Assessment of the policy framework's impact on the renewable energy generation expansion in the Brazilian power grid

ICAT Initiative for Climate Action Transparency

Initiative for Climate Action Transparency – ICAT

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Product 2 – Report on VRE and biomass expansion under current policies

ICAT Brazil Project phase 3

September 2023

Initiative for Climate Action Transparency – ICAT

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List of Acronyms

ACR	Regulated Trading Environment
ACT	Assessing Low Carbon Transition
ACT-DDP	Assessing Low Carbon Transition – Deep Decarbonization Pathways
AFOLU	Agriculture, Forestry, and Other Land Use
AGE	Adjustment Auction
ANEEL	National Electric Energy Agency
BEN	National Energy Balance
BNDES	National Bank for Economic and Social Development
CBios	Biofuel Emission Certificates
CCEAR	Energy Trading Contracts in a Regulated Environment
CCEE	Electric Energy Trading Chamber
CEOs	Chief Executive Officer
CEPEL	Electric Energy Research Center
CIMV	Interministerial Committee on Climate Change and Green Growth
CNPE	National Council of Energy Policy
COP	Convention on Climate Change
COPPE	Alberto Luiz Coimbra Institute of Graduate Studies and Engineering Research
CPS	Current Policies Scenario
DDP BIICS	Deep Decarbonization Brazil, China, India, Indonesia, and South Africa
DDS	Deep Decarbonization Scenario
DEMO	Demographic Parameter Estimation Model
DG	Distributed Generation
ELETROBRAS	Brazilian Electric Power Company
EPE	Energy Research Company
ESEP	Electric System Expansion Planning Model
GHG	Greenhouse Gas
GW	Gigawatts
HPP	Hydroelectric Power Plant
iCS	The Institute for Climate and Society
IEPM	Integrated Energy Planning Model
IKI/BMU	International Climate Initiative / Nuclear Safety
iNDC	Intended Nationally Determined Contribution
IRENA	International Renewable Energy Agency
LEE	Existing Energy Auction
LEN	New Energy Auction
LER	Reserve Energy Auction

LFA	Alternative Sources Auction
LSI	Isolated System Auction
LT-MCM	Long-Term Macroeconomic Consistency Model
MATRIZ	Brazilian Energy Mix Model
MME	Ministry of Mines and Energy
NAMAs	Nationally Appropriate Mitigation Actions
NDC	Nationally Determined Contribution
PAP	Proinfa Annual Plan
PDE	Ten-Year Energy Expansion Plan
PERS	Social Renewable Energy Program PERS
PLANDEPE	Petroleum Refining Study Model
PNE	National Energy Plan
PNMC	National Policy on Climate Change
ProGD	Power Generation Development Program
Proinfa	Incentive Program for Alternative Sources of Electric Energy
REN	Aneel Normative Resolution
RenovaBio	National Biofuels Policy
SCEE	Electric Energy Compensation System
SDG	Sustainable Development Goal
SHPP	Small Hydroelectric Power Plant
SIN	National Interconnected System
TFP	Total Factor Productivity
UFRJ	Federal University of Rio de Janeiro
UN	United Nations
UNFCCC	United Nations Framework Convention on Climate Change
UNICA	Union of the Sugarcane and Bioenergy Industry
VRE	Variable Renewable Energy

Forewords

This report is part of the ICAT Brazil Project phase 3, hereafter referred to as ICAT project, which is implemented by Centro Brasil no Clima (Brazil Climate Centre – CBC) in partnership with Centro Clima (PPE/COPPE/UFRJ) with support from the Initiative for Climate Action Transparency (ICAT) and technical support from the UNEP Copenhagen Climate Centre (UNEP CCC).

The previous phases of the ICAT project aimed at the enhancement of the transparency framework in Brazil by developing MRV indicators to assess climate policies and actions at the national (1st phase) and subnational (2nd phase) level. These phases developed mitigation scenarios that provide critical insight for policy development at the national and sub-national levels and proposed MRV indicators to track the implementation of the Brazilian NDC.

The third phase of the ICAT Brazil project, which started in March 2023, builds off insight gained from the first two phases, by providing a detailed analysis of the electricity sector in Brazil. The project assesses the potential expansion of the power sector in the country through variable renewable energies (wind and solar photovoltaic) and biomass, the sustainable development impacts of sectoral policies by applying the ICAT's Sustainable Development Methodology and contributes for the Just Energy Transition planning in Brazil.

This report is the Output 2 of the ICAT project, prepared by Centro Clima/COPPE/UFRJ, and presents an analysis of existing energy policies and their potential impact on the expansion of Variable Renewable Energy (VRE) and biomass sources as established in the work plan of the ICAT Brazil Project phase 3. The goal of this analysis is to gain insights into the role of current policies in shaping the future landscape of sustainable energy in Brazil. Additionally, this report outlines the construction of a 'current policies' scenario (CPS) and compares its results with scenarios developed by PNE 2050 (National Energy Plan).

1 Introduction

Evaluating the impact of the expansion of renewable electricity generation is a crucial and timely topic of discussion in the context of a country's energy goals and environmental concerns. The composition of the electricity mix significantly impacts the carbon intensity of the economy and decarbonizing the sector is paramount to a country to achieving the 2050 net-zero target. In Brazil, the energy transition is a process that entails a gradual increase in the share of renewables in the country's electric mix, which includes both grid and off-grid electricity sources, already heavily reliant on renewable sources (Figure 1).

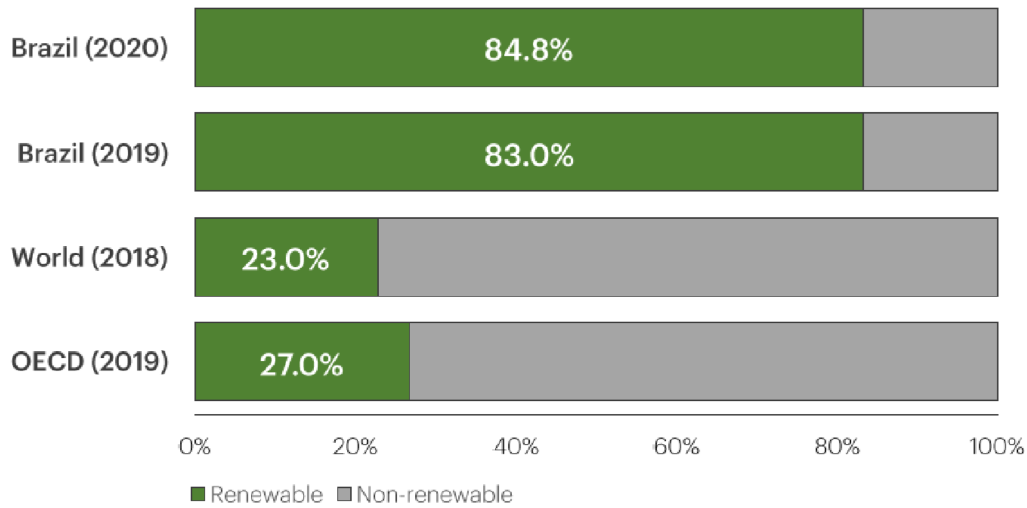

Figure 1 – Share of renewable energy in the Brazilian electricity mix and in the rest of the world (%)
Source: EPE (2021a)

Historically, Brazil's electricity mix has been dominated by hydroelectric power. The construction of large hydroelectric power plants in the last century played a crucial role in meeting the country's electrical needs. However, this over-reliance on hydropower has brought challenges, such as vulnerability to prolonged droughts that have affected electricity supply.

Biomass power generation has been a part of Brazil's energy landscape for several decades. Biomass cogeneration, which involves the production of electricity mostly from sugarcane bagasse and black liquor, was incorporated into the energy system as an early strategy to diversify the energy mix. This approach leveraged Brazil's abundant biomass resources and contributed to reducing the dependence on hydroelectric power.

In 2001, a water shortage crisis brought about significant transformations in the electrical system, leading to a national reevaluation of the Brazilian electricity mix with fossil fuel plants being constructed in an urgency regime. In 2015 and 2021, Brazil faced other significant water crises, leading to reservoirs falling to unexpectedly low levels. During these last two periods, what are known as "tariff flags" were put into effect. This was due to the fact that distributors had to procure electricity at a higher cost from thermoelectric plants, and as a result, consumers experienced higher electricity bills.

Therefore, diversifying the electricity mix was an important strategy to ensure the country's electricity security. By incorporating intermittent sources, Brazil reduces its dependence on hydroelectric power, making it less vulnerable to fluctuations in supply. Besides security reasons, Brazil began investing in intermittent sources, such as solar and wind, for several reasons, including:

- Harnessing natural potential: Brazil has significant potential for solar and wind energy due to favourable climatic conditions. Investing in these sources allows the country to harness abundant natural resources;
- Carbon emissions reduction: The use of intermittent sources contributes to reducing greenhouse gas emissions. This is crucial for meeting emissions reduction targets and addressing climate change concerns;
- Stimulating the renewable energy sector: Investment in intermittent sources of energy stimulates the growth of the renewable energy sector, creating jobs and economic opportunities. It also promotes technological innovation;
- Increased resilience of the electrical system: Diversifying the energy mix with intermittent sources can increase the resilience of the electrical system by reducing reliance on a single energy source, making it less susceptible to extreme weather events or supply disruptions;
- Attracting investments: Brazil attracts international investments by promoting clean and renewable energy sources, which can benefit the country's economy; and

- Meeting environmental goals: Investment in intermittent sources contributes to meeting environmental commitments and sustainable energy targets, both nationally and internationally.

Thus, the incorporation of variable renewable sources of electricity is part of a broader strategy to diversify Brazil's energy mix, make it more sustainable and resilient, and address environmental and energy challenges in the country. An evaluation of the potential expansion of renewable electricity generation in the Brazilian grid is important so that actions and public policies that contribute to decarbonization and just energy transition in society can be carried out, by reducing the use of fossil sources even further.

This report assesses the impact of government current policies and initiatives on the expansion of clean electricity sources in Brazil, which include solar, wind, hydroelectric, and biomass energy. It is grounded in previous scenario exercises that utilize an integrated modeling approach, as further elaborated in section 2. These scenarios simulate the Current Policy Scenario (CPS) and examine the potential increase in the shares of variable renewable energy sources and biomass as influenced by existing policies. The results are then compared to those outlined in the National Energy Plan (PNE 2050), developed by the Brazilian Energy Research Company (EPE). The analysis evaluates installed capacity and electricity generation data, categorized by energy source, to provide valuable insights into the role of variable renewable energy sources in Brazil's electricity sector.

In the introduction, the main objectives of this report are presented. In section 2, the sectoral context in the country is provided. In section 3, the methodological approach employed in this study is described, and the previous studies on which this work is based are outlined, and in section 4, an examination of sectoral policies and their long-term impact is conducted. Transitioning to section 5, a deep dive into the description of the newly introduced current policy scenario and its outcomes takes place, followed by section 6, which details PNE 2050 (Plano Nacional de Energia, in Portuguese), a collection of studies supporting the government's long-term strategic design for the energy sector's expansion. Section 7 encompasses a comparison between the values of the PNE and those of the new scenario. Lastly, in section 8, the conclusions are presented.

The upcoming report will involve a revision of the Deep Decarbonization Scenario (DDS), which was also previously developed by Centro Clima. This comprehensive endeavor will include crafting a comparative analysis of the outcomes generated by a more ambitious mitigation scenario, specifically focusing on the electric mix, associated costs, and greenhouse gas (GHG) emissions. This analysis will highlight the differences between CPS and DDS, estimate cost and GHG emissions, with particular emphasis on variable renewable and other renewable energy sources.

2 Sectoral country context

Brazil recorded an annual power consumption of 586 TWh in 2022, with a consistent annual growth rate of 3% over the last two decades as shown in Figure 2 (EPE, 2023a). The demand growth has been driven by economic development, urbanization, technological advancements, energy-intensive industries, improved standards of living, and government policies. Due to the growing electricity demand, there is an undeniable need for investments in supply assurance.

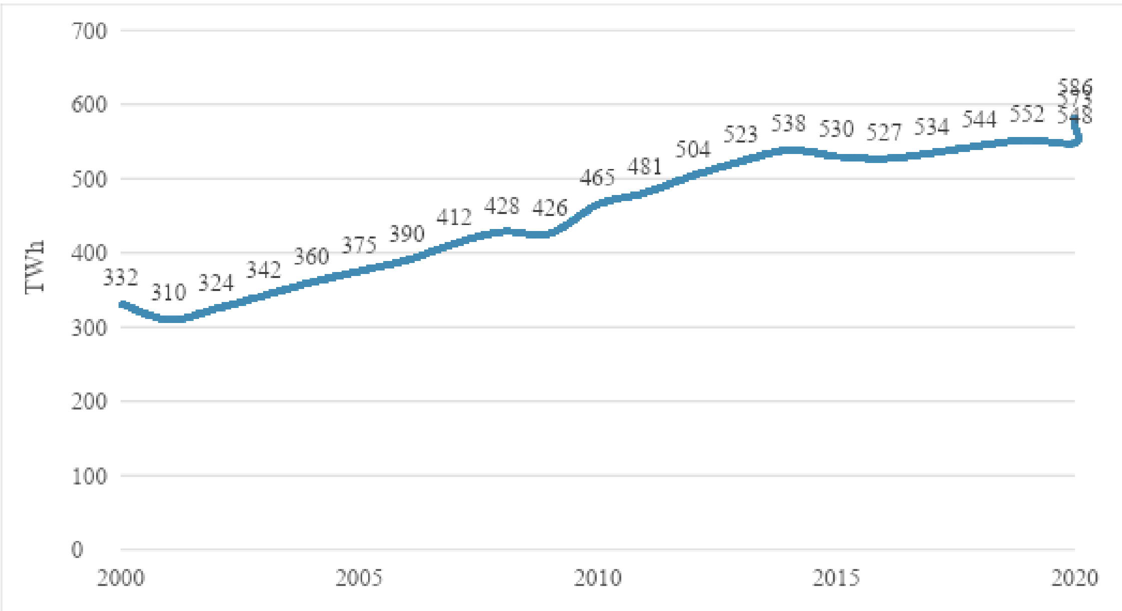

Figure 2 – Total electricity demand (2000 – 2022)
Source: Authors based on EPE (2023a)

In 2020, the average per capita electricity demand in Brazil stood at 2,946 kWh. It's noteworthy that nearly all households in the country already have access to electricity sources (EPE, 2022a; EPE, 2023a). Figure 3 provides a sector-wise breakdown.

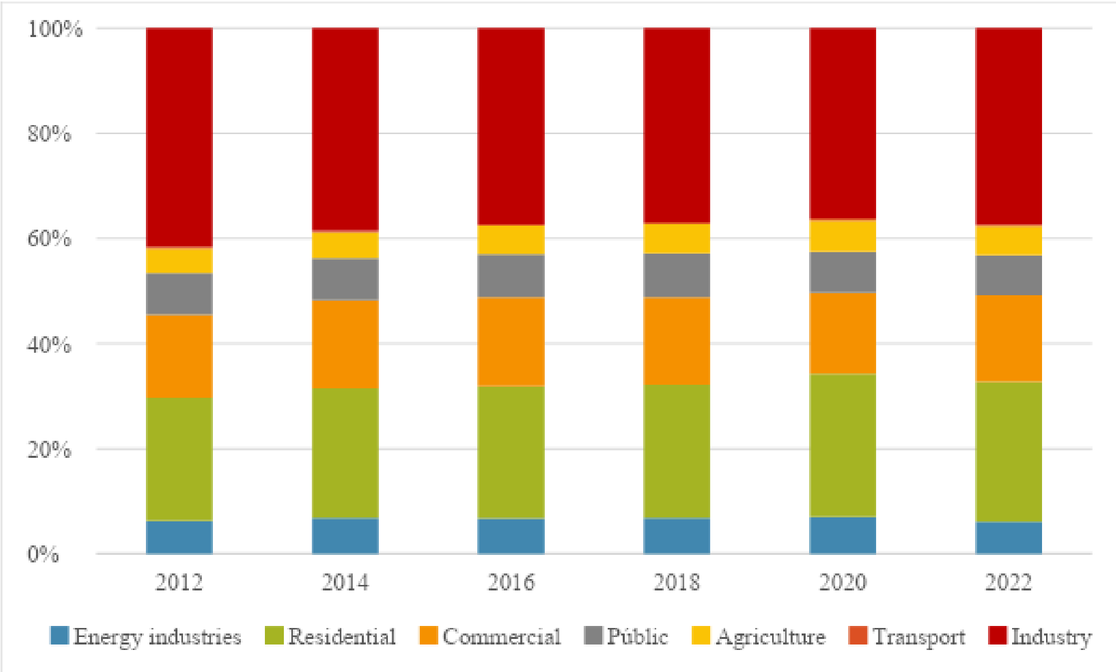

Figure 3 – Sectoral shares of electricity demand (2012-2022)
Source: Authors based on EPE (2023a)

Despite the increase in electricity demand, Brazil has made significant developments in electricity efficiency in recent years. In 2001, the country passed the National Energy Efficiency Law, which created the Procel program, a national energy efficiency program that has implemented a variety of measures to reduce electricity consumption in all sectors of the economy (BRASIL, 2001).

