

# HYDROPOWER AND CLIMATE CHANGE

Reflections on adapting and enhancing the resilience of the Brazilian electricity sector

Understanding the relationship between climate change and hydropower production is key to support planning studies that aim to enhance the resilience of the Brazilian electricity system. This Fact Sheet discusses the role of hydropower in Brazil, outlines climate-related risks, describes EPE's approach to this issue, and identifies pathways for adapting the electricity system to climate change.

## 1 Understanding the context

## 2 Identifying climate risks

## 3 Developing pathways

Hydropower has historically been the **primary source of electricity generation in Brazil.**

**HPP + SHP  
425,966 GWh**



**60.2%**  
**OF THE ELECTRICITY  
GENERATED IN 2023**

Brazilian Energy Balance –  
BEN 2024 | Base Year: 2023 (EPE, 2024)



Beyond electricity generation, **hydropower plants provide essential services** to the **National Interconnected System (SIN)** including:

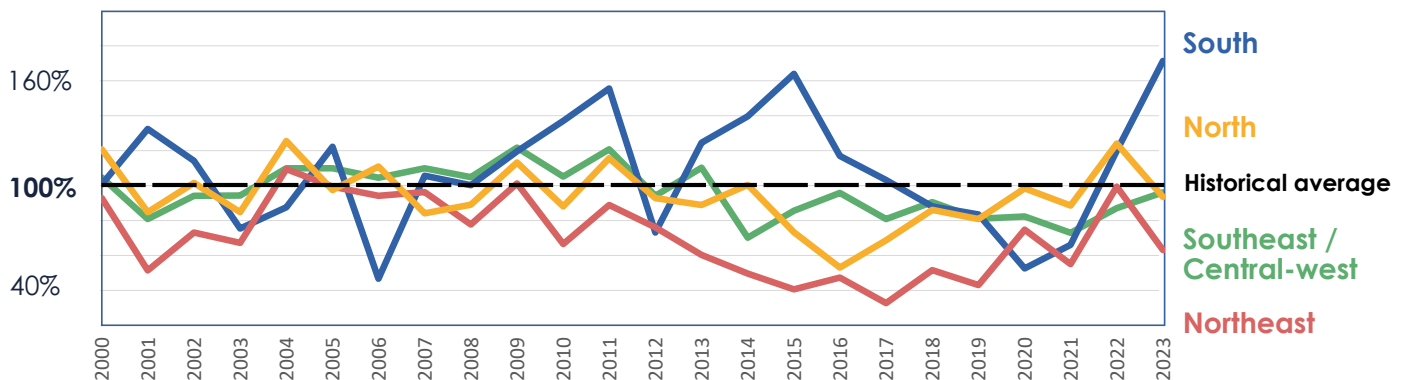
- ◆ **Energy is stored** in reservoirs, allowing water inflow regulation and continuous electricity generation throughout the year, even during periods of low rainfall.
- ◆ **Operational flexibility** to respond to load fluctuations, enabling hydropower generation during peak demand or when output from other variable sources — especially solar — is reduced.
- ◆ **Frequency and voltage regulation**, which are fundamental for the stability of the power grid.



**Hydropower generation is highly sensitive to the natural variability of the hydrological regime.** That is, periods of drought or intense rainfall directly affect power plant generation. The Natural Energy Inflow chart illustrates the variation in inflows over recent years and the periods with flows above or below the average for the historical period.

### Annual Variation of Natural Energy Inflow, as a % of the historical average

Natural Energy Inflow represents the inflows to hydropower plants converted into units of electrical energy.



