TRANSMISSION AND CLIMATE CHANGE

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

Understanding how climate change could affect the power transmission system is essential to support planning aimed at enhancing the resilience of the Brazilian electricity system. This Fact Sheet discusses the role of electricity transmission in Brazil, presents climate risks, describes how EPE has been addressing this issue, and highlights pathways for adapting the electricity system to climate change.

1 *Understanding the context*

2 *Identifying climate risks*

3 *Developing pathways*

99,4%

of Brazil's total electricity demand in 2024 was supplied by the SIN.

188,000

kilometers

of transmission lines in the SIN Main Network (voltages from 230 kV to 800 kV)

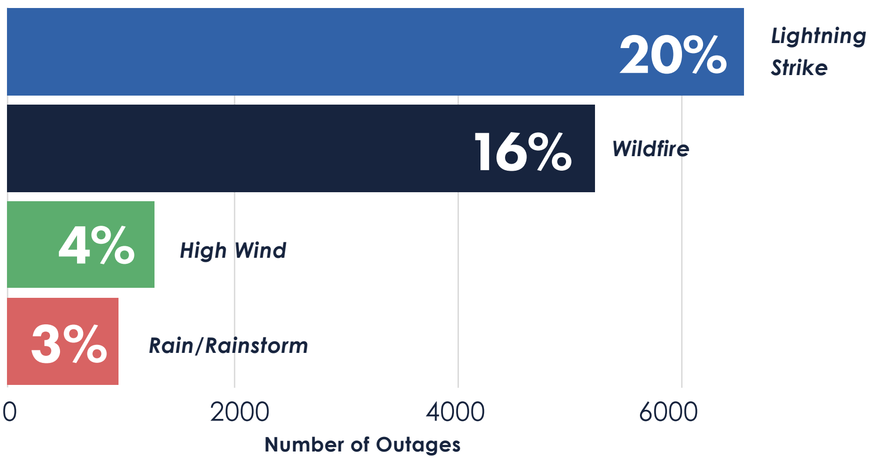
The National Interconnected System (SIN) is an energy generation and transmission system consisting of four subsystems – South, Southeast/Central-West, Northeast and North – where the transmission network fulfills the following strategic functions:

- **IInterconnecting** the subsystems to enable flexible management of available energy resources, allowing the exploitation of complementarities across generation sources, large-scale energy transfer to load centers, and of system operation optimization;
- Ensuring the **stability**, **security and flexibility** of the electrical system, maintaining its balance amid disturbances such as generation or transmission failures or sudden load variations;
- Strengthening the **Energy Transition process** by allowing the integration and expansion of renewable energy sources, which are fundamental to achieving a sustainable and resilient power system.

Of the 116 identified causes of transmission line outages, four are associated with climatic factors, accounting for 43% of all outages recorded between 2014 and 2023, with lightning strikes and wildfires standing out as the most significant factors.

*Other 112 causes account for 57%
Source: Brazilian National System Operator (ONS), 2024. Elaboration: EPE, 2025.

Distribution of Transmission Line Outage Causes



This document focuses on the electric power transmission system. The distribution of low-voltage electricity to households and small consumers is not within the scope of this publication.

WHAT HAS BEEN HAPPENING?

Recent events, which have been occurring with increasing intensity and frequency, suggest potential impacts of climate change on power transmission.

2009

A severe storm caused a short-circuit fault on the transmission line between Itaberá (São Paulo) and Ivaiporã (Paraná), shutting down three lines that transmit electricity from Itaipu, **triggering a blackout across 18 Brazilian states, the Federal District and Paraguay**, affecting 45% of the country's electricity consumption.

2013

A **wildfire** in the state of Piauí caused a short-circuit in two 500 kV transmission lines (a double contingency event), leading to the **collapse of the electric power system in Brazil's Northeast region**. As a result, all nine states in the region experienced a **blackout lasting up to four hours**, with a load cut of 10,900 MW

2014

A lightning strike in the state of Tocantins caused a short-circuit on two 500 kV transmission lines (a double contingency event), resulting in a **blackout that affected 11 states** and disrupted power supply to approximately 6 million consumers, with a **load cut of 6,787 MW**.

2016

Severe windstorms in the state of São Paulo caused **8 transmission towers to collapse**, resulting in the automatic tripping of transmission lines in the Main Grid of the National Interconnected System (SIN).