Procel has implemented a number of successful programs, including minimum energy performance standards for appliances and equipment; energy labelling programs; energy efficiency audits and retrofit programs for buildings and industry; and public awareness and education campaigns. As a result of Procel's efforts, Brazil has achieved significant energy savings. For example, 22.10 billion kWh saved in 2022, which represented 4.35% of total electricity consumption in Brazil, enough to supply 11.16 million households (PROCEL, 2023).

In addition to Procel, other initiatives are underway to promote energy efficiency in Brazil. For example, the Brazilian government launched the National Energy Efficiency Plan in 2022, which sets ambitious goals for reducing energy consumption in the country (MME, 2023). The plan includes a number of measures, such as improving the energy efficiency of buildings, industry, and transportation. Furthermore, the government has launched programs to support the development and adoption of renewable energy technologies, such as solar and wind power. These technologies can help to reduce Brazil's reliance on fossil fuels and improve the country's energy efficiency. Some of those policies will be further described in section 3.

Electricity's journey to consumers covers extensive distances. In Brazil, hydroelectric plants are located far from large urban centres. Irrespective of the energy's origin, it is conducted through a high-voltage transmission grid. The length of this network exceeds 100 thousand kilometres due to the vastness of the country. High voltage becomes imperative for transmitting substantial power quantities with minimal losses. Upon reaching the substations, the voltage is reduced and subsequently distributed through the distributor's network, ultimately reaching end users. This ensures the electricity supply to consumers.

The National Interconnected System (SIN) enables the connection of electrical networks across nearly the entirety of Brazil's geographical expanse (around 183 thousand km). The transmission grid facilitates the exchange of power between different subsystems, capitalizing on collaborative advantages and leveraging the distinct hydrological patterns within various basins. The planning cycle of the electricity sector for the period from 2023 to 2037 reveals that the energy consumption in isolated systems in 2023 is projected to account for only 0.6% of the total energy load in the National Interconnected System (SIN), as per data provided by ONS (EPE, 2022a), which supplies approximately 1.5% of the country’s population.

The isolated systems in the Amazon region are highly diverse, ranging from remote locations to urban centres, each with varying population sizes and energy demands. These systems are primarily powered by thermoelectric plants running on diesel oil, known for its high cost and significant pollution. The electricity sources for these isolated systems primarily consist of 96% diesel and fuel oil, with smaller contributions from natural gas (2.2%), biomass (1.1%), and hydroelectric generation (0.7%) (EPE, 2021b).

These plants serve only the isolated systems of the region, and the energy is brought to these populations through energy distributors. In isolated systems of more difficult access, diesel is transported by rivers, by means of boats or even in a hybrid way (land and river).

Although the SIN transmission lines are connected to hydroelectric plants in the Amazon region, neighbouring communities are not supplied by them due to different aspects: remote access, cultural, environmental, economic, political, among others that create barriers to the connection of these areas.

Figure 4 indicates the changes in the primary energy sources used for electricity generation since 2000, with hydroelectricity being the dominant source in Brazil's power system. Nevertheless, constructing new large hydroelectric plants has become increasingly challenging, as most of the untapped potential is in ecologically vulnerable areas in the Amazon region.

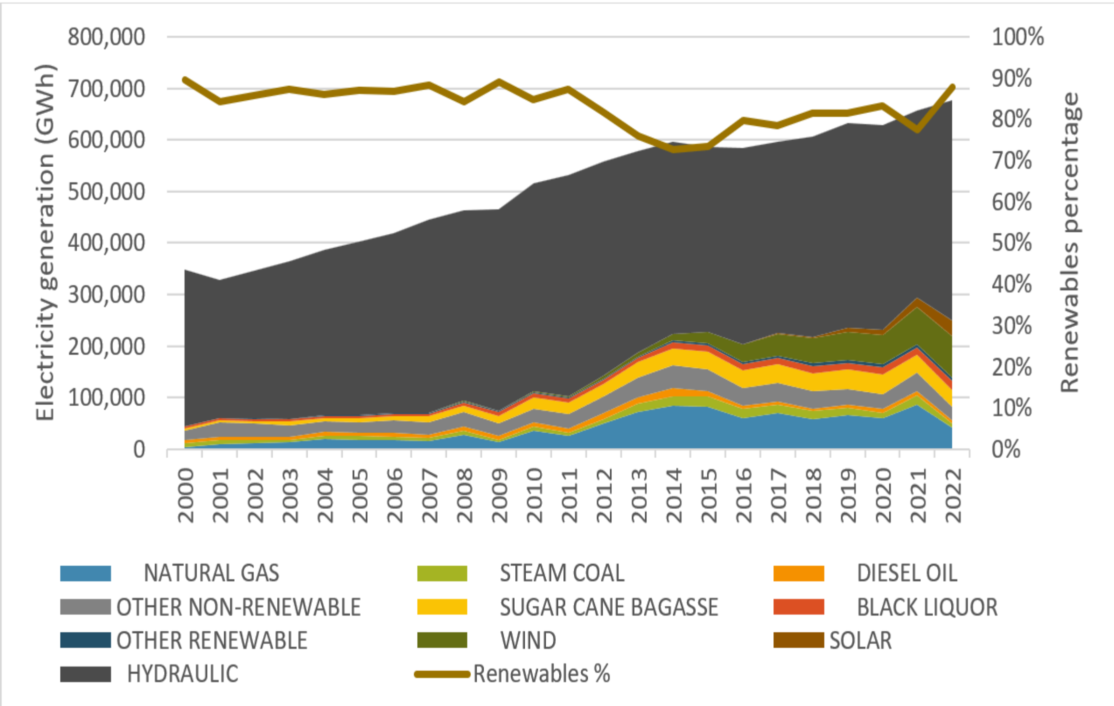

Figure 4 – Detailed sources of electricity generation (2000-2022)
Source: Authors based on EPE (2023b).
Note: Renewables include hydro, biomass, solar and wind.

The Brazilian power sector is moving towards a more diversified energy mix, with new renewable sources such as wind and solar becoming increasingly prominent. To incentivize the adoption of wind, small hydro, solar, and biomass technologies, various measures have been implemented, including discounted tariffs, reduced import taxes, and subsidies. Moreover, natural gas has been employed as a supplementary energy source when renewable resources prove insufficient, accounting for 6% of power generation in the year 2022.

According to Figure 5, variable renewable sources (wind and solar) made up 16% of Brazil's electricity generation in 2022, with wind accounting for 12% and solar 4% (EPE, 2023b).

Thus, the Brazilian electricity mix differs from the others due to the great importance of hydropower and biomass plants, so the percentage of expansion of VREs may reach lower levels when compared to the ideal percentage of 70%, as described as a "good practice" by the New Climate Institute (2018). Brazil has a high potential to achieve a 100% renewable mix but including hydro and biomass.

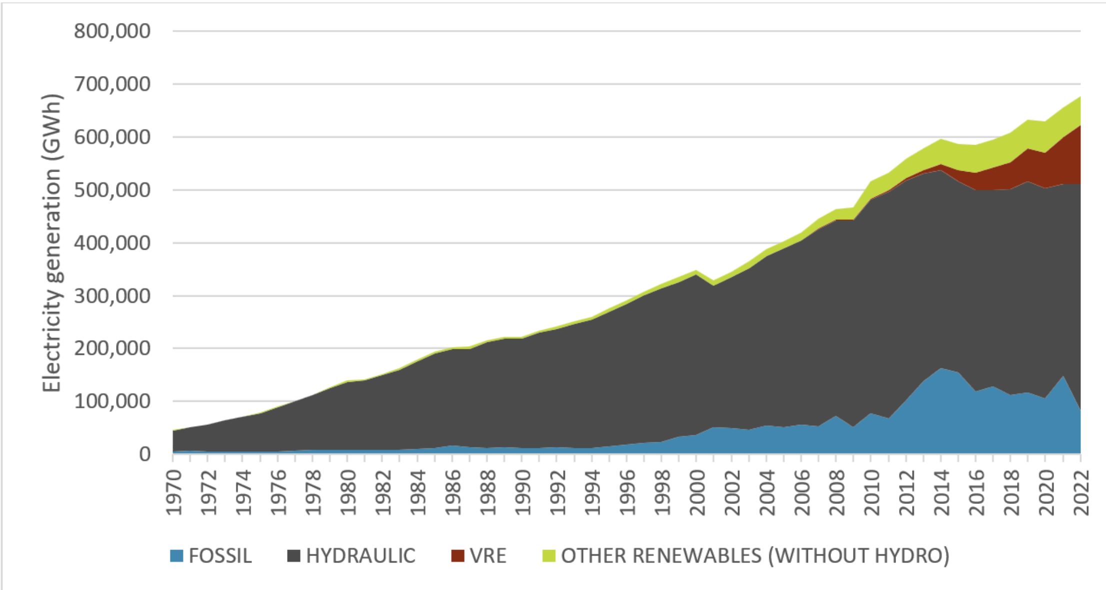

Figure 5 – Aggregated sources of electricity generation by origin: fossil fuels, hydroelectricity, VRE and other renewables (1970-2022)
Source: Authors based on EPE (2023b)

Electricity generation from biomass, wind and solar has been growing significantly over the last few years, as detailed in Figure 6. Bioelectricity generation peaked in 2020, when it reached 58,742 GWh, and remained at high levels in the following years. Wind energy experienced exponential growth, culminating in a peak production of 81,631 GWh in 2022. Solar energy has displayed more recently, yet remarkably, achieving an output of 30,126 GWh.

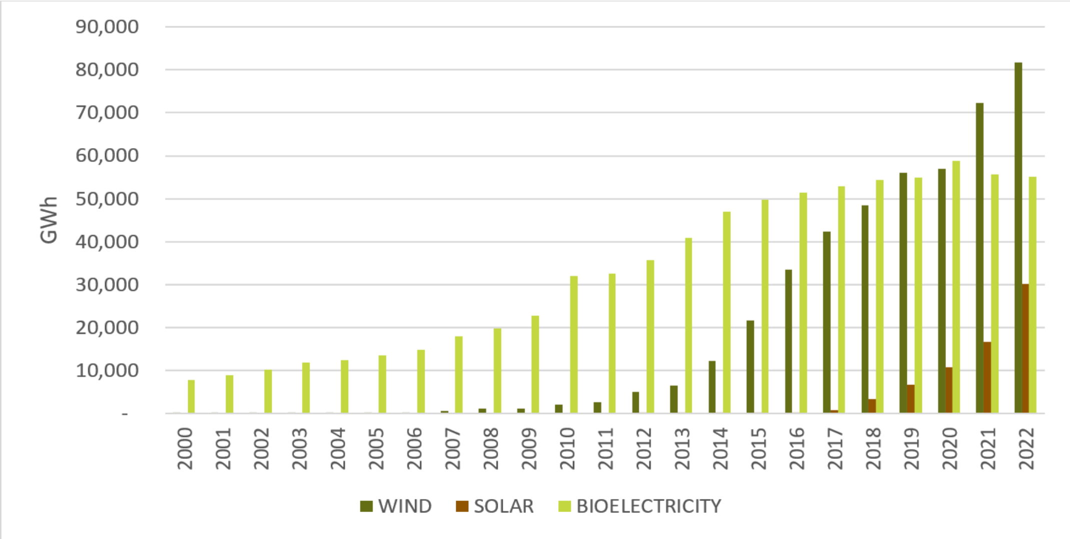

Figure 6 – Non-hydro renewable electricity sources: biomass, wind and solar (2000- 2022)
Source: Authors based on data from EPE (2023b)

In terms of installed capacity, solar energy surpassed wind energy for the first time in 2022, becoming the second largest source in the country by reaching 23.9 GW of operational installed power. It is important to point out that 17 GW comes from distributed generation. In addition, photovoltaic solar energy represents 94% of distributed generation in the country and is responsible for the intense increase registered in micro and mini-distributed generation in recent years. Wind energy, in turn, reached 23.7 GW. Figure 7 shows the evolution of the installed capacity of these electricity sources.

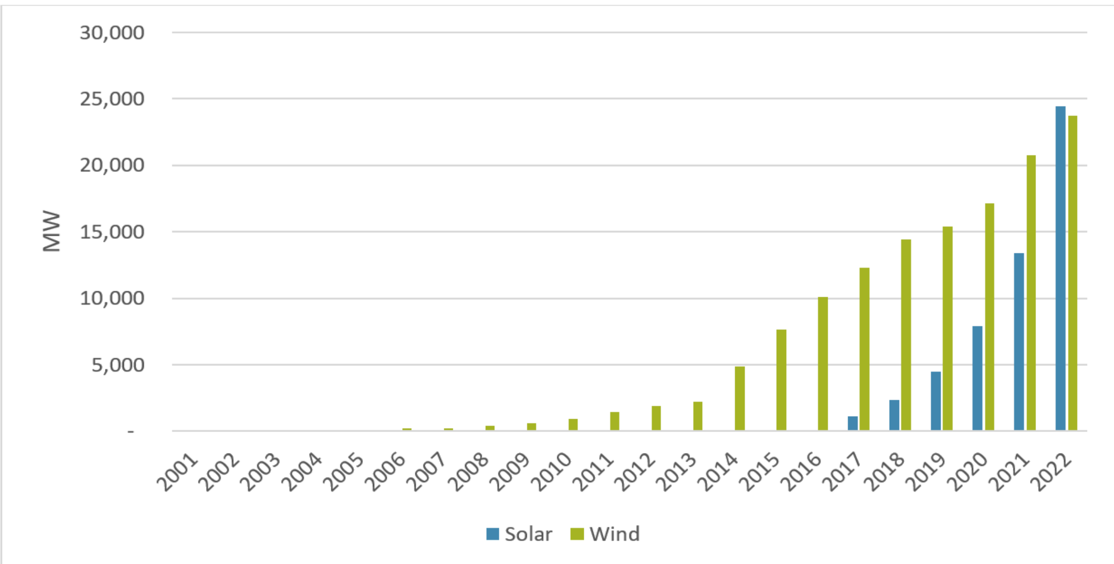

Figure 7 – Installed capacity of wind and solar energy (2000-2022)
Source: Authors based on data from EPE (2023b)

The emission factor of power generation in Brazil varies annually, primarily depending on the hydrological conditions of the year. These conditions have a substantial impact on the output of hydropower plants. Hence, this dynamic also impacts the carbon intensity of the power sector, as it requires the utilization of fossil fuel sources during periods of limited hydropower availability. In 2020, when the nation faced water scarcity, the average emission factor stood at 85.2 kgCO_2eq/MWh. This constituted about 34% of the emission factor seen in Europe, 24% of that in the United States, and merely 12% of that in China. By 2022, the factor had decreased to 61.7 kgCO2eq/MWh (EPE, 2023a).

Brazil appeared to be making significant strides in its endeavor to attain the first version of the NDC which had a target of incorporating 23% of non-hydro renewable energy sources into its power generation portfolio by 2030 (INSTITUTO TALANOA et al., 2021, LA ROVERE et al., 2021). Although the last NDC version submitted to the UNFCCC in 2022 does not mention sectoral targets, Brazil keeps the challenge of effectively managing its abundant and diverse energy resources to help meeting the economywide target. The country benefits from a favorable position concerning energy resources that exhibit low GHG emissions, which are plentiful, competitive, diverse, and have spatial and temporal complementarities. The key to ensuring energy security lies in the pursuit of a diversified energy mix.

3 Methodological approach

Given the climate emergency and the urgent need to enhance greenhouse gas (GHG) mitigation efforts in the Brazilian economy, this study has developed a GHG emission scenario under current policies (CPS) for the Brazilian power sector, projecting its implications through 2060. Subsequently, as mentioned, a Deep Decarbonization Scenario (DDS) will be developed to estimate the maximum potential for increasing renewable energy sources.