(National System Operator, 2024)

# WHAT HAS BEEN HAPPENING?

Recent events suggest potential impacts of climate change on hydropower production

## 2014

**Inflow rates to hydropower plants were significantly below the historical average** in the Southeast/Central-West and Northeast subsystems<sup>1</sup> due to prolonged **drought conditions**. **The SIN's storage levels fell to the lowest point on record.**

In contrast, the North region experienced **exceptionally high rainfall** which led to a historic flood of the Madeira River and **temporary shutdown of generation at the Santo Antônio Hydropower Plant.**

## 2020 - 2021

The storage levels of the SIN dropped to critically low thresholds while **the inflows to hydropower plants remained below historical averages due to a prolonged drought**. This situation placed the **Brazil's electricity supply on high alert.**

A series of strategic measures were implemented, successfully averting the need for energy rationing.

<sup>1</sup> The National Interconnected System (SIN) comprises four subsystems: South, Southeast/Central-West, Northeast, and North, which are interconnected by transmission lines that enable electricity to be transferred among them.

## 2012

The onset of a **prolonged drought period**, marked by several consecutive years of below-average rainfall and river inflows across various regions of Brazil, particularly in the Northeast.

## 2017

**The SIN's reservoir storage level fell to the second lowest point on record**, driven by persistent **drought conditions since 2012**. The reservoirs of the Serra da Mesa Hydropower Plant (GO) and the Furnas Hydropower Plant (SP) also reached their lowest historical levels.

## 2023 - 2024

Due to **extreme drought and low river flows in the Amazon basin**, the Santo Antônio Hydropower Plant (RO) **was forced to halt operations**, while the Ferreira Gomes and Cachoeira Caldeirão plants (AP) operated intermittently.

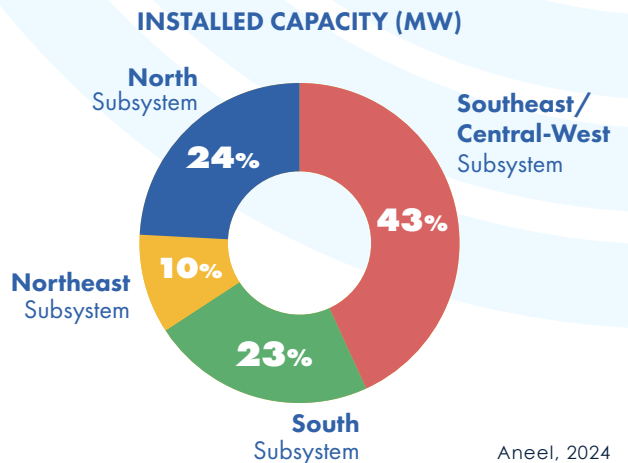
**Intense rainfall in the southern region put several power generation and transmission infrastructures at risk.**

Partial dam breaches occurred at the 14 de Julho Hydropower Plant and the Salto Forqueta Small Hydro Plant. Seven additional plants were classified as at risk.

# WHERE ARE THE HYDROPOWER PLANTS LOCATED IN BRAZIL?



Hydropower plants are distributed across all regions of Brazil, located in areas with distinct hydrological and geographical characteristics. The Southeast/Central-West subsystem accounts for the largest share of installed capacity in large-scale hydropower plants, followed by the North, South, and Northeast subsystems.

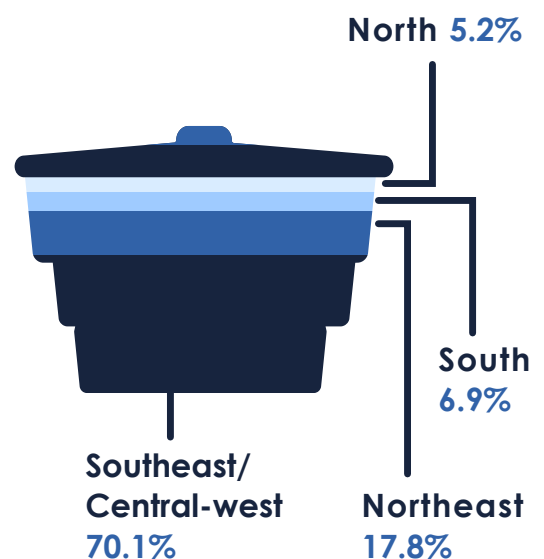


Brazil's vast territorial expanse and climatic diversity result in river basins with distinct hydrological conditions. **This hydrological variability enables seasonal complementarity among the subsystems:** when certain basins experience low water availability, others may compensate for the generation shortfall, thereby enhancing the security and resilience of the national electricity supply.