2021

Due to the **critical hydrological scenario**, with reduced hydroelectric generation in the Southeast region, it was necessary to increase electricity transfers from other regions, such as the North and Northeast, **raising the energy transfer to levels close to the security limits of the existing transmission lines**.

In 2021, **Wildfires caused 886 automatic trips** in the transmission network, the highest number recorded since 2014.

2023

A historic drought in the Madeira River, in Rondônia, led to the shutdown of the Santo Antônio power plant and **disrupted the operation of one of Brazil's largest electric power transmission lines**, which connects the North and Southeast regions, **posing challenges to maintaining the stability of the SIN**.

A heatwave in November in the Southeast region caused a sharp **increase in transmission network loadings** due to higher electricity consumption.

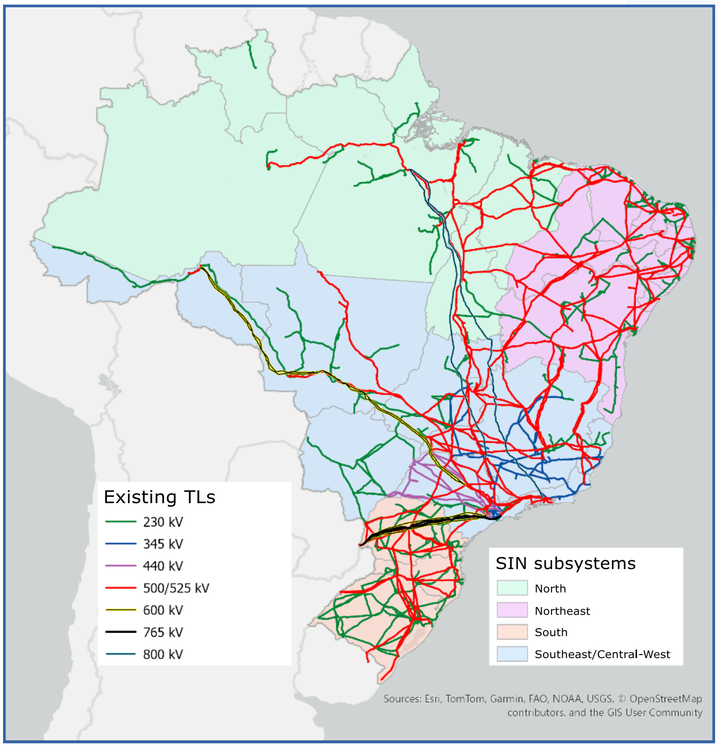
2024

Intense rainfall in the South region exposed multiple power generation and transmission infrastructures to risk. **Wind gusts and intense rainfall caused tower collapses and flooding**. At the peak of the event, more than a dozen **substations were flooded and 40 transmission lines became unavailable.**

2025

A storm caused the **collapse of 5 transmission towers** connected to the Belo Monte power plant, in the state of Pará. The affected asset transmits electricity to the South and Southeast regions of the country.

WHERE ARE THE TRANSMISSION LINES LOCATED IN BRAZIL?

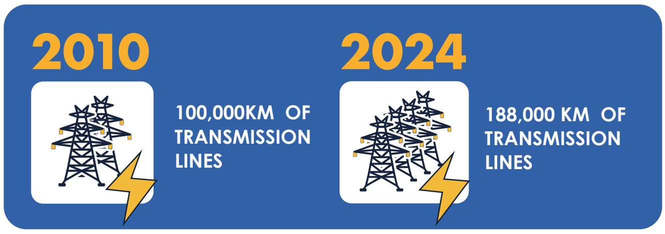


Brazil's transmission grid spans 188,000km, with a predominance of voltage levels at 230 kV and 500/525 kV, which together account for approximately 163,000km of the total length. The high-voltage direct current (HVDC) transmission lines, operating at 600 kV and 800 kV, represent the longest segments of the grid.