Centro Clima uses an integrated modeling approach that links a set of six sectoral models to a CGE model (IMACLIM-BR): four energy demand models (transport, industry, buildings, and agriculture energy demand); an AFOLU model; and an energy supply model (MATRIZ). Finally, a waste model completes the estimates.

The complexity of sectoral models in Centro Clima projects varies based on several factors. These include the sector's significance in the country's overall emissions profile and the level of potential mitigation identified by its team of experts, and the availability of data for conducting intricate modeling. Given these considerations, more detailed modeling efforts are allocated to sectors such as transportation and the energy supply sector.

In the industrial sector, the model encompasses a range of mitigation measures, particularly those related to biomass utilization and process enhancements. Agriculture (with focus on agricultural practices) is also a sector with a huge potential, but along with the industrial sector, has a moderate level of details regarding databases. For waste management, different levels of success in achieving sanitation policies' goals are simulated and treatment technologies are explored, with and without biogas recovery. When it comes to modeling deforestation, a simplified approach is adopted due to the inherent complexities involved. The implementation of government initiatives to curtail deforestation, to varying degrees of success of past efforts, depending on the scenario is considered.

In sectors where the potential for mitigation is limited, such as energy demand in agriculture, residential, public, and commercial sectors, simplified techniques are employed. These techniques are elaborated in section 4.2 where the methods for estimating electrical demand are presented (and they are also applied to fuel-related modeling). For agriculture, public services, and the commercial sector, efficiency gains in future years of the scenario reflect the progress achieved through autonomous technical progress and policies in the historical data series. For the residential sector, a proxy is used for future demand.

To develop the scenarios for the ICAT project, the initial task required calibrating an updated version of the mathematical model for energy supply (MATRIZ). This new version features a higher granularity for analyzing the electricity supply-demand balance across different time frames and locations and was selected due to the cooperation between Centro Clima (PPE/COPPE/UFRJ) and CEPEL (Electric Energy Research Center). MATRIZ is an optimization model that minimizes the supply cost of meeting an energy demand projection. For the ICAT project, Centro Clima updated the

Current Policy Scenario (CPS) for electricity demand and generation. This scenario was previously developed by Centro Clima in projects reported in the next subsections.

3.1 Qualitative storyline and quantitative assumptions – approaches for scenario construction

During the 2020-2023 period, Centro Clima collaborated with other projects in the field of the ICAT Brazil Project phase 3, such as: 2.1.1 DDP BIICS; 2.1.2 the ACT-DDP project ; 2.1.3 the Climate and Development Initiative; and 2.1.4 the DecarBoost project.. These projects' designs considered quantitative modeling and stakeholders' inputs obtained during project events and bilateral meetings. This collaboration between the technical team and stakeholders helps validate results and reduce uncertainty around political risks. It also creates awareness among investors about potential mitigation actions opportunities in Brazil. The following sections briefly introduce the projects previously mentioned and highlight the involvement of key stakeholders in the results of Centro Clima studies.

3.1.1 DDP BIICS Project

The DDP BIICS Project was developed with the support of the International Climate Initiative (IKI) of the German Federal Ministry for the Environment, Nature Conservation and Nuclear Safety (BMU). The project drew on the community developed through the Deep Decarbonization Pathways Project and shared methodological insights with members of the 2050 Pathways Platform to support their process of developing long-term strategies. These pathways have been presented to the public and used in domestic decision-making processes. The methodology and findings from this project are shared with experts and practitioners globally, as well as with members of the 2050 Pathways Platform to aid in the development of long-term strategies.

The DDP BIICS Project is a collaborative initiative to understand and show how individual countries can transition to a low-carbon economy with a focus in Brazil, India, Indonesia, and South Africa.

Two scenarios were developed for each of the countries: the Deep Decarbonization Scenario (DDS) and the Current Policy Scenario (CPS). These scenarios provide detailed descriptions at the sector level, focusing on specific areas of interest chosen by each country.

The project also emphasized the extraction of essential policy insights that can directly inform national-level policy discussions. These insights encompass various aspects, including:

- Identification of primary synergies and trade-offs with non-climate national objectives;
- Prioritization of short-term policies and actions, with a particular focus on areas where deviations from the current trajectory are urgently needed;
- Analysis of investment patterns;
- Assessment of key international facilitators and accelerators that can drive domestic transitions.

By organizing the findings in this manner, the aim is to offer a clear and actionable roadmap for policymakers and stakeholders in each country. Centro Clima's research developed within the scope of DDP BIICS presented a design of qualitative stories and quantified scenarios of GHG emissions along decarbonization paths aligned with the Paris Agreement (Centro Clima, 2022).

3.1.2 ACT-DDP Project

The objective of the ACT-DDP Project was to boost efforts to reduce GHG emissions in Brazil's main economic sectors and also to align with the global objectives of the Paris Agreement. Sectors covered by the project and dialogues include energy, cement and livestock. The project stands out for its innovative approach, as it combines the evaluation methodology of the ACT (Assessing Low Carbon Transition) initiative of companies' carbon reduction strategies and the basic approach of the DDP (Deep Decarbonization Pathways) initiative to develop routes and realistic decarbonization scenarios by 2050 (ACT-DDP PROJECT, 2021).

The differential of the ACT-DDP project is that the focus was at a company level, so academic activities gain companies as partners. This engagement of partner companies gives concreteness to what was being produced. Therefore, there was the creation of original complementary insights, enriching the projects, and bringing benefits to ICAT products.

The study created a plan for reducing GHG emissions in Brazil, using a combination of qualitative narratives and quantitative data. The research process involved input from stakeholders and followed a step-by-step approach, including reviewing initial scenarios developed by Centro Clima – the Current Policies Scenario (CPS) and the Deep Decarbonisation Scenario (DDS) – identifying obstacles to implementing the DDS, and developing policy solutions.

Dialogues were organized with stakeholders from the selected sectors. In general, the first part of each meeting was focused on the presentation by the Centro Clima team of the national and sectoral scenarios. In the second part, partner companies from each sector were invited to make presentations on their actions and policies for mitigating GHG emissions, contributing to the Project with insights.

3.1.3 Climate and Development Initiative: Visions for Brazil 2030

The Climate and Development Initiative (C&D) aimed to bring together Brazil's political leaders and experts to collaborate in creating a shared vision for the decarbonization and development of the country's economy during the current decade. The scenarios developed through this initiative were considered vital in guiding the decisions of public and private stakeholders in the short and medium term, with the Brazilian climate change commitments to the Paris Agreement serving as a framework for a development plan that encompassed economic, social, and environmental aspects (Unterstell & La Rovere, 2021).

Technical discussions were led by Centro Clima, while high-level political consultations were carried out by the Talanoa Institute. The Institute for Climate and Society (iCS) provided support for the project, enabling a diverse group of organizations, networks, and coalitions to participate between May and October 2021.

The starting point was the Brazilian Deep Decarbonization Scenario, from the DDP BIICS project, but during the process, new assumptions were added to some mitigation actions and stakeholders requested a more ambitious scenario, that simulated an end to deforestation in the Amazon and Atlantic Forest by 2030 instead of 2050. Around 300 experts and leaders from various sectors, including subnational governments, civil society organizations, and companies attended the Initiative.

Its principal outcome was presented as a suggestion from civil society for a more ambitious Brazilian NDC until 2030, with a reduction in GHG emissions ranging from 66 to 80%, in contrast to the Brazilian government's new commitment of a 50% reduction (as compared to the reference year of 2005) as presented to the UNFCCC in March 2022.

The report was published in Brazil and at various events throughout COP 26. The Initiative provided a list of recommendations for each presidential candidate running for the 2022 elections in Brazil.

3.1.4 Decarboost Project

The Decarboost initiative aimed to accelerate progress in countries such as Argentina, Brazil, and Peru toward low-carbon societies, fostering investments aligned with sustainable development. This project was also developed with the support of IKI /BMU. It facilitated dialogues between the public and private sectors, making significant contributions to the formulation of the next set of Nationally Determined Contributions (NDCs) and establishing a regional equilibrium on a global scale (DECARBOOST, 2023).

This collaborative effort engaged experts and stakeholders from diverse sectors. Notably, the Decarboost project uniquely focused on analyzing barriers to achieving Brazil's GHG reduction targets and identifying potential strategies to attain them.

Throughout the Decarboost project, Centro Clima consulted multiple stakeholders to validate selected barriers across Brazil's economic sectors and strategies to overcome them. This inclusive approach captured insights from specialists, enabling the creation of a comprehensive Mitigation Plan. This plan not only outlines strategies for meeting climate goals but also identifies investment opportunities that yield multifaceted benefits for the nation's climate objectives and economy.

3.2 MATRIZ Model

The MATRIZ model (projection of the Brazilian energy mix) (LISBOA, M.L.V. *et al.*, 2012) is used to represent the Brazilian energy system, with minimization of the total cost of investment and operation of the system, choosing the best configuration in terms of capacity expansion and energy supply in the evaluated horizon.

The MATRIZ model is continuously developed by the Electric Energy Research Center (Cepel). It is an energy system optimization model capable of determining scenarios for the Brazilian energy mix evolution – details the electricity supply, biofuels, and oil refining sectors (including fugitive emissions). The MATRIZ model is a support tool for long-term energy system expansion planning studies, and it was used in the National Energy Plans, prepared by the Ministry of Mines and Energy (MME) and the Energy Research Company (EPE).

The MATRIZ model like the MESSAGE model[1], is based on a technical engineering approach to describe the energy system, from resource extraction to energy services provision through energy flows. The energy system is represented as a set of primary energy reserves and a set of specialized technologies capable of transforming energy reserves into energy services. The transformations occur in a chain, passing through several energy levels: primary, secondary, final and useful (DEA/CEPEL, 2016). At each energy level, energy forms are defined, which will be transformed into others through technologies (power plants, coal plants, refineries, natural gas production units and others), constituting different energy chains (Figure 8).

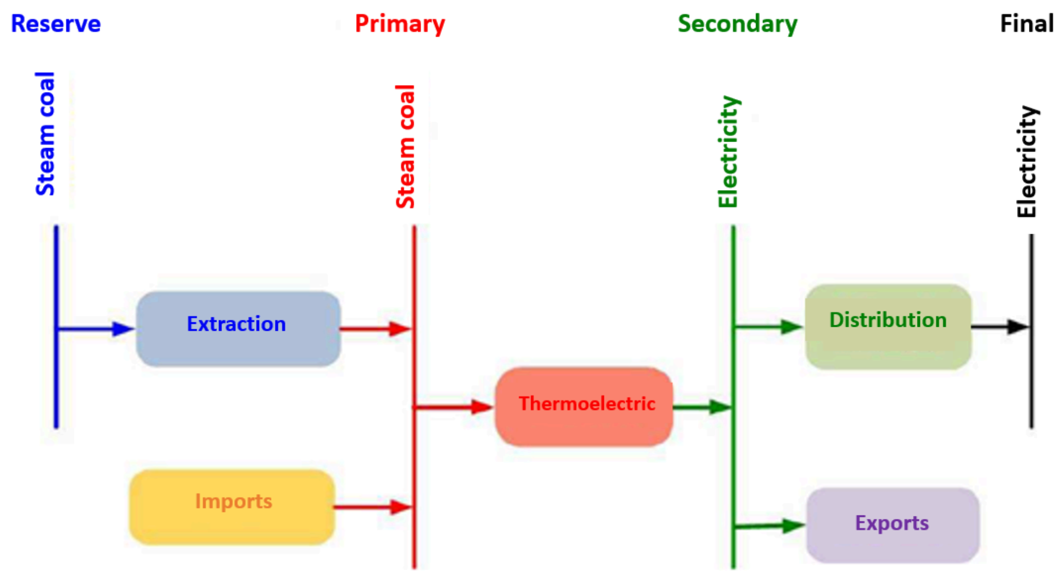

Figure 8 – Schematic diagram of the coal chain (simplified example)
Source: (DEA/CEPEL, 2016)

[1]The Energy Supply Model – International Institute for Applied System Analysis (IASA)

MATRIZ is a large bottom-up computational model, based on linear programming, which receives exogenous input data, such as the evolution of energy demand, availability of energy resources, technologies, fuel prices and the basic characteristics of transformation technologies.

The objective function minimizes the present value of the total cost of investment and operation of the energy system, the optimal solution. A viable solution to the problem is defined as any supply alternative for the various energy sources capable of meeting the expected energy demands for the considered scenario (electricity demands by subsystem regions and fuels by type), satisfying all other restrictions provided (capacity limits of electricity generation sources, minimum and maximum capacity factors per source, power transmission limits between regions, processing capacity and refining profiles of existing and new refineries, import and/or regasification of natural gas, availability of sugarcane bagasse cane for thermoelectric generation). To consider the significant seasonal and diurnal variations in the final energy supply and demand, energy consumption and production values are calculated for each season of the year and each load level. Technologies are represented in an aggregated form, as individualized representation would significantly increase the complexity of the integrated analysis of energy chains.

As a result, the model presents the optimal values of installed capacity by source and annual flows of energy corresponding to the production of electricity and fuels, imports, exports, and energy exchange between regions, at each period, for the entire study horizon.

The duration of each period is defined by the user and can be one or more years. With the increased penetration of intermittent sources, efforts have been made to improve the representation of intraday variations in the generation of these sources and system loads, seeking a more realistic approach to the operation (LISBOA, M L V *et al.*, 2023). Each period is subdivided into four seasons of the year, and, in each season, there are eight levels (Figure 9). This degree of detail (use of intraday profiles by representative chronological levels for each seasonal season) is important for representing fluctuations in solar and wind supply and demand. This mathematical formulation was implemented in a new version of the MATRIZ model.

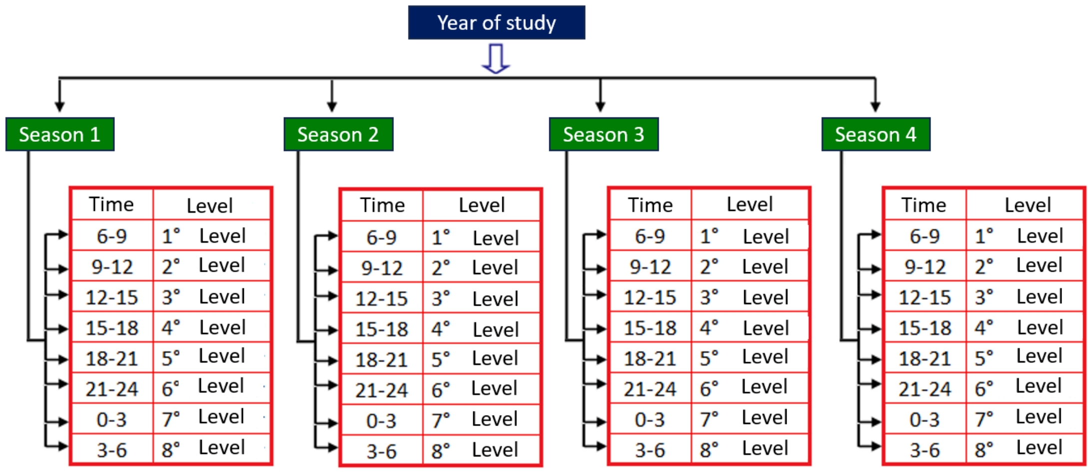

Figure 9 – Diurnal (up to 8 levels) and/or seasonal variations in the MATRIZ model

Source: Authors

Note: In the example, the day is divided into 8 levels of 3 hours each, a total of 24 hours a day.

In other words, the new version of the MATRIZ model provides higher granularity to the match between electricity demand and power generation dispatching, which is a key feature to assess the potential contribution of VRE such as solar and wind energy to power generation. Due to the complexity of the Brazilian electricity sector, nine operating subsystems are considered, and each analysis period is detailed in four stations and eight load levels. This level of representation of the system adopted in the model is essential to assess energy security, ensuring that the system meets seasonal and horo-seasonal demands in all subsystems.

The integration of VRE gives rise to supplementary complexities (such as VRE prediction accuracy, limitations in flexibility, determination, and distribution of operating reserves) and incurs extra expenses (including the establishment of new ancillary services). Hence, when conducting long-term planning analyses, it becomes imperative to consider a detailed representation of the system operation. This ensures an equilibrium balance between a cost-effective strategy (encompassing investment and anticipated operational expenditures) and the system's reliability, security, and complexity of the system operation.