## ENERGY STORAGE

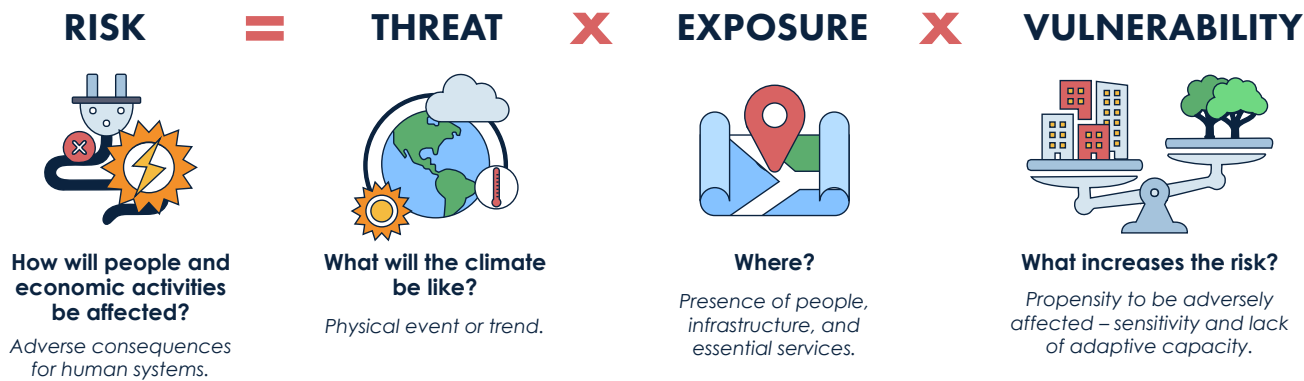
The main regulation reservoirs are located in the **Southeast/Central-west subsystem**, which accounts for 70% of the country's total storage capacity. The Paraná River basin is particularly prominent, along with its key tributaries: the Paranaíba, Grande, Tietê, and Paranapanema rivers. The Northeast subsystem holds nearly 20% of Brazil's storage capacity, with the São Francisco River basin as its most significant contributor.

**In the North**, hydropower plants generally feature low hydraulic heads and high inflow volumes, **operating as run-of-river facilities** with limited storage capacity.



ONS, 2024

# IDENTIFYING CLIMATE RISKS



Climate Risk Assessment Methodology of the Intergovernmental Panel on Climate Change (IPCC)

## HOW CLIMATE THREATS CAN IMPACT THE HYDROPOWER GENERATION?

The increase in global average temperature leads to impacts on atmospheric circulation systems and the hydrological cycle, consequently affecting precipitation patterns. Changes in precipitation patterns, in terms of volume, seasonal variability, and geographic distribution, can influence water availability for hydropower production, complicating reservoir management and electricity production.



### Decrease in annual mean precipitation levels

- ◆ Decline in water resource availability and mean hydro generation
- ◆ Reduction in storage reservoir levels and hydropower plant efficiency



### Increase in mean annual precipitation

- ◆ Increase in water availability and potential for expansion of average hydropower generation
- ◆ Increase in sediment transport and reservoir siltation



### Increase in the frequency and duration of droughts

- ◆ Reduction in hydropower generation at run-of-river plants
- ◆ Need for increased storage capacity and improved reservoir management
- ◆ Increase in water uses and operational restrictions



### Increase in the magnitude and duration of extreme rainfall events

- ◆ Water level limitation for flood control
- ◆ Occurrence of flows exceeding project reference values
- ◆ Increase in sediment transport and reservoir siltation
- ◆ Loss of hydraulic head due to downstream water level rise