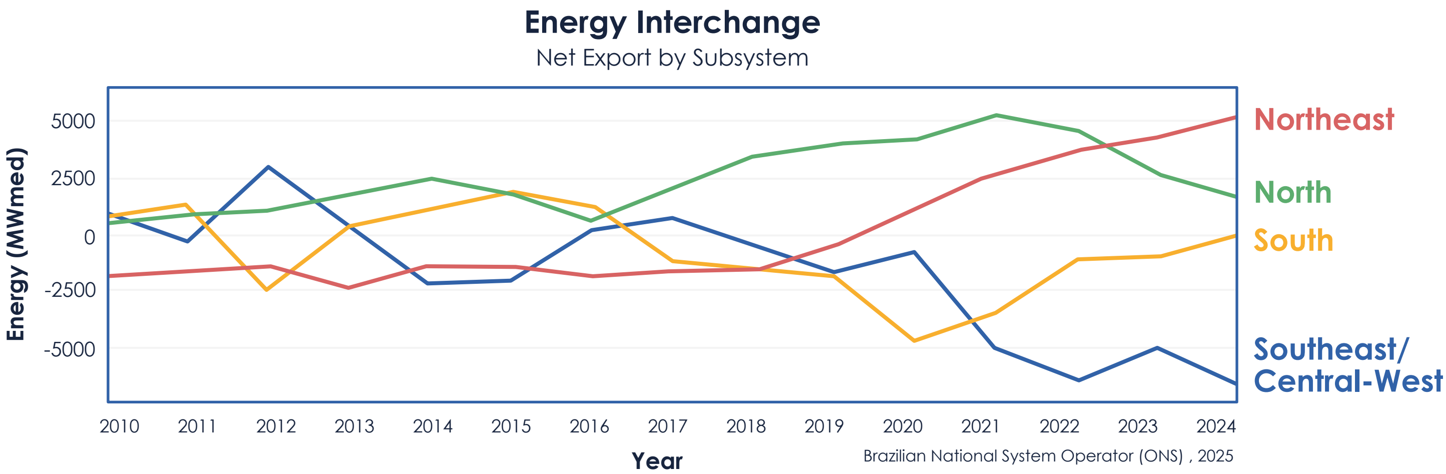
The Southeast/Central-West subsystem concentrates most of the transmission lines, representing approximately **45% of the total grid length**, while the Northeast (22%), South (17%), and North (16%) subsystems share the remaining infrastructure.

Between 2010 and 2024, the length of the country's transmission lines **grew by 88%**, increasing the capacity for power exchange between subsystems, improving grid redundancy, reliability, and expanding interconnection to new regions.

The expansion of transmission infrastructure enables regions with higher generation capacity to supply those with greater energy demand, optimizing the use of the country's energy resources and leading to cost reductions.



Due to the diversification of the power matrix and the increasing share of **renewable sources** such as wind and solar, **the energy transfer capacity between different regions** (energy interchange) becomes increasingly essential for balancing supply and demand. The chart below highlights how the Northeast region has solidified its role as an energy exporter in recent years, driven by renewables, while the Southeast/Central-West has expanded its imports, remaining the main consumption center.

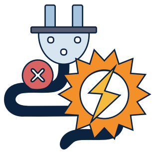


Brazilian National System Operator (ONS) , 2025

A **more integrated and robust grid** minimizes the risks of supply interruptions, while also **enhancing the resilience of the electrical system** in the face of extreme weather events and consumption peaks.

IDENTIFYING CLIMATE RISKS

RISK = THREAT X EXPOSURE X VULNERABILITY



How will people and economic activities be affected?

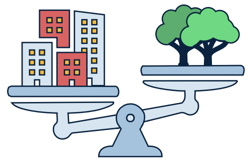
Adverse consequences for human systems.

What will the climate be like?

Physical event or trend.

Where?

Presence of people, infrastructure, and essential services.



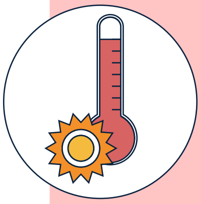
What increases the risk?

Propensity to be adversely affected – sensitivity and lack of adaptive capacity.

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

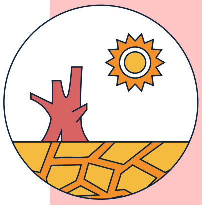
HOW CLIMATE THREATS CAN IMPACT THE ELECTRICITY TRANSMISSION SYSTEM ?

Brazil's energy transmission system is predominantly composed of overhead lines and substations, which makes it especially vulnerable to a range of climate-related events. Such conditions can directly affect the operation of transmission networks.