Evaluating the impacts of VRE requires enhanced granularity in both temporal and spatial dimensions. The MATRIZ model can capture the temporal and spatial interdependencies among key energy sources (such as wind speeds, solar radiation, hydro inflows, and biomass availability). This approach enables the exploitation of potential "portfolio effects," which can mitigate overall variability, subsequently enhancing supply reliability and cost efficiency. Moreover, an evaluation of portfolio advantages requires detailed transmission system operations and constraints.

The model allows the specification of the amount of GHG produced by each technology and calculates the total cost of each scenario (investment and operation cost). It is also possible to insert in the objective function a penalty for the emission of a certain gas. In this way, it is possible to represent the carbon pricing internally in the model, simply defining the price considered for carbon emissions as a penalty per ton of "CO_2 equivalent emitted".

The use of the MATRIZ model makes it possible to simulate scenarios of optimized expansion of the production capacity of all energy sources available in the country in the horizon of 2050, their respective GHG emissions, and to consolidate projections of the Brazilian Energy Mix consistent with the general premises established in the definition of the scenarios considered.

The MATRIZ model has been used by the Centro Clima technical team since 2017 to develop a representation of the Brazilian electricity sector. Several projects and scenarios have already been developed using this software, including those projects described above. In all these projects, scenarios were simulated for the Brazilian electricity sector, with a focus on the growth of renewable energies, and all had a broad phase with stakeholders' engagement in the power sector. The stakeholder consultation phases were very important in collecting feedback and improving the representation of the power system in the model.

4 Policies implemented and their long term impact

This section presents an analysis of Brazil's legal and regulatory framework for the expansion of VREs and biomass, focusing on the sectoral policies affecting electricity consumption and generation.

4.1 Brazilian emission objectives and Nationally Determined Contribution (NDC) pledge

Brazil has played a relevant role in international climate change negotiations since its beginning in 1992, as a host country of UNCED. In 1997, it was the only non-Annex I country to propose the design of the Kyoto Protocol, based on the historical contribution of each country to global warming. In 2001, the country was also a driving force leading the establishment of a CDM (Clean Development Fund) established through the Marrakesh Accords. It has become one of the three developing countries with a larger number of CDM projects hosted.

Domestically, in 2008, after the creation of an Inter-ministerial Climate Change Commission, the first National Climate Change Plan was approved (BRASIL, 2008). Considering the intensification of international discussions and the signing of several agreements that address climate change, the National Policy on Climate Change (PNMC), Law n. 12,187/2009, was established aiming to make economic and social development compatible with the protection of the climate system and defined as principles, objectives, guidelines, and instruments for resilience to climate change (BRASIL, 2009).

Brazil made its first commitment to reduce GHG emissions in 2009 when presenting its NAMAs pledges to the United Nations Framework Convention on Climate Change (UNFCCC) as part of the PNMC (BRASIL, 2009). This voluntary commitment aimed to reduce emissions from a projected business-as-usual scenario by 36.1% and 38.9% by 2020. According to Decree n. 7,390/2010, which regulates the National Policy on Climate Change (PNMC), the baseline for greenhouse gas emissions for 2020 was estimated at 3.236 GtCO2-eq. Therefore, the corresponding absolute reduction was established between 1.168 GtCO2-eq and 1.259 GtCO2-eq. According to MCTI (2022), emissions in 2020 reached 1.676 GtCO2-eq, a reduction of 48%, corresponding to a mitigation of 1.673 GtCO2-eq, far beyond the pledges.

In addition to the mitigation goal of the policy, nine sectoral mitigation and adaptation plans were also established through Decree n. 7,390/2010, defining regulatory legal frameworks for adaptation and mitigation actions. (EPE, 2019). Among the sectoral plans, the Ten-Year Energy Expansion Plan (PDE) provided an indication, rather than a determination, of the anticipated growth prospects for the energy sector over the ten-year horizon."

Eventually, Brazil was very active in the negotiations leading to the signature of the Paris Agreement of the UNFCCC, at COP21 in Paris, 2015 (Waisman H., Torres Gunfaus M., Pérez Català A., Svensson J., Bataille C., Briand Y., Aldana R. et al. 2021). Thus, Brazil has demonstrated its ability to play a leading role in the decarbonization process of the world economy.

In 2015, Brazil presented its Intended Nationally Determined Contribution to the UNFCCC Conference of the Parties (COP21) (iNDC, hereafter referred to as NDC, following its ratification in 2016) (Brazil 2015). The Brazilian NDC pledge consists of an economy-wide, absolute mitigation target. The economy-wide goal was to reduce GHG emissions by 37% in 2025 and has an indicative target of reducing 43% by 2030, compared to the 2005 as the base year. It also presented the means of implementation in its annex. Economy-wide absolute targets, consistent with the sectors present in the National Inventory of Greenhouse Gas Emissions for 2025 and 2030, always compared with 2005. Brazil will update its national inventories for the historical series based on the 2006 IPCC Guidelines or any subsequent guidelines that may come to replace them.

Brazil has updated its NDC target twice since Paris, in 2020 and 2022. In 2020, the Brazilian government presented its first NDC to the UNFCCC (Brasil 2020), confirming the 2030 target and updating the base-year value. The 2005 value of 2.1 $GtCO_2e$ presented in 2015 had come from the Second National Inventory, and the updated value of 2.8 $GtCO_2e$ presented in 2020 came from the Third National Inventory, implying a substantial change in the commitment. The absolute economy-wide GHG emissions cap increased from 1.3 to 1.8 $GtCO_2e$ in 2025 and from 1.2 to 1.6 $GtCO_2e$ in 2030 (GWP-100, IPCC AR5). With an increase in the absolute emission goals for 2025 and 2030, instead of showing increased ambition, the Brazilian NDC violate the spirit of the Paris Agreement that is based on a premise of the progression of the efforts of countries in the continued reduction of their goals of GHG emissions. Since 2015, when the Brazilian government submitted its NDC, no plan was submitted to ensure that the original goals would be achieved (La Rovere et al. 2021f). On the other hand, the new first NDC also included an indicative target of reaching climate neutrality by 2060 (Brazil 2020). In 2021, the Brazilian president announced the country's commitment to achieving climate neutrality by 2050 at the Summit of Climate Leaders organized by the US President. In addition, civil society is increasingly mobilized through environmental NGOs and a pioneer climate litigation process started in Brazil by a process to request that the Court rules the government to present a really more ambitious NDC to the UNFCCC, as the first NDC (2020) would not meet the criterion of increased ambition as requested by the Paris Agreement (Waisman H., Torres Gunfaus M., Pérez Català A., Svensson J., Bataille C., Briand Y., Aldana R. et al. 2021).

In 2022, at the first NDC second update, Brazil (Brazil 2022) confirms its commitment to reduce its GHG emissions in 2025 by 37%, compared with 2005. Additionally, Brazil commits to reduce its emissions in 2030 by 50%, compared with 2005. Brazil's commitments also include a long-term objective to achieve climate neutrality by 2050. In this update, was informed that the quantification of the reference indicator is based on the total net emissions of GHG in the reference year of 2005 reported in the "National Inventory of Anthropogenic Emissions by Sources and Removals by Sinks of Greenhouse Gases not controlled by the Montreal Protocol". Brazil will adopt the latest National Inventory Report available and submitted to the UNFCCC by the time of the assessment of the results of the NDC. The absolute levels of emission targets for 2025 and 2030 will have to be changed again to 1.6 and 1.5 $GtCO_2e$/year, to reflect the new figure of 2.6 $GtCO_2e$/year for 2005 presented in the Brazilian Fourth National Communication recently submitted to the UNFCCC[2]. The first NDC second update is stronger than its 2020 update but remains weaker than its original NDC submitted in 2015. This updated NDC still allows higher emissions than Brazil's first submission, in contrast to the Paris Agreement's principles of progression and no backsliding. Table 1 and Figure 10 lists the targets included in the Brazilian NDCs.

This year, the 2023 update of Brazil's NDC to the Paris Agreement, announced at the Climate Ambition Summit (New York), returns the country's climate ambition to the level of the First NDC of 2015: Emission levels of 1.32 $GtCO_2e$ (reduction of 48%) in GGE by 2025 and 1.20 $GtCO_2e$ (reduction of 53%) in GGE by 2030.

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[2] For each new inventory, the entire time series must be recalculated to accommodate new data, methods, etc., ensuring comparability between values from past and recent years. The discrepancies in total GHG net emissions in 2005, verified between the 2nd, 3rd, and 4th National Communications, can be attributed to a significant change in the values considered for the 'Land Use Change' subtotal within the AFOLU sector (La Rovere et al. 2021f).

Table 1 – GHG net emissions in Brazil (2005-2020) and targets for 2025 and 2030

NDC version	GHG emissions and targets (GtCO2e – GWP AR5)					
	Base Year 2005	2010	2015	2020	2025	2030
NDC (2016) (base year value = approx. the 2nd Brazilian Inventory)[a]	2.10				1.32 (-37%)	1.20 (-43%)
1st NDC update (2020) (3rd Brazilian Inventory)[a]	2.83	1.36			1.78 (-37%)	1.61 (-43%)
2nd NDC update (2020) (4th Brazilian Inventory)[a]	2.56	1.33	1.56		1.61 (-37%)	1.46 (-43%)
3rd NDC update (2022)[a] (no absolute values given in NDC document)	The value of "the latest National Inventory Report available and submitted to the UNFCCC by the time of the assessment of the results of the NDC"				-37%	-50%
4th NDC update (2023) (4th Brazilian Inventory until 2015)[b]	2.56	1.33	1.56	1.78[3]	1.32 (-48%)	1.20 (-53%)

Sources: [a]Brazilian NDC documents presented to the UNFCCC; [b]Approved by the Interministerial Committee on Climate Change and announced at the Climate Ambition Summit; and [3]Annual emission estimates of greenhouse gases – 6th edition (2022).

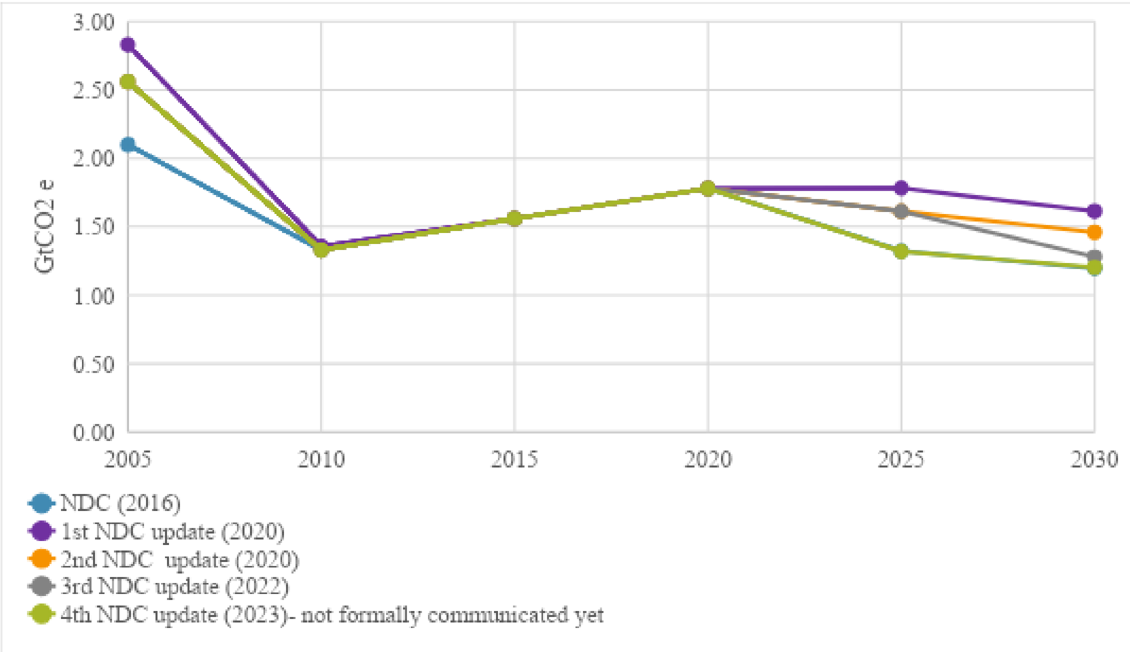

Figure 10 – Changes in the first Brazilian NDC

Source: Adapted from Brazil 2015, 2022; MCTIC 2016, 2021, 2022; Brasil 2020; La Rovere et al. 2021f
Note: absolute values of the "3rd NDC updated" simulated using the 4th national inventory values since the pledges in this version refer only to percentage values.

Recently, on International Environment Day 2023, the Brazilian government published five new climate decrees aimed at contributing to decarbonization (BRASIL, 2023), they are (Table 2).

Table 2 – New climate decrees aimed at contributing to decarbonization

Decree	Specification
n. 11,546/2023	Establishes the National Council for the 30th Conference of the Parties to the United Nations Framework Convention on Climate Change COP30, which will be hosted by Brazil
n. 11,547/2023	Provides for the Technical Committee of the Low Carbon Industry
n. 11,548/2023	Establishes the National Commission for the Reduction of Greenhouse Gas Emissions from Deforestation and Forest Degradation, Conservation of Forest Carbon Stocks, Sustainable Forest Management and Increase of Forest Carbon Stocks – REDD+;
n. 11,549/2023	Amends Decree n. 9,578/2018, which provides for the National Fund on Climate Change and the National Policy on Climate Change;
n. 11,550/2023	Provides for the Interministerial Committee on Climate Change.

Source: Authors

4.2 Energy Efficiency Initiatives in Brazil

The intricate relationship between energy efficiency and sustainable profitability has become increasingly apparent in recent years. In an era where technology catalyzes wealth creation and long-term economic growth, harnessing the power of energy-efficient practices has emerged as a pivotal driver of success. Energy efficiency policies and measures may include minimum energy efficiency indices (or consumption indices), comparative labeling (compulsory or voluntary) and endorsement seals (EPE, 2022b). Brazil has been carrying out these initiatives since the creation, in 1984, of the Brazilian Labeling Program (PBE), which began to develop comparative labels of equipment performance. The most relevant initiatives are:

a) **Brazilian Labelling Program**

The Brazilian Labelling Program was created in 1984. Coordinated by Inmetro (National Institute of Metrology, Quality, and Technology), it is a program that classifies products providing information on the performance of appliances and equipment considering attributes such as energy efficiency, noise and other criteria that can influence the choice of consumers, who will then be able to make more conscious purchasing decisions. It also stimulates the competitiveness of the industry, which must produce increasingly efficient products. It provides:

- Product Evaluation: The PBE evaluates various types of products, including appliances like refrigerators, washing machines, air conditioners, and lighting products;
- Energy Efficiency Classification: Products are classified based on their energy performance, with labels indicating their efficiency levels, typically ranging from A (most efficient) to E (least efficient);
- Consumer Information: The program provides consumers with clear and standardized energy labels that help them compare products and choose more efficient options;
- Consumer Empowerment: By making energy efficiency information readily available, the PBE empowers consumers to make informed decisions that can reduce their energy consumption and lower their electricity bills;
- Market Influence: The PBE has a significant influence on the market by encouraging manufacturers to develop and produce more energy-efficient products to meet consumer demand;
- Energy Conservation: Through its labeling and information dissemination efforts, the PBE contributes to energy conservation and a reduction in greenhouse gas emissions.

Overall, the Brazilian Labelling Program (PBE) plays a crucial role in promoting energy efficiency and sustainability in Brazil by providing consumers with valuable information about the energy performance of products and encouraging the adoption of more efficient technologies.

b) **The National Program for the Conservation of Electric Energy (Procel)**

The National Program for the Conservation of Electric Energy was created in 1985 as a governmental initiative to promote electric energy conservation and efficiency. It plays a pivotal role in Brazil's efforts to conserve electric energy, reduce electricity consumption, and promote sustainable energy practices. It has helped shape the market by encouraging the adoption of energy-efficient products and technologies, ultimately contributing to energy and cost savings for consumers and a reduction in greenhouse gas emissions.

According to the IEA (2023a), it aimed to promote energy efficiency in various sectors of the economy, through effective energy conservation measures. In 2016, a new source of funds and a new governance for the Program were defined (Law n. 13,280/2016). The current subprograms of Procel are: Buildings (Procel Edifica); Industry; Public Lighting (Procel Reluz); Sanitation (Procel Sanear); Education (Procel Education); Municipal Energy Management (Procel GEM); Information (Procel Info); PROCEL Seal; Marketing campaigns; structuring studies.

