2-mw-platform/V90-2-0-MW, 2022. (Accessed 5 December 2022).

[56] Brasil, PNE 2050: Plano Nacional de Energia, Brasília. https://www.epe.gov.br/sites-pt/publicacoes-dados-abertos/publicacoes/PublicacoesArquivos/publicacao-227/topico-563/RelatorioFinaldoPNE2050.pdf, 2020. (Accessed 27 March 2021).

[57] S. Pfenninger, I. Staffell, Long-term patterns of European PV output using 30 years of validated hourly reanalysis and satellite data, Energy 114 (2016) 1251–1265, https://doi.org/10.1016/J.ENERGY.2016.08.060.

[58] ONS, Histórico da Operação. http://www.ons.org.br/paginas/resultados-da-operacao/historico-da-operacao, 2022. (Accessed 14 August 2022).

[59] B. Zakeri, J.D. Hunt, M. Laldjebaev, V. Krey, A. Vinca, S. Parkinson, K. Riahi, Role of energy storage in energy and water security in Central Asia, J Energy Storage 50 (2022) 104587, https://doi.org/10.1016/J.EST.2022.104587.

[60] D. Huppmann, M. Gidden, O. Fricko, P. Kolp, C. Orthofer, M. Pimmer, N. Kushin, A. Vinca, A. Mastrucci, K. Riahi, V. Krey, 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. 112 (2019) 143–156, https://doi.org/10.1016/j.envsoft.2018.11.012.