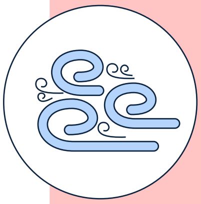
Rising temperatures

- High temperatures decrease the operational efficiency of transmission lines and transformers.
- Heatwaves and sustained high temperatures modify electricity demand patterns and may lead to overloading of the transmission network.



Increase in the frequency and duration of droughts

- Increases the probability of wildfires.
- Facilitates the accumulation of particulate matter on insulators, thereby increasing the risk of short-circuits.

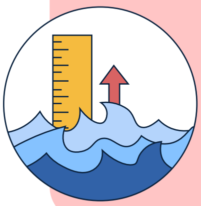


Increase in the frequency and intensity of high winds

- Can lead to structural damage or cause the collapse of transmission line towers.

Increase in the magnitude and duration of extreme precipitation

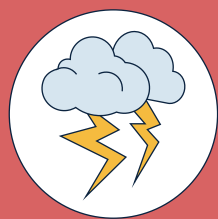
- May lead to flood events at substations.
- Landslides and flooding can cause damage to transmission infrastructure



Sea Level Rise

- Can cause structural damage and corrosion of transmission infrastructure in coastal areas.

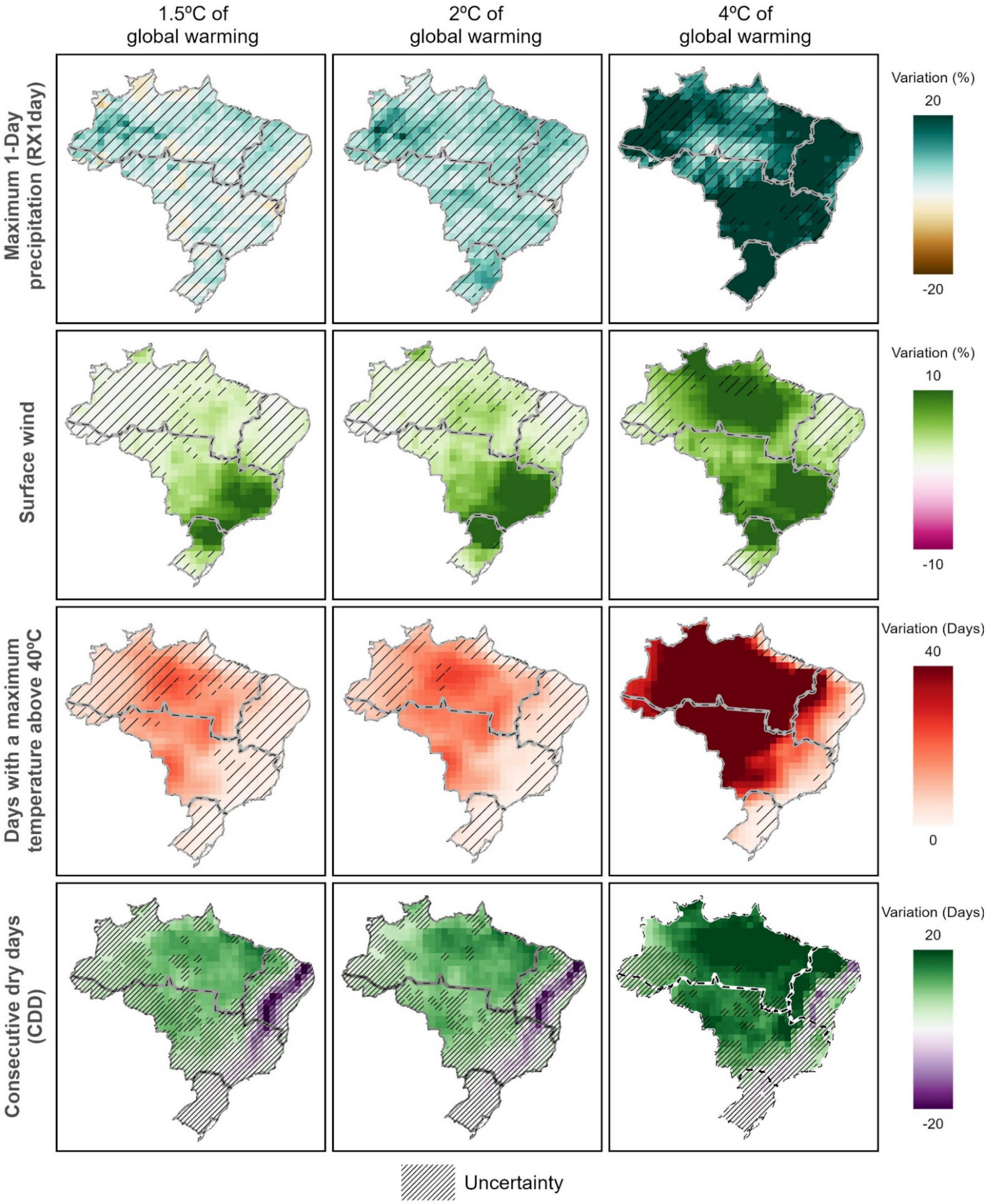
High temperatures, dry weather and high wind increase **fire weather** conditions, increasing the risk of wildfires that can affect the power transmission system.