Recently, in line with the guidelines of the National Energy Policy Council (CNPE), Procel's role was reaffirmed through Decree n. 9,863/2019, which mentions the objectives of the Program in promoting actions of electric energy efficiency in the generation, transmission, and distribution of energy, as well as for the end user, aimed at: increasing the competitiveness of the country; postponing investments in the electricity sector; and reducing greenhouse gas emissions.

The Procel Seal indicates to the consumer the products that present the best levels of energy efficiency within its category (air-conditioning, fans, washing machines, refrigerators, lighting products, electric ovens and stoves, televisions, etc). Thus, when buying an appliance and choosing the one with the Procel seal, the consumer will know that the product consumes less energy than another equivalent without the seal, providing savings in the electricity bill and causing less impact on the environment (EPE, 2023c). Summing up, it provides:

- Energy Efficiency Standards: Procel establishes energy efficiency standards and criteria for various types of equipment and appliances, including refrigerators, air conditioners, and lighting products;
- Procel Seal: Procel awards the Procel Seal to products that meet or exceed the energy efficiency standards set by the program. The seal is a recognized mark of energy efficiency in the Brazilian market;
- Public Awareness Campaigns: Procel conducts public awareness campaigns to educate consumers, businesses, and industries about the importance of energy conservation and the benefits of using energy-efficient products and practices;

- Technical Assistance: The program provides technical assistance and guidance to industries, businesses, and consumers to help them implement energy-saving measures;
- Research and Development: Procel supports research and development initiatives aimed at improving energy efficiency technologies and practices;
- Monitoring and Reporting: Procel monitors and reports on energy consumption trends, the impact of energy efficiency measures, and the performance of energy-efficient products in the market;
- Regulatory Support: The program collaborates with regulatory agencies to integrate energy efficiency considerations into regulations and policies.

Procel has played a pivotal role in Brazil's efforts to conserve energy, reduce electricity consumption, and promote sustainable practices. It has helped shape the market by encouraging the adoption of energy-efficient products and technologies, ultimately contributing to energy and cost savings for consumers and a reduction in greenhouse gas emissions.

c) **Other initiatives**

- National Plan for Energy Efficiency (PNEf): created in 2011, the plan outlines strategies and actions to improve energy efficiency across various sectors, including industry, transportation, and residential;
- National Energy Efficiency Fund: established in 2021, provides funding for energy efficiency projects across the country. Enabling PBE Edifica to be aligned with the Brazilian standard of building performance NBR n. 15575/2021, allows the consumer to have information on the potential consumption of the building or residential unit and also how much it is possible to save energy in relation to a standard building;
- Regulatory Agencies: regulatory agencies, such as the National Agency for Electric Energy (ANEEL) and the National Petroleum Agency (ANP), have implemented regulations and programs to promote energy efficiency in the electric and oil sectors;

- Energy Efficiency Programs: Different regions and states in the country have their energy efficiency programs and initiatives aimed at promoting efficient energy use. These programs often target specific sectors or regions;
- Partnerships: Brazil often collaborates with international organizations and agencies, like the United Nations Development Programme (UNDP) and the World Bank, to further energy efficiency efforts;
- Legislation: Brazil has various laws and regulations that touch on energy efficiency, particularly in the context of environmental and sustainability regulations.

Figure 11 presents a timeline of energy efficiency initiatives in Brazil.

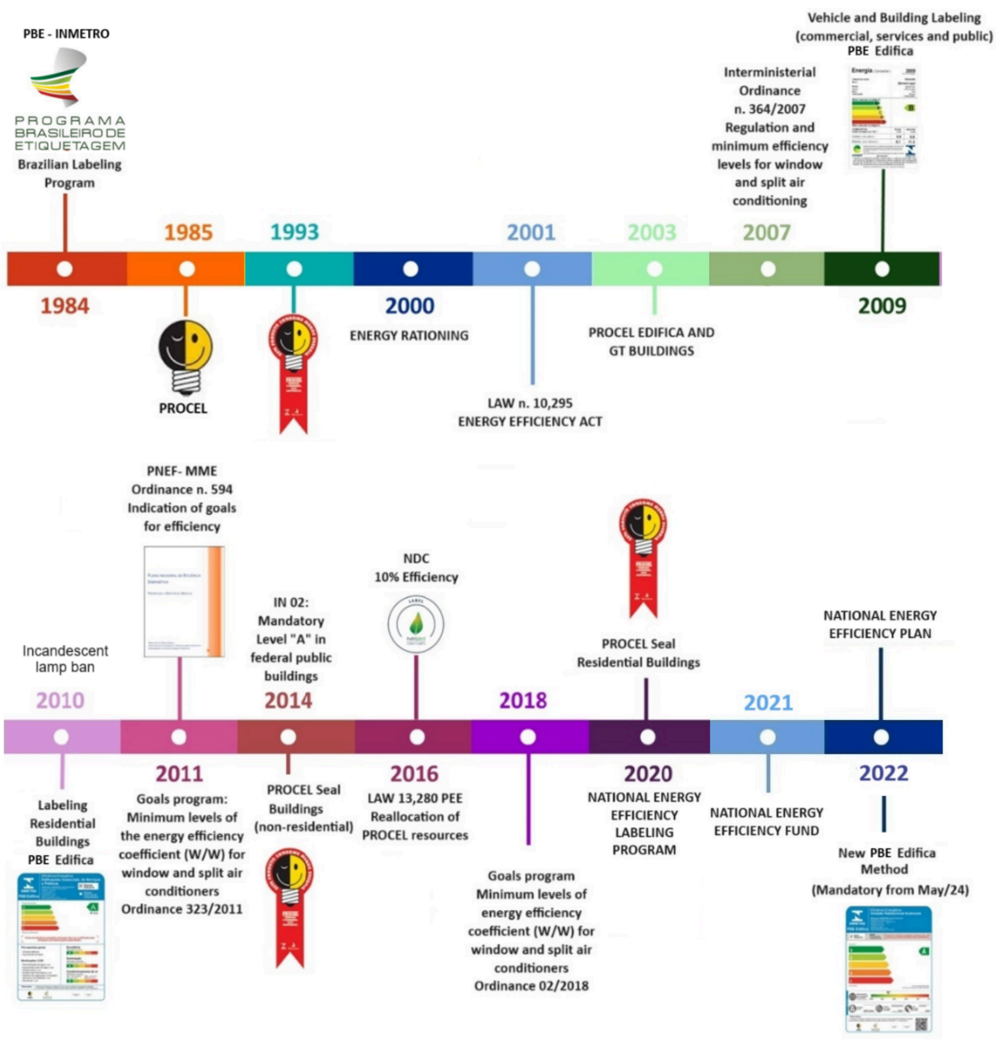

Figure 11 – Timeline of energy efficiency policies
Source: Adapted by the authors from EPE (2022d).

4.3 Incentive Program for Alternative Sources of Electric Energy (Proinfa)

Considered one of the largest incentive programs for alternative sources of electricity in the world, Proinfa was established by Law n. 10,438/2002 (BRASIL, 2002). Proinfa's objective is to increase the participation of renewables, such as small hydroelectric, wind, and thermal biomass plants (ELETROBRAS, 2023).

The cost of these projects is divided into monthly quotas, collected by distributors, transmitters, and cooperatives. The calculation of the quotas is based on the Proinfa Annual Plan (PAP) prepared by Eletrobras and forwarded to the National Electric Energy Agency (ANEEL). The amounts are paid by all free and regulated consumers of the National Interconnected System (SIN), except those classified as low-income.

The forecast of electricity generation of PROINFA plants for 2023 is 11,202,147 MWh, of which 6,879,296.43 MWh of distributors, 128,004.31 MWh of cooperatives (permittees), 846,587. 61 MWh of free consumers of the basic network, 13,807.71 MWh of free consumers of the licensees and 3,334,450.94 MWh of free consumers of the distributors (ANEEL, 2022).

4.4 Energy auctions

Brazil has one of the richest experiences in the world in renewable energy auctions, having held auctions of wind, solar, biomass and small hydropower plants. The 2004 Brazilian market reform introduced several types of energy auctions, each designed to achieve a different political goal. Two types of auctions have been instrumental in promoting renewable energy: regular auctions of new energy and auctions of reserves (IRENA, 2017).

At present, energy auctions stand as the primary avenue for energy procurement in Brazil. These auctions are conducted by the Chamber of Electric Energy Commercialization (CCEE) under the delegation of ANEEL. Auctions are market mechanisms that aim to increase the efficiency of energy contracting, seeking to ensure supply at the lowest cost. All SIN distributors contract their resources to serve their market in the Regulated Trading Environment (ACR). The negotiations adopt the criterion of lowest tariff to define the winners, aiming at the tariff modality. To ensure the diversity of the mix and the modernization of the mix, the electricity sector conducts various types of auctions by the CCEE in the following Table 3 (CCEE, 2023).

Table 3 – Types of auctions in Brazil

Types of auctions	Detailing
Adjustment Auction (AGE)	It aims to adjust the contracting of energy by distributors, treating any deviations arising from the difference between the forecasts made by distributors in previous auctions and the behavior carried out by their market.
Structuring Auction (LPE)	It is intended for the purchase of energy from generation projects indicated by the resolution of the National Council of Energy Policy (CNPE) and approved by the President of the Republic. The projects have priority of bidding and implementation, in view of their strategic character and public interest.
Reserve Energy Auction (LER)	This event is held to increase the security of energy supply in the National Interconnected System (SIN), with energy coming from specific plants. They can be new or existing ventures.
Existing Energy Auction (LEE)	It serves to contract energy generated by plants already built and that are in operation, whose investments have already been amortized and, therefore, have a lower cost.
New Energy Auction (LEN)	It aims to meet the increased load of distributors. In this case, energy is sold and contracted from plants that are yet to be built.
Capacity Reserve Auction	Modality for capacity reserve contracting to meet the SIN power needs, increasing the reliability of supply. New or existing ventures trade only the power, keeping the energy free for trading in other markets. All auctions are accompanied by an acronym, which represents the time to start delivery of the contracted product. Ex: New Energy Auction A-6.
Isolated System Auction (LSI)	This event aims to ensure the supply and power to locations of the Isolated System with tariff modicity.
Auction of Alternative Sources (LFA)	Established to meet the market growth in the regulated environment and increase the participation of renewable sources – wind, biomass, and Small Hydroelectric Power Plant (SHPP) – in the mix.

Source: Authors based on CCEE (2023)

The utilization of auctions to enhance electricity supply emerged as a mechanism introduced during the electricity sector reform and was further solidified through active collaboration among various entities within the Brazilian Electric Sector (EPE, 2023). Regulated auctions for power generation and transmission constitute essential pillars of the regulatory framework governing the Brazilian Electric Sector, as defined by the Electric Energy Commercialization Law (Law n. 10.848/2004).

The auctions of Alternative Sources (LFA) were instituted to meet the market growth in the regulated environment and increase the share of renewable sources – wind, biomass, and Small Hydroelectric Power Plant (SHPP) – in the mix.

The Alternative Sources Act is specifically targeted at renewable sources (hydraulic, biomass and wind). In 2007, Brazil hosted its inaugural Alternative Energy Sources Auction, conducted online. The energy transacted during this event was intended for the electric power distribution market, with participating distribution companies acting as buyers. Successful entrepreneurs from the auction proceeded to enter into Energy Trading Contracts in a Regulated Environment (CCEAR) with these companies (EPE, 2023).

The contracting of the auctions can be classified as A-6, A-5, A-4, A-3, A-2, A-1 and the deadlines for the beginning of the supply of the contracted energy are, respectively, 6 years, 5 years, subsequently, up to 1 year (CCEE, 2019).

In addition to these, wind sources have also started to participate in new energy auctions (LEN) and reserve energy auctions (LER). LEN auctions can be differentiated into two types: A-3 (three years for its start) and A-5 (five years for its completion). To participate in an auction, the project must be registered with the Energy Research Company (EPE). Once enabled, companies virtually participate in a platform of the Electric Energy Trading Chamber (CCEE).

In addition to the auctions, companies can also install renewable energy generation plants on their own, as long as they comply with the regulations of the electricity sector and obtain the necessary authorizations from the competent bodies.

4.5 Distributed Microgeneration and Minigeneration of Electric Energy (MMDG) and the Electric Energy Compensation System (EECS)

With ANEEL Normative Resolution n. 482/2012, consumers became able to generate their own electricity from renewable sources or qualified cogeneration and supply the surplus to the distribution network in their locality, for subsequent compensation of verified energy consumption. These are Distributed Microgeneration and Minigeneration of Electric Energy (MMDG) and the Electric Energy Compensation System (EECS).

The key points of the resolution include:

- Net Metering: The resolution introduced a net metering system, allowing consumers who generate surplus electricity from renewable sources to feed it back into the grid and receive compensation for the excess power produced. This meant that consumers could offset their electricity bills with the energy they generated, effectively reducing their energy costs;

- Connection Standards: The resolution established technical standards and requirements for connecting small-scale renewable energy systems to the grid, ensuring the safety and reliability of the electrical system;
- Timeframe: It set a timeframe for the compensation of surplus energy, allowing consumers to accumulate credits for excess electricity produced over the course of five years. Any power surplus not used within this timeframe would be credited to the consumer's next electricity bill;
- Expansion of Renewable Energy: ANEEL Normative Resolutionn. 482/2012 played a significant role in promoting the growth of distributed solar and other renewable energy installations in Brazil, making it more financially viable for individuals and businesses to invest in clean electricity technologies.

It is important to highlight that the ANEEL Normative Resolution n. 482/2012 defined the basic rules of the category, allowing the existence and growth of distributed generation in Brazil. Later, those rules were improved by the ANEEL Normative Resolution n. 687 of 2015 and more recently new rules were imposed with the publication of law n. 14,300/2022 (described in section3.10).

4.6 Distributed Electric Power Generation Development Program (ProGD)

Launched by the Ministry of Mines and Energy in 2015, the Distributed Electric Power Generation Development Program (ProGD) is a program to encourage and foster the development of distributed generation, based on renewable sources. The program offers several benefits to the consumer, one of them being the low investment cost and the possibility of financing with faster returns.

Although it has solar energy as its main target, the program stimulates the wind energy microgeneration sector with the creation of more favorable credit lines and financing incentives for industries that manufacture components from renewable sources and the creation of energy credits between consumer-generator and distributor (BRASIL, 2015).

4.7 National Biofuels Policy (RenovaBio)

RenovaBio is an initiative of the Ministry of Mines and Energy, launched in December 2016, which aims to expand the production of biofuels, based on predictability and environmental, economic, and social sustainability (EPE, 2023). The program sets decarbonization goals, aiming to gradually increase the share of biofuels in the Brazilian energy mix. To meet its targets, distributors can purchase Biofuel Emission Certificates (CBios) issued by biofuel producers, based on the emissions avoided throughout the lifecycle of the respective biofuels produced.

Through that, the program aims to contribute to overcoming the technical and economic challenges to be faced by the sector and to the best use of the opportunities that are posed to the country, from a broad debate with all the agents that make up the biofuels market.

One of the benefits of RenovaBio is to stimulate bioelectricity, which is electricity produced from agricultural wastes, such as sugarcane bagasse and considered renewable and sustainable energy sources. In the sugar-energy sector, for example, bioelectricity plays an important role. According to the Union of the Sugarcane and Bioenergy Industry (UNICA), bioelectricity generated from sugarcane is the 4^{th} most important source of the Brazilian electricity mix. In 2022, the bioelectricity production of sugarcane was 18,400 GWh, representing 72% of all electricity generation from biomass in the country.

It is worth mentioning that in 2022 only 15% of the potential was used. If all the biomass from the sugarcane plantations was used, bioelectricity would have the technical potential to reach 151,000 GWh, which would represent meeting more than 30% of the energy consumption in the National Integrated System.

The bioelectricity expansion in the national system depends on factors such as incentives, availability and cost of biomass, and investment in infrastructure and technology. The growth of this energy source in Brazil can contribute to a more diversified and sustainable electricity mix. Stimulated by RenovaBio and a favorable business environment, bioelectricity for the grid has the potential to grow by more than 55% by 2030 (EPE, 2020).