### Rising temperatures

- ◆ Increase in reservoir evaporation and reduction in water availability
- ◆ Reduction in equipment efficiency



Although **influenced by precipitation variability**, energy generation depends on the **inflows to hydropower plants**, which are determined not only by rainfall patterns but also by a range of other factors, such as **the flow-regulation capacity of reservoirs, water use within the river basin, evapotranspiration, and additional aspects that affect water runoff, including vegetation cover and soil type.**



## **WHAT CHARACTERISTICS INCREASE THE VULNERABILITY OF HYDROPOWER PLANTS TO THE IMPACTS OF CLIMATE CHANGE?**

### ***Run-of-river reservoirs***

Run-of-river hydropower plants have little to no storage capacity in their reservoirs, relying directly on the river's natural flow to generate electricity. As a result, their operation may be influenced by periods of increased precipitation or hydrological scarcity.

### ***Hydropower plants located in river basins with competing water uses***

Climate change can worsen conflicts over water use, especially during severe droughts, reducing the availability of resources and the operational flexibility of hydroelectric plants. Under Federal Law 9.433/1977, when water is scarce, priority is given to human consumption and animal watering.

### ***Hydropower plants in environmentally degraded river basins***

Watersheds with low vegetative cover and impermeable surfaces reduce the capacity of the soil and vegetation to retain and infiltrate water, leading to increased surface runoff, soil erosion, and the siltation of rivers and reservoirs.

### ***Hydropower plants designed based on reference flow rates lower than those potentially resulting from climate change***

Extended droughts can cause river flows to drop below the minimum required for operation, forcing hydropower plants to shut down. On the other hand, heavy rainfall can exceed design limits, triggering spillway releases or even threatening the integrity of the structures.

### ***Reservoirs with large flooded surface areas***

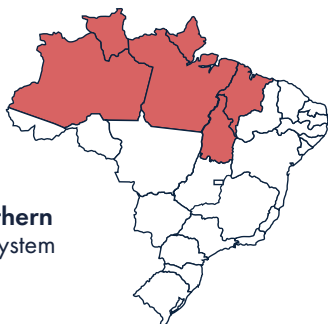
Reservoirs with large surface areas are more susceptible to evaporation, as they provide an extensive area exposed to heat and wind.

Vulnerability is the tendency or predisposition to be adversely affected. It encompasses a variety of concepts and elements, including sensitivity or susceptibility to harm and a limited capacity to cope and adapt (IPCC, 2021).

## SUBSYSTEMS

## CHARACTERISTICS AND TRENDS

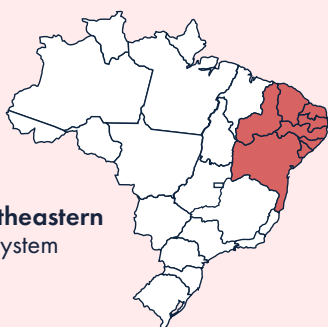
Northern Subsystem



A region predominantly composed of low-head hydropower plants, with limited storage capacity, **run-of-river configurations**, and **large inflows subject to significant seasonal variability**.

**The Northern subsystem** is responsible for exporting electricity to other regions during certain periods of the year. **There is a projected trend of decreasing annual precipitation and a reduction in average annual power generation.**

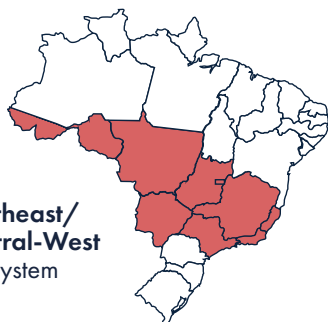
Northeastern Subsystem



**The Northeast region** hosts some of the most important storage reservoirs within the National Interconnected System (SIN). The regional climate is predominantly semi-arid, characterized by numerous intermittent rivers. It is also a region with major irrigation hubs and multiple water users across different sectors.