Lightning during storms increases the risk of strikes on transmission equipment, which can lead to system outages.

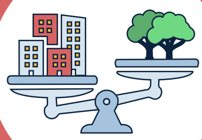
WHAT ARE THE CLIMATE TRENDS FOR BRAZIL?

IPCC climate projections indicate the following trends in relevant climate variables with potential impacts on the power transmission system:



Projected changes for global warming levels of 1.5°C, 2°C, and 4°C relative to 1995–2014. Interactive Atlas (IPCC, 2021).

The power transmission system's vulnerability **to climate change** is closely linked to the exposure of its **infrastructure** to extreme weather events and to structural and systemic issues.



WHAT CHARACTERISTICS INCREASE THE VULNERABILITY OF THE POWER TRANSMISSION SYSTEM TO THE IMPACTS OF CLIMATE CHANGE?

Extensive Infrastructure

Transmission lines are linear infrastructure systems that extend over large areas and interconnect most of Brazil's territory. Therefore, they are more exposed to weather-related threats.

Limited Network Redundancy

Regions supplied by transmission networks without alternative pathways for energy transmission are more vulnerable to supply disruptions in the event of faults.

Insufficient Energy Exchange Capacity among Subsystems

The ability to transfer energy between subsystems enables the flow of electricity from surplus to deficit areas, helping mitigate the impact of extreme events such as severe droughts, storms, and heat waves, which can strain the power system.

Transmission Lines Dimensioned for Climatic Conditions Different from Those That May Occur Due to Climate Change

Infrastructure projects may not be adequately dimensioned to support future climatic conditions. For example, conductors and materials may have been designed for lower average air temperatures and towers may have been engineered for lower wind speeds.

Infrastructure in areas susceptible to flooding

Substations in areas susceptible to flooding are more vulnerable to climate change, as intense rainfall events can cause flooding and resulting disruptions to power supply.

Aging Infrastructure

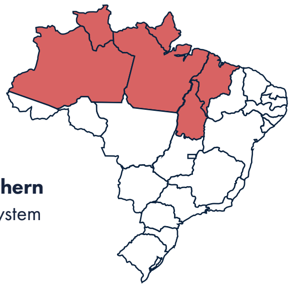
Older transmission lines are more susceptible to failures if they do not receive adequate maintenance.

Access and Maintenance Challenges

Limited-access environment, such as dense forests and mountainous regions, hinder inspections, repairs, and emergency recovery efforts.

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

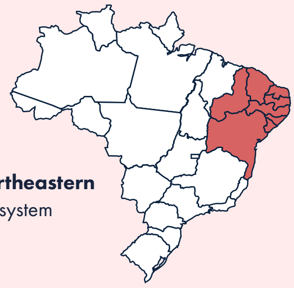


Northern
Subsystem

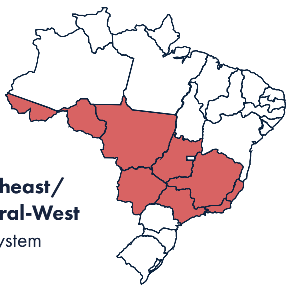
This subsystem has extensive territorial coverage, high socio-environmental sensitivity, and limited access routes, posing challenges for the implementation of new transmission lines. It consists of **systems with radial characteristics, featuring localized load density, positioned far from main transmission trunks**. These characteristics increase the system's vulnerability to climate change impacts due to the lack of network branching and difficult access.