4.8 Just Energy Transition Program (Law n. 14,299/2022)

Law n. 14,299/2022 creates the Just Energy Transition Program (TEJ), aligning carbon neutrality goals with socioeconomic impacts and the valorization of mineral and energy resources. This program aims to prepare the state of Santa Catarina for the probable closure, by 2040, of the coal-fired thermoelectric generation activity. Thus, the program aims to promote the end of coal exploitation in the region in a timely, responsible and sustainable way.

In this sense, the environmental, economic and social impacts and the valorization of energy and mineral resources will be observed in line with the carbon neutrality to be achieved following the goals defined by the Federal Government, which will also include the contracting of electricity generated by a thermoelectric plant (Jorge Lacerda Thermoelectric Complex – CTJL).

According to CASA CIVIL (2022), the Just Transition Plan has a council (Decree n. 11,124/2022) that will establish:

i) The planning of the necessary actions to fulfill the objective of the Just Energy Transition Program;

ii) The guidelines to be observed by the organs, entities, and public and private institutions for the development of the Just Energy Transition Program; and

iii) The actions, those responsible, the deadlines and, when applicable, the respective sources of funds for the development of the Just Energy Transition Program.

4.9 Exploration of Offshore Wind Energy Regulation (Decree n. 10,946/2022)

Decree n. 10,946/2022 provides for the assignment of use of physical spaces and natural resources in inland waters under the domain of the Union, territorial sea, exclusive economic zone and on the continental shelf for the generation of electricity from offshore enterprises, called “prismas” (prism) (BRASIL, 2022b).

The decree covers all offshore electric generation technologies, but it is important to highlight the current prominence of offshore wind energy in Brazil. This sector has been developing over the years, mainly due to the interest of stakeholders who want to expand this source. Currently, there are 78 projects under licensing with the Brazilian Institute of the Environment and Renewable Natural Resources (IBAMA), the environmental agency responsible for licensing, totalling 189 GW (IBAMA, 2023).

The decree needs to be refined to avoid regulatory and environmental problems in the future, because although wind energy is a renewable source with a relatively lower environmental impact compared to other energy sources, it can still cause relevant environmental impacts, and some aspects are not considered during its expansion planning.

Therefore, some actions should be carried out for the improvement of the decree and enhancement of efficiency in the expansion of offshore wind energy, such as: the inclusion of the analysis of environmental aspects during the assignment on the use of prisms, creation of a marine spatial plan with definition of the prohibited areas for the development of offshore wind projects, definition of a methodology for the selection of the winning company in case of overlapping of multiple projects (which is already being observed in the numerous requests for overlapping of areas in the applications for environmental licensing at the IBAMA), definition of the steps to be carried out by entrepreneurs for the presentation of Declarations of Prior Interference (DIPS), creation of a one-stop shop for the presentation of DIPS, and creation of an incentive policy for this source, for example, through exclusive auctions (DECARBOOST, 2023).

4.10 Legal Framework for Distributed Generation (Law n. 14,300/2022)

The publication of Law n. 14,300/2022, known as the "Legal Framework of Distributed Generation", established the legal framework of distributed microgeneration and mini generation, the Electric Energy Compensation System (SCEE) and the Social Renewable Energy Program (PERS), one of the most important topics for the electricity sector.

Distributed micro and mini generation, better known as distributed generation (DG), are modalities that allow the generation of one's own energy with renewable sources on site or near the point of consumption, allowing one to generate and receive energy credits in the monthly bill. DG differs from centralized generation, which is composed of large power plants connected to the National Interconnected System, the electrical system that brings energy to consumption through a transmission and distribution network. In recent years DG has grown considerably, and for reasons of cost and versatility, photovoltaic solar technology accounts for more than 98% of the installations in the segment in the country.

Aneel Normative Resolution n. 482/2012 (REN 482) initially defined the basic rules of the category. It was later improved by Aneel Normative Resolution n. 687/2015 (REN 687), including the definition of the maximum power of 75 kW for microgeneration systems and 5 MW for mini generation. In addition, REN 482 established the SCEE, allowing the consumer to inject the surplus energy generated into the distribution network.

In 2022, Law n. 14,300 brought a new possibility for the distribution of energy credits and promoted some technical changes in the following modalities (BRASIL, 2022a), including:

- Power of the projects – Distributed mini-generation systems of 75 kW and 5 MW were classified as distributed mini-generation until January 6, 2023. After this date, there was a major change in the distributed mini-generation part, which for non-dispatchable sources reduced the limit from 5 MW, as it was in REN 482, to 3 MW. The change does not apply to dispatchable sources (biomass, SHPP, for example) that continue with the 5 MW limit;
- Use of credits – Possibility of reallocating surplus credits to other consumer units of the same holder in the same concession area. The distributor has up to 30 days to operationalize this procedure and in REN 482 this was not possible;
- Unification of ownership – Authorizes the consortium, cooperative, condominium, volunteer or building to transfer ownership of electricity bills to the consumer–generator. This allows a shared generation to fit as remote self-consumption and prevents the project from paying ICMS[3] on electricity, facilitating the transfer of credit between participating consumers.

In this way, the law established the rules for all those involved in the SCEE and brought legal certainty. Since the publication of the law, more than 780,000 micro and mini-generation connections have been made effective by distributors throughout Brazil, totaling more than 7.6 GW of installed power. These figures represent an increase of 60% in the number of connections and 54% of the installed capacity when compared to the 13 months before the publication of the law. About 47% of the total connections and 44% of the installed capacity recorded since 2009 occurred after the

[3] Tax on the circulation of goods and transportation and communication services.

publication of the law (ANEEL, 2023). The evolution of GD from 2012 to 2022 is presented in Table 4 below.

Table 4 – Evolution of distributed generation (2012-2022)

Year	Amount of Micro and Mini generators (n. of connections)	Installed Capacity (kW)
2012	5	449.8
2013	51	1,412.98
2014	287	2,742.58
2015	1,353	16,491.88
2016	6,587	63,261.26
2017	13,735	156,150.36
2018	35,708	429,146.39
2019	123,638	1,592,549.85
2020	226,612	2,903,378.36
2021	458,224	4,606,717.90
2022	753,861	7,371,655.18
Cumulative Total	**1,655,819**	**17,479,313.79**

Source: Authors based on ANEEL (2023)

In addition, Law n. 14,300/2022 also created the "*Social Renewable Energy Program*", aimed at financing the installation of photovoltaic generation and other renewable sources for low-income consumers. The resources come from the Energy Efficiency Programme (EEP)[4] and complementary sources, or, from part of other revenues of the activities developed by the distributors converted to the tariff modicity in the tariff review processes.

4.11 Environmental Credit Line

Recognizing the escalating concerns of consumers, investors, and the market regarding investments in renewables for GHG emission mitigation, financial institutions have come to acknowledge the imperative of aligning with contemporary standards of environmental and social responsibility. As a result, many of these institutions have embraced a range of incentives, measures, and credit offerings that propel progress in this pivotal direction.

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[4] The EEP aims to promote the efficient use of electricity in all sectors of the economy. To this end, the concessionaires and licensees of public services of electricity distribution are obliged to apply annually an amount of their net revenue in research and development of the electric sector, as provided for in Law n. 9,991/2000.

The cornerstone of incentives within the electricity sector resides in the provision of credit lines strategically tailored to bolster projects that actively contribute to sustainable development. These credit lines are pivotal in fostering the establishment and growth of enterprises dedicated to generating electricity from renewable sources. Among the credit options available, two noteworthy offerings stand out:

- BNDES Finem – BNDES Power Generation, an initiative supporting the expansion and modernization of energy generation via renewable and natural gas thermoelectric sources nationwide (BNDES, 2023a;2023b;2023c); and
- Bank of Brazil Renewable Energy Credit, on financing residential photovoltaic systems (BB, 2023).

Furthermore, BNDES administers the National Fund for Climate Change (FNMC) in collaboration with the Ministry of the Environment and Climate Change. This fund serves as a catalyst for diverse initiatives, including renewable energy projects, by providing essential resources to facilitate project implementation, conduct studies, and extend financial support towards endeavors dedicated to combating climate change.

5 Centro Clima Current Policy Scenario (CPS): long-term power supply simulation

Centro Clima simulated two GHG emissions scenarios in Brazil until 2050 for the DDP BIICS (La Rovere et al., 2021) and the Climate and Development Initiative (Unterstell, La Rovere et al., 2021) among other studies, as mentioned in section 2. These exercises provide a framework for analyzing economy-wide and sectoral indicators of a decarbonization pathway. The Current Policies Scenario (CPS) follows the trend of ongoing mitigation actions. The Deep Decarbonization Scenario (DDS) goes beyond the NDC target and follows a GHG emissions trajectory compatible with the global objective of 1.5ºC of the Paris Agreement, achieving net-zero emissions in 2050. The DDS will be presented in a subsequent report.

For the ICAT Brazil Project phase 3, the scenarios are being updated based on the availability of new data and the decision to extend the previously estimated values to 2060, from the original estimation of 2050.

5.1 CPS General Assumptions

In this section, the general assumptions of the CPS in the sectors whose modelling is related to electricity demand and supply are presented.

a) Transport

- No increase in mitigation ambition after 2030;
- Continuation of current incentives for biofuels and energy efficiency;
- Electromobility incentives limited to experiments in metropolitan areas;
- End of sales of internal combustion engine (ICE) cars expected in 2050;
- Lower proportion of public and non-motorized transport;
- Rail and water transport activities grow at levels below their potential.

b) Industry

- The Brazilian industry accounted for 26% of the national GDP in 2019;
- Industry sector emissions correspond to about 16% of the country's total and most emitting sectors are cement, iron & steel, and chemical;
- 75% of emissions come from energy consumption, and 25% from IPPU (Industrial Processes and Product Use);
- Productivity gains follow the trend;
- Same performance of current mitigation policies and measures.

c) Agriculture, Forestry and Other Land Use (AFOLU):

- Agriculture is a key driver of Brazilian economic growth;
- Brazil is a leading exporter of soybeans, beef, and cellulose;
- The scenario assumes continuation of historical food preference trends;
- Global meat consumption per capita increases due to income and population growth;

- Agriculture production increases significantly overtime;
- Crop area increases moderately;
- Beef production grows considerably;
- Reforestation and restoration do not increase significantly.

d) Energy Supply:

- Offshore oil and gas production from the pre-salt layer increases steadily;
- Assumed oil price trajectory: 64 USD[5]/barrel from 2025-2050;
- Increasing shares of Brazilian oil production directed towards exports;
- Hydro, wind energy, and photovoltaics are the main sources of power generation;
- Decommissioning of old thermopower plants and replacement with renewables;
- Natural gas plays an important role in dispatchable power generation.

The energy demand of the agriculture, households, commerce and public sectors follow historical trends.

5.2 Electricity demand in CPS – ICAT Brazil Project phase 3

The electricity demand estimates for the ICAT project update Centro Clima's long-term emission scenarios and extend the horizon from 2050 to 2060. These scenarios were initially built upon estimated values for the period spanning 2020 to 2022. However, the current demand review draws upon the latest data sourced from the National Energy Balance up to 2022. Notably, the GDP figures for the recent years have also been revised.

In addition to these modifications, the approach incorporates new population estimates derived from the recently released census data. These comprehensive updates collectively contribute to the refinement of sectoral energy demand projections within

[5] The barrel price is sourced from the 'Announced Pledges' scenario of the International Energy Agency's World Energy Outlook 2022 (IEA, 2023b).

the framework of the same underlying scenarios and narrative concepts. The aim is to ensure the accurate modelling of energy supply up to 2060.

5.2.1 Macroeconomic projections

Following the adverse economic impacts stemming from the 2015-2016 recession and the 2020-2021 pandemic, Brazil has finally resumed a more robust growth trajectory. In 2021, the GDP growth rate was 5%, and in 2022 it was 2.9%. It was only in 2022 that Brazil's GDP surpassed its 2014 value (in BRL terms).

For the short-term growth rate projections up to 2026, the scenario relies on the FOCUS report forecasts, as compiled by the Central Bank of Brazil. Based on these growth forecasts, in terms of per capita GDP, it is anticipated that the 2013 value (in BRL) will only be surpassed in 2026. For the long term, the scenario assumes gradually diminishing growth rates. For the period 2027-2030, an annual GDP growth of 2.5% was projected. For the 2031-2040 period, an annual GDP growth rate of 2.25% was considered. For the 2041-2050 timeframe, an annual growth rate of 2.0% was assumed. Lastly, for the 2051-2060 timeframe, GDP growth rates get to 1.75% annually.

Given these assumptions, Brazil's GDP would reach approximately 1.2 times its 2022 value by 2030, 1.8 times by 2050 and 2.1 times by 2060. The macroeconomic assumptions used in this study are in Table 5, Table 6 and Table 7.

Table 5 – Estimates of the evolution of the Brazilian GDP (2005-2060)

Year	Annual growth (%)
2005	3.20
2010	7.50
2015	-3.55
2020	- 3.28
2021	4.99
2022	2.90
2023 – 2030	2.18
2031 -2040	2.25
2041 – 2050	2.00
2051 – 2061	1.75

Source: Authors
Note: Data until 2022

Table 6 – Estimates of the evolution of the sectorial GDP shares (2005-2060)

Year	Agriculture	Industry	Services
2005	5.2%	29.0%	65.8%
2010	5.3%	28.1%	66.6%
2015	5.6%	26.8%	67.6%
2020	6.3%	25.9%	67.8%
2025	6.3%	25.8%	67.9%
2030	6.3%	25.7%	68.0%
2035	6.3%	25.6%	68.1%
2040	6.4%	25.4%	68.2%
2045	6.6%	24.9%	68.6%
2050	6.7%	24.3%	69.0%
2055	6.8%	23.4%	69.8%
2060	6.9%	22.5%	70.6%

Source: Authors
Note: Data until 2020

Table 7 – Estimates of the evolution of the sectoral GDP (2005-2060)

Year	Sectoral GDP (BRL billion)			
	Agriculture	Industry	Services	Total
2005	373	2,079	4,717	7,168
2010	473	2,509	5,946	8,927
2015	525	2,522	6,352	9,399
2020	575	2,377	6,225	9,178
2025	656	2,7	7,108	10,464
2030	739	3,028	8,015	11,782
2035	836	3,364	8,968	13,168
2040	946	3,738	10,034	14,718
2045	1,07	4,038	11,142	16,25
2050	1,211	4,36	12,371	17,941
2055	1,337	4,578	13,652	19,567
2060	1,476	4,807	15,057	21,34

Source: Authors
Note: Data until 2020

To estimate the population over the study period, the study used historical data updated by the Brazilian Institute of Geography and Statistics (IBGE, 2023) for 2000, 2010 and 2022 with interpolation of values between these years. The projection from 2023 to 2060 was estimated based on the population growth rates of the series made available by the IBGE estimates (IBGE, 2020).

Table 8 – Estimates of the evolution of the Brazilian population (2005-2060)

Year	Population (hab.)
2005	180,173,246
2010	190,755,799
2015	195,883,596
2000	169,590,693
2005	180,173,246
2010	190,755,799
2015	195,883,596
2020	201,011,393
2025	207,033,003
2030	212,552,554
2035	216,621,982
2040	219,217,809
2045	220,380,162
2050	220,175,663
2055	218,632,145
2060	215,783,243

Source: Authors based on IBGE (2020) and IBGE (2023)
Note: data until 2020

5.2.2 Residential sector electricity demand

To estimate electricity demand within the residential sector (households), the study employed the per capita electricity consumption of Italy in 2020 as a proxy for Brazil's anticipated value in 2060. This approach, considering the distinct developmental stages of the two countries, provides insight into potential trends and factors that could contribute to aligning the consumption levels of a developed nation with that of a developing one over time. It was assumed that Brazil would reach a residential consumption of 1.2 MWh/inhabitant in 2060, 40 years behind Italy.

From 2012 to 2022, average household consumption increased from 153 kWh/month to 179 kWh/month, a 17% growth. In the same period, per capita consumption went from 0.61 to 0.77 MWh/inhabitant an increase of 26%) and the total electricity demand increased by 32% due to the increase in the population in the period (ACENDE BRASIL, 2023). Employing a linear interpolation (TWh/Mhab), the study computed intermediate figures spanning from 2022 to 2060. Thereafter, the per capita electricity consumption was multiplied by the projected Brazilian population for each year encompassed by this period. This systematic approach enabled a holistic estimation of residential electricity demand throughout the timeline.

5.2.3 Transport sector electricity demand

Electricity demand projections have been revised based on the baseline update from 2019 to 2022 reported by EPE (2023a). It is noteworthy that the updated values of the new baseline were restricted to rail passenger transport since the electricity demand of road vehicles is not reported by EPE (due to the still limited fleet in circulation of electric vehicles and plug-in hybrids).