Climate projections indicate an **increase in the intensity and duration of droughts**, placing additional pressure on hydropower reservoirs to meet competing water demands.

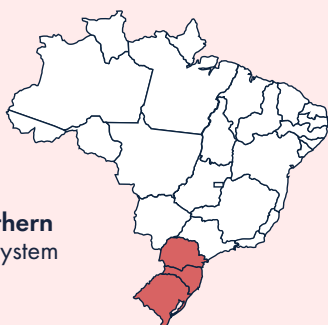
Southeast/Central-West Subsystem



**Southeast and Central-West Brazil** concentrate the main storage reservoirs of the National Interconnected System and a high density of water resource users.

**Climate Scenarios indicate uncertainties regarding the behavior of average rainfall.** However, there is evidence of an **increase in extreme flow events, as well as in the intensity and duration of droughts, which increases pressure on hydroelectric reservoirs** to control flooding and to support other water uses.

Southern Subsystem



**In the South**, trends indicate an increase in average streamflow, which may benefit power generation through new projects, as well as modernization and repowering of existing facilities.

**However, the projected rise in the intensity of extreme rainfall events calls for careful attention and local assessments regarding spillway capacity and potential risks to infrastructure.**

## MAIN CLIMATE RISKS ASSOCIATED WITH HYDROPOWER PLANTS:

- ✦ Reduction in hydropower production;
- ✦ Infrastructure safety.

# DEVELOPING PATHWAYS

## WHAT ARE THE CHALLENGES OF INCORPORATING THE EFFECTS OF CLIMATE CHANGE INTO PLANNING STUDIES?

### Uncertainties related to future hydrological availability

Climate change presents a significant challenge for planning studies, particularly for systems that are heavily reliant on renewable energy sources: future climate conditions cannot be represented solely based on historical climate data. In this context, **projecting future climate scenarios is a complex task. Climate models incorporate a considerable degree of uncertainty** due to factors such as the difficulty in predicting future greenhouse gas emissions and population growth. These uncertainties are further compounded by the simplifications required for the mathematical representation of hydrological systems.

These **uncertainties** must be acknowledged as an inherent aspect of the **impossibility of deterministically predicting the future**, underscoring the need to develop **new tools and methodologies** to account for them.

Therefore, planning approaches should be grounded in **scenario development**, which, while not exact predictions, help to **identify possible future** conditions and inform **adaptive strategies**.

### Complexity of the energy system

**The interdependence among different energy sources, demand patterns, infrastructure, and markets makes the incorporation of climate change impacts into planning studies particularly challenging.** Changes in any one of these elements can trigger cascading effects throughout the system.

Shifts in energy and environmental policies have a substantial impact on the long-term strategic planning of the power sector, shaping decisions on investment priorities, technology choices, and operational frameworks.

These factors emphasize the necessity of flexible and resilient planning, capable of adapting to the uncertainties brought about by both climate variability and regulatory changes.

### Balancing Risk and Investments

In the context of climate change adaptation in the electricity sector, balancing risks and costs involves seeking solutions that **ensure both the security of electricity supply and tariff affordability**. On one hand, it is necessary to invest in more resilient infrastructure and emerging technologies. On the other hand, such investments must avoid imposing excessive costs on consumers or undermining the sector's competitiveness.

Striking this balance is essential to ensure that the power sector can continue to operate efficiently and securely in a context of increasing climate uncertainty, without compromising its economic and socio-environmental sustainability, as well as Brazil's energy security.

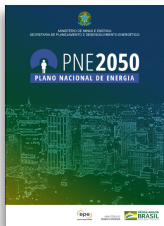
In the context of climate change, the pursuit of **effective solutions** must simultaneously promote the **adoption of robust policies and measures** capable of ensuring energy security across a wide range of possible future scenarios, as well as **flexible** approaches that can be adjusted or adapted over time as new data and information become available and climate projections evolve.