Note: The AC/RO System, although connected to the Southeast/Central-West Subsystem, also has these characteristics.

This subsystem has experienced the largest transmission expansion in recent years. It is currently **the largest energy exporter in the electricity system**, relying predominantly on variable renewable energy generation, whose resources are directly influenced by climate changes. These characteristics present challenges for network operation.



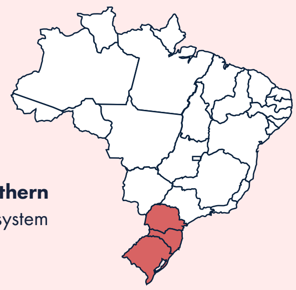
Northeastern
Subsystem



Southeast/ Central-West
Subsystem

This subsystem has the **highest energy demand, supported by key transmission backbones, and a dense network of transmission lines**. Expanding the grid faces challenges related to socio-environmental impacts, high land acquisition costs, and limited land availability. Population concentration amplifies stress on the power grid, which is already undergoing natural aging, posing significant operational challenges during peak demand events. On the other hand, this subsystem excels in data availability and monitoring and, most notably, offers the greatest operational flexibility, primarily due to the presence of hydropower plants with regulation reservoirs. **Additionally, it also experiences a high incidence of wildfires and lightning strikes.**

This subsystem relies heavily on energy imports, as local demand exceeds its generation capacity. Expanding the network presents challenges related to socio-environmental impacts, high land acquisition costs, and limited land availability. Heat waves causing load peaks can be particularly difficult to manage. On the other hand, the subsystem benefits from international interconnections, which serve as an alternative to enhance supply security. Projections of extreme rainfall and severe winds are especially relevant for the Southern Subsystem. In this context, infrastructure susceptibility is a key concern, with transmission lines with significant exposure to high winds and substations located at elevations prone to flooding.



Southern
Subsystem

MAIN CLIMATE RISKS RELATED TO TRANSMISSION:

- **Power Supply Interruptions and Infrastructure Damage**
- **Reduced Transmission Capacity**

DEVELOPING PATHWAYS

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

Design and Reliability Criteria vs. Uncertainties:

Defining **new infrastructure design and planning criteria based on climate projections** is essential for enhancing **the resilience of the transmission system**. However, there is a significant degree of **uncertainty associated with climate models, particularly regarding** the projection of extreme winds and the frequency and duration of droughts. In addition, challenges arise form the limited availability of sufficiently long historical data series on wind and lightning, hindering robust trend analysis.

Generally, the reliability criterion adopted in the planning and operation of the National Interconnected System (SIN) is the N-1 criterion, meaning the system must withstand the loss of any single network element without service interruption. It must also maintain system stability, frequency, and voltage levels, and avoid equipment and assets overloads. In certain areas, particularly at the subsystem's interconnections and state capitals supply points, the N-2 criterion may be applied. **Adopting more conservative reliability criteria** increases system redundancy but also raises investments associated with transmission.

Transmission Resilience vs. Investment vs. Environmental Impact:

Climate change poses significant challenges to transmission infrastructure, requiring more **robust networks capable of withstanding extreme weather conditions**, including intensified heatwaves, more frequent storms, and extreme wind events. However, adaptation involves substantial costs associated with **equipment modernization, the deployment of advanced monitoring technologies**, and system expansion with increased **redundancy**.

The key challenge is **balancing the need for greater resilience with the economic feasibility and environmental impacts associated with the deployment of new transmission lines and substations**. This requires smart investment strategies, the use of more resilient materials and the adoption of innovative solutions that ensure long-term network reliability without compromising the financial sustainability of the sector and costs for grid users.

Infrastructure Restoration:

Transmission system equipment is typically large-scale, creating **logistical challenges for manufacturing and transportation**, particularly in remote areas. Additionally, these assets require specialized labor, and their components are often unavailable in stock for immediate maintenance or replacement, which presents a challenge in the event of tower collapses or transmission equipment failures.

Given the need to balance resilience, economic feasibility, and environmental impacts, operating a fully risk-free transmission system is not viable. Therefore, establishing methods and procedures for rapid recovery following climate-related events is essential to minimize disruptions for consumers.