The estimates for the years between 2023 and 2030, then, project the new baseline values from the revised socioeconomic data, also considering the assumptions established in the DDP BIICS and the Climate and Development Initiative (C&D) studies. Compared to the previous figures, they are also limited to this mode of transport. The results of the following two decades (2030-2040 and 2040-2050) are similar to the projects mentioned, given the maintenance of the established premises (enterprises and penetration of electric vehicles) and the saturation of the capacity of rail passenger transport (with marginal expansion).

Finally, the projection of electricity demand for the horizon 2050-2060 was made from the estimate of the transport activity (p.km and t.km) of each mode and its correlation with the macroeconomic variables of GDP and GDP per capita. Regarding the projection of electricity demand from road transport, in addition to the variables mentioned, the study considered the maintenance of the pace of penetration of electric vehicles and plug-in hybrids in the circulating fleet verified in the DDP BIICS and C&D studies for the period 2045-2050.

5.2.4 Industry sector electricity demand

The electricity demand of the industrial sector was calculated based on the overall energy demand. Therefore, the study updated the projection of total energy demand until 2050 by applying the coefficient of the energy demand elasticity with respect to the C&D project industry's GDP (Figure 12) to the revised estimates of the industrial sector's GDP used in the ICAT Brazil Project phase 3. For the years 2051-2060, this study made a linear projection of the elasticity starting from 2036 and applied it to the revised estimates of the industrial sector's GDP used in the Brazil Project phase 3 for that period.

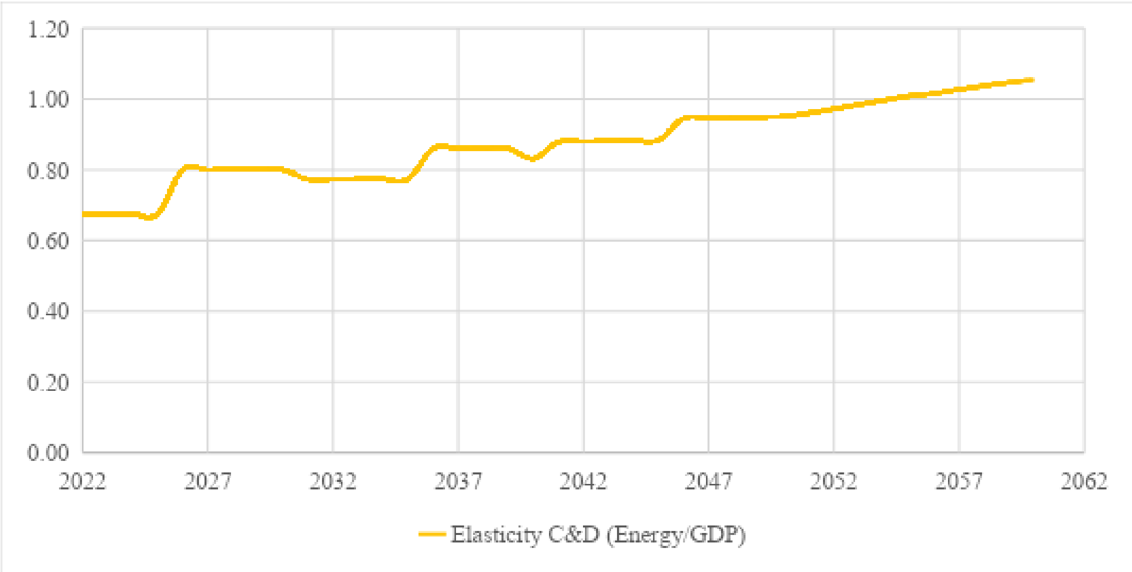

Figure 12 – Estimates of elasticity of total industry energy consumption to industry GDP, in C&D project (2022-2060)
Source: Authors

Subsequently, to estimate the electricity demand, the study utilized the historical percentage of electricity's contribution to the overall energy demand in the industrial sector. This percentage, which was recorded in 2022 and remained constant throughout the period until 2060 (at 21.7%), was employed in the calculations.

5.2.5 Energy sector electricity demand

The MATRIZ model treats the evolution of electricity consumption across various sectors—residential, transportation, industrial, commercial, public, and agricultural—as exogenous. However, when it comes to electricity demand within the energy sector for energy generation (referred to as energy sector electricity consumption), the model adopts an endogenous approach. The estimate of electricity demand within the energy sector relies on data concerning the production, efficiency, and utilization of each technology employed throughout the comprehensive energy chain, which includes both fuels and electricity.

5.2.6 Electricity demand from other sectors

A similar approach was applied to the commercial, public, and agricultural sectors. To estimate their energy demands, the study employed linear functions that correlated their historical data on energy demand with the sectoral GDP from 1995 to 2013. These years were chosen for the econometric analysis, as the years 2014 and 2015 were excluded due to negative variations in the Brazilian GDP.

After establishing the linear functions based on the selected years, newly projected sectorial GDP estimates until 2060 determine the total energy demand for each of these sectors. Afterward, the percentage of electricity's contribution to this demand was calculated. To determine this share, a linear projection was performed using the data from the last 10 years (2013-2022). This allowed the projection of the expected percentage of electricity's participation in the energy demand for future years.

Equation 1 is the linear function used to estimate the total energy demand of the commercial sector, with a coefficient of determination (R^2) equal to 0.9615.

$$y = 1.4537x - 1,583 \qquad \text{Equation 1}$$

Equation 2 is the linear function used to estimate the total energy demand of the public sector, with a coefficient of determination (R^2) equal to 0.8124.

$$y = 0.387x + 1,424.6 \qquad \text{Equation 2}$$

Equation 3 is the linear function used to estimate the total energy demand of the agriculture sector, with a coefficient of determination (R^2) equal to 0.7634.

$$y = 13.979x + 2,872 \qquad \text{Equation 3}$$

5.2.7 Results of electricity demand estimates

In CPS, the aggregate electricity consumption experiences an increase of almost 106 % from 2020 to 2060, reaching 1,132 TWh (Table 9 and Figure 13). Examined by sector, there is the following percentage growth in electricity consumption in this period: residential (62%); transport (3,956%); industry (89%); public sector (90%); commercial sector (153%); agriculture (154 %); and energy sector (43%).

Table 9 – Estimates of electricity demand in CPS (TWh)

Year	Households	Transport	Industrial	Public	Commercial	Agriculture	Energy	Total
1995	63.6	1.2	127.2	23.1	32.3	9.2	8.3	264.9
2000	83.6	1.3	146.9	29.2	47.5	12.9	10.5	331.9
2005	83.2	1.2	175.4	32.7	53.5	15.7	13.5	375.3

2010	107.2	1.7	203.4	37.0	69.7	18.9	26.8	464.8
2015	131.2	2.1	198.1	43.5	91.5	26.8	37.2	530.3
2020	148.9	2.0	198.4	42.8	84.8	32.5	38.3	547.8
2025	164.5	2.7	226.5	45.3	91.8	31.6	36.9	599.3
2030	178.7	4.3	248.4	49.4	105.8	36.3	43.4	666.3
2035	192.2	7.0	269.5	53.7	120.6	41.9	44.6	729.5
2040	204.7	13.1	295.0	58.5	137.1	48.4	44.2	801.0
2045	216.1	23.8	315.7	63.5	154.3	55.9	47.3	876.6
2050	226.1	46.9	339.5	69.2	173.4	64.6	50.5	970.2
2055	234.7	68.3	356.2	75.1	193.4	73.2	52.6	1,053.5
2060	241.7	81.7	374.7	81.6	215.3	82.8	54.7	1,132.5

Note: Data until 2020.
Source: Authors

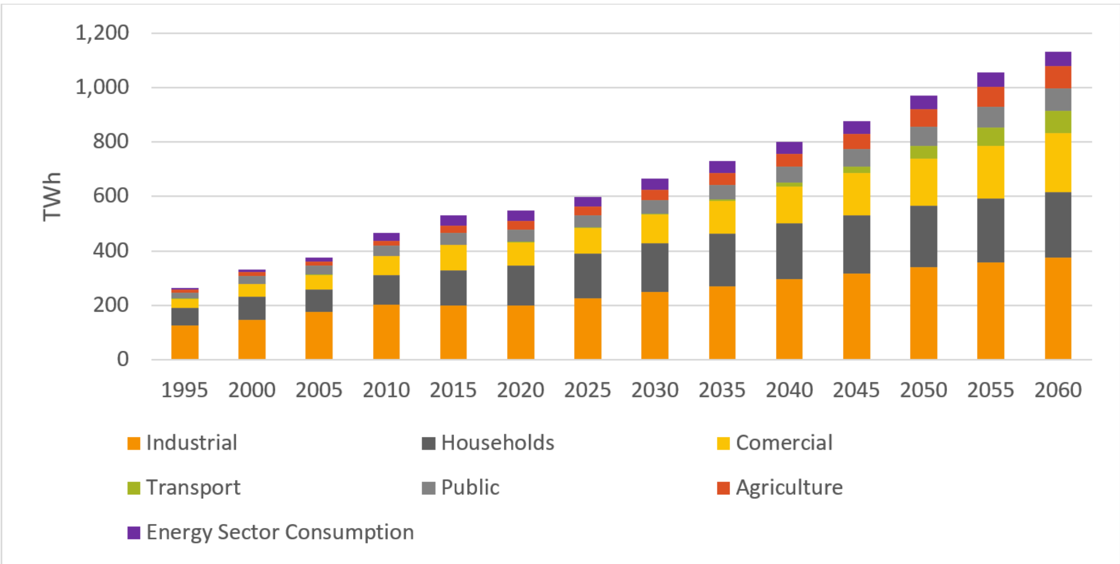

Figure 13 – Estimates of sectoral electricity demand in the CPS (TWh, 2000 – 2060)
Source: Authors

5.2.8 Evolution in electrical intensity across demand sectors in the CPS

In transport sector energy efficiency gains are expected in internal combustion engine vehicles, plug-in and non-plug-in hybrids, as well as battery electric vehicles. Other technologies such as fuel cells will not play a significant role. Until 2035, advancements in engine energy efficiency are focused on internal combustion and non-plug-in hybrid variants, mainly driven by the results of the Rota 2030 and Rota 2040 programs. Between 2035 and 2045, the most pronounced increments are observed in plug-in hybrid vehicles. Finally, in the 2045-2060 horizon, efficiency improvement is concentrated on battery electric vehicles (Table 10).

Nevertheless, the incremental improvements in energy efficiency are attenuated by the ongoing trend of increased usage of larger vehicles, such as SUVs, and the increasing prevalence of individual motorized transport to the detriment of public transport. In the latter case, the attractiveness of bus-based public transportation remains diminished, while passenger railway transport capacity becomes saturated, leading to a reduced capture of new users.

Tax incentives for inland navigation and coastal shipping expand the use of water transport. In rail transport, operational improvements, coupled with more efficient propulsion systems and regenerative braking, account for a 10% increase in energy efficiency by 2060. Freight railways continue to rely solely on diesel-electric locomotives. Moreover, the pattern of transported commodities in freight railways undergoes a slight change, with a decrease in the proportion of ores and an increase in agricultural products, thereby decreasing the transported mass (and efficiency). In aviation, advancements in aerodynamics, mass reduction, and operational enhancements are responsible for a 35% gain in energy efficiency by 2060. Improvements in powertrain systems and the reduction of mass in ships contribute to a 18% increase in energy efficiency in water transport by 2060.

Table 10 – Energy efficiency in the transport sector, by mode (base year 2015=1)

Year	MJ/pass-km				MJ/t-km			
	Air	Water	Rail	Road	Air	Water	Rail	Road
2015	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
2020	1.06	1.10	1.65	1.16	0.97	0.61	1.00	0.98
2030	0.79	0.96	0.95	0.95	0.89	0.61	1.00	0.93
2040	0.76	0.87	0.90	0.90	0.79	0.61	0.92	0.86
2050	0.71	0.80	0.90	0.83	0.69	0.61	0.92	0.79
2060	0.65	0.78	0.85	0.67	0.62	0.61	1.00	0.70

In Brazil, per capita electricity consumption remains notably low. With the expected growth of the GDP, an increase in the residential sector's electricity intensity is anticipated. This suggests that as the economy expands, so too will the demand for electrical power in households. Table 11 illustrates the residential sector electricity per capita intensity.

Table 11 – Intensity of residential sector electricity demand (base year 2015=1)

Year	2015	2020	2025	2030	2035	2040	2045	2050	2055	2060
Electricity demand (kwh/capita)	1	1.11	1.19	1.26	1.32	1.39	1.46	1.53	1.6	1.67

In the industrial sector, a decline in the electricity intensity of the industrial GDP is anticipated due to specific energy efficiency measures being implemented. These actions are expected to result in a more efficient use of electricity within the industrial sector as presented in Table 12.

Table 12 – Intensity of industrial sector electricity demand (base year 2015=1)

Year	2015	2020	2025	2030	2035	2040	2045	2050	2055	2060
Electricity demand (kwh/GDP)	1	1.06	1.07	1.04	1.02	1	1	0.99	0.99	0.99

In the commercial sector, electricity intensity is on an increasing, albeit at a limited rate. Conversely, in the public sector, it shows a slight decrease. These indicators mirror the dynamics observed in previous years, reflecting the outcomes of public policies and autonomous technical progress, Table 13 shows the figures.

Table 13 – Intensity of commercial and public sector electricity demand (base year 2015=1)

Year	2015	2020	2025	2030	2035	2040	2045	2050	2055	2060
Commercial (kwh/GDP)	1	0.95	0.9	0.92	0.93	0.95	0.96	0.97	0.98	0.99
Public (kwh/GDP)	1	1.01	0.93	0.9	0.87	0.85	0.83	0.82	0.8	0.79

In the case of agriculture, electricity intensity is on the rise due to an increased electrification rate and the presence of substantial sector-specific tariff subsidies. Table 14 presents the figures.

Table 14 – Intensity of agriculture sector electricity demand (base year 2015=1)

Year	2015	2020	2025	2030	2035	2040	2045	2050	2055	2060
Electricity demand (kwh/GDP)	1	1.11	0.94	0.96	0.98	1	1.02	1.05	1.07	1.1

The increasing per capita demand for electricity in Brazil can be attributed to several factors. Firstly, as the country continues to urbanize and industrialize, there will be a higher concentration of energy-intensive activities in urban areas, such as manufacturing and transportation, leading to a surge in per capita electricity consumption. Additionally, the growing population (until 2045), coupled with rising standards of living, will drive greater adoption of electrical appliances and technologies in households. On the other hand, with the expected growth of the GDP, decrease in the electricity per GDP intensity is expected. Therefore, as Brazil's GDP continues to grow at a slower pace, the proportional demand for electricity may diminish, consume less electricity per unit of economic output.

Table 15 – Intensity of total electricity demand (base year 2015=1)

Year	2015	2020	2025	2030	2035	2040	2045	2050	2055	2060
Total (kwh/GDP)	1	1.06	1.02	1	0.98	0.96	0.96	0.96	0.95	0.94
Total (kwh/hab.)	1	1.01	1.07	1.16	1.24	1.35	1.47	1.63	1.78	1.94

5.3 Electricity supply in CPS – ICAT Brazil Project phase 3

As mentioned in section 3, Brazil makes great use of power supply from renewable energy sources. In 2022, accounting for utility and distributed generation, hydropower had 53.2% of the total installed capacity (including Hydroelectric Power Plant – HPP and Small Hydroelectric Power Plant – SHPP), solar power 11.8%, wind power 11.5%, and bioelectricity 8%, which ensured the supply of clean energy electricity. The solar component has shown very significant growth in recent years, mainly in the distributed modality. In 2021, distributed solar power surpassed utility generation for the first time, and in 2022 solar distributed generation installed capacity accounted for 17 GW compared to 7.3 GW of utility scale.

As mentioned earlier, hydroelectric plants play a central role in the Brazilian power mix and the greatest hydroelectric potential is found in the Amazon region, characterized by its vast floodplains that offer favourable conditions for dam construction. Nevertheless, this potential is not without controversy due to the significant environmental impacts associated with the flooding of extensive forest areas. The recent transition to the run-of-the-river hydroelectric model, without reservoirs, seeks to mitigate these impacts, directing the focus to smaller-scale projects and less environmental interference. It is needed rigorous planning and comprehensive environmental impact assessment.