# HOW HAS THE TOPIC BEEN ADDRESSED BY EPE?

Click on the images to learn more.



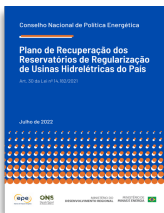
The **Ten-Year Energy Expansion Plan (PDE)** assesses the **expansion prospects** of the energy sector over the next 10 years. For hydropower generation, two thousand hydrological scenarios are used to reflect future **climate variability**. In PDE 2031 and PDE 2034, sensitivity analyses were conducted to evaluate the **resilience** of the power system under **critical hydrological scarcity conditions**.



The **Energy National Plan (PNE)** aims to guide the **long-term strategy of the energy sector in Brazil**. The Energy National Plan 2050 identified key challenges including **uncertainties** about the effect of climate change on **energy supply** and ensuring **supply security** during extreme events. In the upcoming Energy National Plan 2055, currently under development, **climate dynamics** have become central to the discussion of future scenarios.



The study **Water Scarcity in 2021 – Diagnosis and Opportunities for Electricity Supply Expansion Planning** analyzed structural factors that may have contributed to the **challenges in energy supply during the 2020/2021 drought**, including an assessment of historical hydrological patterns and the potential impacts of climate change.



The **Hydropower Reservoir Recovery Plan (PRR)** proposes **31 actions** over a **10-year** horizon that aimed at enhancing the **climate resilience of the power system**. These actions are structured around four thematic pillars: physical characteristics of the reservoirs, mathematical modeling, operational and expansion planning, and reservoir operation dynamics.



EPE has been discussing solutions to enhance **the resilience of radial systems located in the Northern region**, with the objective of maintaining electricity supply under critical hydrological scenarios, such as those observed in 2023 and 2024. The study for **Acre and Rondônia** has been completed, while the study for **Amazonas, Amapá and Roraima** is still under development.



The **database of socio-environmental indicators and statistics related to climate risk, mitigation, and adaptation in the energy sector** is currently under development. Its objective is to provide a tool capable of identifying **trends and monitoring information** relevant to **national energy planning** from a **climate change** perspective.



The study '**Impacts of Climate Change on Power Generation Planning**' is currently under development in partnership with GIZ with the support of MME, INPE, and ANA. Its objective is to assess the **resilience of the generation mix** by considering the effects of **climate change** on the availability of **renewable energy resources**, as well as on **electricity demand**.

# WHAT ACTIONS CAN BE TAKEN?



## Fostering Technology and Innovation

- ◆ Encourage the modernization and repowering of existing power plants.
- ◆ Expand energy storage technologies, including hydropower plants with regulation reservoirs, pumped-storage hydropower (PSH), and battery systems.
- ◆ Foster research and development of new technologies for power generation, transmission and storage.



## Methodology Improvement

- ◆ Incorporate future projections into the scenario planning of hydrological availability.
- ◆ Enhance the representation of hydro generation in operational simulation models.
- ◆ Reevaluate the criteria used to ensure compliance with system operational requirements.
- ◆ Review the criteria for site assessment and sizing of hydropower plants.
- ◆ Establish guidelines to support project scale adaptation.
- ◆ Monitor and systematize data related to threats, vulnerabilities, and risks.



## Advancing Regulatory Frameworks

- ◆ Develop new market designs aimed at enhancing systemic resilience.
- ◆ Review regulations considering system attributes and requirements (storage, flexibility, ancillary services, and peak demand response).
- ◆ Create regulatory incentives to promote the adoption of adaptation measures at the project level.



## Enhancing Communication

- ◆ Engage with stakeholders in the sectors of energy, water resources, environmental management, and other relevant sectors.
- ◆ Establish collaborative relationships with research and technology development organizations.
- ◆ Promote dialogue on issues related to hydropower plants and climate change.

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