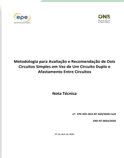
Climate change affects both energy supply and demand directly impacting the sizing and expansion of the electrical grid. To ensure the grid's reliability and resilience, it is essential to understand how these factors alter load patterns and to **develop solutions that enable the adaptation of transmission infrastructure**.

HOW HAS THE TOPIC BEEN ADDRESSED BY EPE?

Click on the images to learn more.

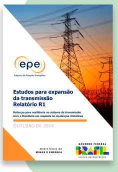
The Ten-Year Energy Expansion Plan (PDE) assesses the **expansion prospects** of the energy sector over the next 10 years. In the PDE 2034, one of the key focuses was enhancing the **resilience of the electrical system** in the face of **extreme climate events**.

The Energy National Plan (PNE) aims to guide **the long-term strategy of the energy sector in Brazil**. In the PNE 2055, currently under development, there is a notable emphasis on discussing uncertainties related to the resilience of the electrical system in future scenarios.



The Technical Note "Methodology for Assessing Two Single Circuits Instead of a Double Circuit and Defining Optimal Separation Distance" prepared by EPE and ONS, established criteria to enhance the resilience of the transmission system in strategic regions of the SIN with a high incidence of outages caused by lightning strikes and wildfires.

The Hydroelectric Reservoir Recovery Plan (PRR) proposes **31 actions** over a **10-year** horizon that contribute to the climate **resilience of the power system**. Among the proposed measures, particular emphasis is given to the expansion and reinforcement of transmission systems, as well as the monitoring of key lines that support regional power exchange.



The Study on Climate Resilience of the Acre/Rondônia System aimed to evaluate the transmission system under **critical climate conditions**. The proposed projects would enable approximately a **twofold increase in the import and export capacity of this subsystem**. EPE is also conducting studies on the systems of the states of **Amazonas, Roraima and Amapá**, with the objective of enhancing **the resilience of radial systems located in the North of the country**.

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

The Climate Plan is the implementing instrument of the National Climate Change Policy. Within this context, EPE contributed to the preparation of the **Energy Sector Adaptation Climate Plan** (currently under revision following Public Consultation), which already integrates some of the adaptation initiatives referenced above.

Climate change demands the continuous improvement of methodologies and criteria used for electric power transmission planning. In this regard, EPE has sought to incorporate climate risks into the planning reports for new transmission lines and substations (R1 Reports). In 2024, following the floods in Rio Grande do Sul, EPE recommended to the Ministry of Mines and Energy (MME) the withdrawal of Lot 2 from Auction 02/2024 to reassess the location of projects in vulnerable areas, an action that reinforces the commitment to adapt transmission infrastructure planning to extreme events. Additionally, the company's technical teams participate in sectoral forums to assimilate technological innovations that enhance the efficiency and resilience of the National Interconnected System.

WHAT ACTIONS CAN BE TAKEN?

Fostering Technology and Innovation

- Encouraging research and development into new transmission technologies (e.g., flexible transmission systems - FACTS devices, new conductors for transmission lines) and smart grids.
- Expand energy storage technologies.
- Conduct research and development to enhance technologies for monitoring and forecasting extreme weather events.

Advancing regulatory frameworks

- Promote regulations that encourage adaptation measures, as well as effective response and mitigation strategies.
- Review expansion and operational planning criteria to balance costs and benefits for the population.
- Reevaluate system reliability criteria in the context of emerging climate scenarios.
- Define limits, concepts, and standards regarding extreme weather events.

Strengthen infrastructure and response capacity

- Strengthen infrastructures and implement equipment with greater resilience to future climatic conditions.
- Monitor and systematize data related to threats, vulnerabilities, and risks.
- Conduct systematic mapping of critical infrastructure and equipment and continuously evaluate the adoption of preventive measures.
- Develop response plans for emergency situations.
- Develop joint solutions among sector stakeholders to strengthen emergency response capacity.

Methodology Improvement

- Review the criteria for sizing and site identification of new transmission lines and substations.
- Consider climate and impact data in planning, such as areas susceptible to flooding and landslides.

Enhancing communication

- Creation of dedicated committees for monitoring climate risks and responding to extreme events.
- Coordinate with stakeholders from the energy, water resources, environmental, and related sectors.

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