The inventory of Brazilian hydroelectric potential reaches a total capacity of 154 GW of HPP, of which 52 GW are available for expansion and 102 GW are already in operation or construction. Of this potential, only about 12 GW are in areas devoid of interference in conservation units and indigenous lands, emphasizing the complex interaction between energy expansion and environmental preservation (EPE, 2020a). In the North region (Amazon), where 32 GW of available capacity is concentrated, only 2.95 GW are located outside conservation units and indigenous lands, highlighting the need to balance the imperatives of energy development with the protection of sensitive ecosystems (EPE, 2021b).

In quantitative analyses and scenario projections, the installed capacity expansion is significantly affected by whether the inventoried potential with interference in protected areas is available for the model. Thus, the study considered two possibilities: a first case, when all inventoried potential is available – called CPS1 with total HPP potential; and a second case, when only the inventoried potential without interference with protected areas (conservation units and indigenous and quilombola lands) is available – called CPS 2. Therefore, two current policy scenarios were developed and are described below:

- CPS 1 – total HPP potential – this scenario is based on current GHG emission trends including all existing policies and measures. It represents the most likely emissions level the country would achieve if the implementation of the mitigation measures follows the current path. This scenario encompasses the total inventoried hydroelectric potential for HPP as outlined in PNE 2050. During the expansion period, 52 GW is available in the MATRIZ model's subsystems, with 1.96 GW until 2031, as per the PDE 2031 (EPE, 2022b), and the remaining from 2032;
- CPS 2 is based on the same assumptions as CPS 1 but considers only HPPs that do not interfere with protected areas (conservation units and indigenous and quilombola's lands). During the expansion period, 12 GW is available in the MATRIZ model's subsystems (2.95GW specific in the north region), with 1.96 GW until 2031 as per the PDE 2031 (EPE, 2022b) and the remaining from 2032.

5.3.1 Scenarios results

In both scenarios, the expansion of the generation capacity is being responded predominantly by wind and solar sources, with a consequent reduction in the relative share of hydroelectricity (Table 16). The increasing expansion of wind and solar sources has reinforced their role as complementary sources, guaranteeing the safety of the system's operation.

Solar power technology in the model encompasses both centralized (utility-scale) and distributed (small-scale) photovoltaic energy generation. In both scenarios, distributed solar capacity will expand to 49.9 GW by 2060. Concerning wind energy, onshore technology is the exclusive source of wind power in the CPS scenarios. Although offshore wind technology was included as an expansion option, the model did not select it due to its high installation cost. Despite being available for expansion, the offshore wind failed to demonstrate competitiveness against other options. Even with cost reductions, especially in CAPEX, technical-economic and regulatory developments remain necessary in Brazil. These factors could modify competitiveness and unlock the utilization of this technology, ultimately yielding significant future benefits to the electrical system.

Table 16 – Estimates of installed capacity, by sources, in CPS1 and CPS2 (2020-2060)

Energy source	Historical	CPS 1 Total HPP potential (GW)				CPS 2 Without interference in protected areas (GW)			
	2020	2030	2040	2050	2060	2030	2040	2050	2060
Hydroelectric (HPP and SHPP)	109	111	136	147	147	111	123	128	131
Wind	17	28	42	60	75	28	42	60	75
Solar (utility and small distributed solar)	8	46	49	49	60	46	52	52	62
Biomass	15	17	22	31	37	17	23	28	31
Bagasse	12	13	17	24	27	13	17	19	21
Other Biomass (Firewood-Wood and Black-Liquor)	3	4	5	7	10	4	7	9	10
Natural Gas	15	21	9	18	37	21	16	34	55
Nuclear	2.0	3.4	2.8	2.8	2.8	3.4	2.8	2.8	2.8
Coal	3.2	3.2	1.5	0.0	0.0	3.2	1.5	0.0	0.0
Petroleum Derivatives (Liquids) and Other	7.7	2.5	1.0	0.9	1.0	2.5	1.0	0.9	1.0

Non-Renewable									
Total	**177**	**231**	**263**	**308**	**359**	**231**	**261**	**305**	**358**

Source: Authors

Biomass and natural gas will replace hydropower role and complement wind and solar contributions. In 2060, the required installed capacity of hydropower is 147 GW in CPS 1 (132 GW of HPP and 15 GW of SHPP) and 131 GW in CPS2 (113 GW of HPP and 17 GW of SHPP). Onshore wind capacity reaches 75 GW in both scenarios, while photovoltaic systems account for 62 GW in CPS1 and 60 GW in CPS2. Biomass reaches a higher level (37 GW) in CPS1 than in CPS2 (31 GW). Natural gas still plays an important role in dispatchable power generation, at a lower level in CPS1 (37 GW) than in CPS2 (55 GW), due to higher hydropower capacity in CPS1. Moreover, old thermopower plants are decommissioned and replaced by renewable power plants (wind, solar photovoltaic, and biomass) due to their lower costs. Thanks to the complement of hydroelectricity in Brazil, large intermittent renewable capacities can be developed effectively.

In CPS, the contribution of hydroelectric plants diminishes from 63% in 2020 to 41% in CPS1 and 37% in CPS2 by 2060 (as shown in Table 17). This decline mirrors the growing competitiveness of other renewable sources in both scenarios. In CPS2, the constraints on constructing new hydroelectric projects, due to their environmental and social impact on protected areas, also play a role. The share of renewable sources in electricity generation continues to expand. Starting from an already impressive 84% of the installed capacity in 2020, it reaches 89% in CPS1 and 84% in CPS2 by 2060. Wind, solar, and biomass combined account for 48% in CPS1 and 47% in CPS2 by 2060. Wind energy experiences a substantial increase in its share within the power mix, going from 10% in 2020 to 21% in 2060. Solar energy also gains prominence, driven by photovoltaic utility-scale plants and distributed generation, contributing 17% in both scenarios by 206

Table 17 – Estimates of installed capacity, by sources, in CPS1 and CPS2 (%, 2020-2060)

Energy source	Historical	CPS 1 Total HPP potential				CPS 2 Without interference in protected areas			
	2020	2030	2040	2050	2060	2030	2040	2050	2060
Hydroelectric (HPP and SHPP)	62%	48%	52%	48%	41%	48%	47%	42%	37%

Energy source	Historical	CPS 1 Total HPP potential				CPS 2 Without interference in protected areas			
HPP	59%	41%	37%	34%	32%	46%	44%	41%	43%
SHPP	3%	5%	5%	5%	5%	3%	4%	4%	4%
Wind	10%	12%	16%	19%	21%	12%	16%	20%	21%
Solar (utility and small distributed solar)	4%	20%	19%	16%	17%	20%	20%	17%	17%
Biomass	8%	7%	8%	10%	10%	7%	9%	9%	9%
Bagasse	7%	5%	6%	8%	7%	5%	6%	6%	6%
Other Biomass (Firewood-Wood and Black-Liquor)	2%	2%	2%	2%	3%	2%	3%	3%	3%
Natural Gas	8%	9%	6%	11%	15%	9%	3%	6%	10%
Nuclear	1%	1%	1%	1%	1%	1%	1%	1%	1%
Coal	2%	1%	1%	0%	0%	1%	1%	0%	0%
Petroleum Derivatives (Liquids) and Other Non-Renewable	4.3%	1.1%	0.4%	0.3%	0.3%	1.1%	0.4%	0.3%	0.3%
Total	**100%**	**100%**	**100%**	**100%**	**100%**	**100%**	**100%**	**100%**	**100%**

Source: Authors

As previously mentioned, the Legal Framework for Distributed Generation was introduced in early 2022. This framework maintains the exemption of the Tariff for the Use of the Distribution System (TUSD in Portuguese) until 2045 for systems with approved access up to January 6, 2023. This provision has continued to fuel the race for new installations. Notably, 8.3 GW of small distributed solar capacity were added in 2022. The momentum continued in the first seven months of 2023, with an additional 4.5 GW of small distributed solar capacity being integrated (EPE, 2023a).

As expected, electricity generation more than doubles between 2020 and 2060, reaching around 1290 TWh (Table 18). In both scenarios, the share of hydroelectricity generation diminishes over the years (from 64% in 2020 to 47% in CPS1 and 42% in CPS2) yet it remains the main source in the country by 2060. In CPS2, given the restriction of interference within protected areas, the contribution of hydroelectric plants to generation is 10% lower at the end of the period. This decrease is offset by other sources, particularly natural gas.

In 2060, wind power sees a substantial rise, positioning itself as the second largest generator, accounting for 24% of this year's overall generation in both scenarios. In CPS1, biomass claims the third spot, contributing 11% to the generation, while natural gas comes in fourth with 9%, and solar takes fifth place with 7%. Shifting to CPS2, the dynamics change: natural gas advances to the third spot, responsible for 14% of the total generation, and biomass follows at 10%. Notably, the most significant role of natural gas within CPS2 lies in its ability to compensate for the reduction in hydroelectric generation.

Another important source is solar, which had a growth of more than 600% from 2020 to 2060, and ranks the fifth position as a generation source by 2060 (with 8% in both scenarios). Nuclear energy follows the same pattern in both scenarios, representing 2% in 2060. Petroleum liquids and other non-renewable do not contribute to electricity generation in CPS1 but have a tiny participation in CPS2, given the reduction in hydroelectric generation. Finally, coal power plants achieve their end of life between 2040 and 2045.

Table 18 – Estimates of power generation, by sources, in CPS1 and CPS2 (TWh, 2020-2060)

Energy source	Data	CPS 1 Total HPP potential (TWh)				CPS 2 Only HPP without interference in protected areas (TWh)			
	2020	**2030**	**2040**	**2050**	**2060**	**2030**	**2040**	**2050**	**2060**
Hydroelectric (HPP and SHPP)	396.4	428.8	529.5	592.6	603.1	428.8	490.5	529.8	542.4
Wind	57.1	110.4	167.3	237.9	303.0	111.9	167.7	240.4	305.5
Solar (utility and small distributed solar)	15.5	79.9	77.2	75.5	96.9	78.3	83.1	82.0	103.3
Biomass	55.6	56.3	79.3	115.2	141.4	56.3	87.7	110.2	124.8
Natural Gas	59.5	43.7	29.3	60.1	122.1	43.7	52.2	115.3	187.0
Nuclear	14.1	24.1	20.8	20.9	21.1	24.1	21.0	21.5	21.8
Coal	11.9	13.9	7.2	0.1	0.0	13.9	7.4	0.1	0.0
Petroleum Derivatives (Liquids) and Other Non-Renewable	9.0	0.0	0.0	0.0	0.0	0.7	1.7	4.2	4.9
Total	**619.0**	**757.1**	**910.7**	**1,102.4**	**1,287.8**	**757.8**	**911.4**	**1,103.7**	**1,289.7**

Source: Authors

5.3.2 Variable renewable energy (VRE) and bioelectricity

The VRE generation, through wind towers and photovoltaic panels, is subject to the availability of wind and sunlight, being dependent on weather conditions that are not controllable. On the positive side, they are genuinely national renewable sources without variable costs.

Bioelectricity in Brazil plays a key role in the diversification of the energy mix, using predominately biomass from sugarcane and firewood as renewable sources for electricity generation. It is important to note that the seasonality of biomass, compared to variable renewables such as solar and wind, introduces a challenge in ensuring continuous electricity supply. While solar and wind generation are subject to climate fluctuations, biomass availability is intrinsically linked to sugarcane harvests and the growth cycle of forests, which can result in variations in supply throughout the year. Therefore, to maximize the contribution of bioelectricity, wind, and solar power in the power mix, it is essential to develop integrated strategies that combine these renewable sources in a complementary way, ensuring a stable and reliable supply of energy throughout the year.

Due to the diversification of the mix (mainly wind and solar) and the reduction of the system's regularization capacity (variability and low controllability), the operation of the electrical system becomes more complex and the need for flexibility in energy systems grows. Investments in new generation technology solutions (contracting flexible sources), efficient use of existing assets, expansion and reinforcement of transmission/distribution, storage, demand-side management, adoption of economic signals with greater granularity (hourly), better techniques resource forecasting (actual dispatch forecast) are part of the flexibility solution (EPE et al., 2017). Flexibility is the ability of a power system to deal with variability and uncertainty in generation and demand, maintaining a satisfactory level of reliability at a reasonable cost, over various time horizons (MOROZOWSKI et al., 2021).

Hydroelectricity has been the main source of generation in the Brazilian electrical system for several decades (power plants with large seasonal and interannual regularization reservoirs). However, in recent years, this ability to regulate reservoirs has been decreasing, as there is a growing demand from the system and socio-environmental restrictions to build new hydroelectric plants with reservoirs.

In the long term, to guarantee maximum demand and adequate reserve to maintain the electric energy service, it will be necessary to increase the operating flexibility of the system, which can be done with storage technologies (reversible hydroelectric power plants or batteries), reassessment of the set of operational restrictions of hydroelectric plants (e.g., minimum and maximum flows, minimum and maximum volumes) and increased power supply with actions to modernize the hydroelectric system (repowering) (EPE et al., 2019, INSTITUTO E+ TRANSIÇÃO ENERGÉTICA, 2022).

For the time being, the existing reservoirs still allow the penetration of significant volumes of renewable generation, accommodating their production variability without entailing significant costs for the operation of the electrical system. Brazil has characteristics that favour the integration of non-dispatchable renewable sources on a large scale. One can highlight the vast interconnected transmission system, which leverages the energy complementarity between plants across various regions. Additionally, the widespread infrastructure of hydroelectric plants with reservoirs deserves mention. Even plants without storage reservoirs can effectively adjust their energy production, exhibiting remarkable generation dispatch flexibility. This operational adaptability helps in preventing unnecessary fuel costs associated with thermoelectric plant dispatch.

With its current hydroelectric capacity (existing reservoirs), transmission system capacity, and portfolio effect (complementarity between sources in different regions), Brazil's electrical system is able to accommodate the expected large input of variable sources in the coming years (EPE et al., 2019). According to our projections, by the year 2060, the proportion of Variable Renewable Energy (VRE) generation in the Brazilian power composition is anticipated to attain 36% in CPS1 and 32% in CPS2. Although these figures might seem modest in contrast to nations with more ambitious VRE targets, it's important to note that the overall renewable energy contribution stands at approximately 90% due to the significant roles played by hydroelectric and biomass sources.

Furthermore, the role of hydroelectric generation and reservoirs in the future of the Brazilian electrical system needs to be better understood and used. As well as generating energy, hydroelectric accumulation reservoirs provide essential ancillary services that stabilize and support the grid. Adjusting water release for energy generation in response to variable demand ensures grid frequency remains within acceptable limits and system stability is maintained. As a result, these reservoirs help maintain proper voltage levels and prevent adverse fluctuations by controlling water release and energy production. An uninterrupted and reliable electricity supply depends on the ability to quickly adapt energy generation to changing demand. Because of this, accumulation reservoirs provide essential ancillary services that contribute to system stability and energy supply quality, ensuring the efficiency and security of the electricity sector. There is a need to regulate new services.

5.3.3 Valuing the different attributes of energy sources and the role of hydroelectric plants

The existing economic signals fall short of effectively facilitating the implementation of optimal technological solutions. The evolution of the electrical system points to the growth of needs such as capacity and flexibility and the attributes of generation sources gain greater importance for the expansion and operation of the interconnected system (MME/EPE, 2021).

There is no single technological solution. It is important to assess the benefits of the sources, in addition to optimizing the operation and planning of the electricity sector, such as the environmental benefits provided by renewable generation sources (MME, 2019). Economically, it is noteworthy that other services, in addition to meeting the energy requirement of the system, can compose the remuneration of generators. This condition can provide new business models and leverage the development of new projects. To better understand, quantify and remunerate these attributes, methodological and market design improvements are still needed (MME/EPE, 2021).

As previously stated, a more comprehensive grasp and optimized utilization of hydroelectric generation and reservoirs are essential for shaping the future trajectory of the Brazilian electrical system. With the greater insertion of variable renewable energy sources, the operation of hydroelectric plants must be modified and its importance for the operation and security of the system increases. Hydroelectric plants, even run-of-river plants, have a certain degree of resource management and the possibility of meeting capacity requirements, flexibility, and various ancillary services (MME/EPE, 2020). The regularization reservoirs, with greater resource storage capacity, function as the system's batteries and contribute to optimizing the use of resources and operating costs. For example, today hydroelectric plants operate at the base of the system but could function as large batteries complementing variable renewable sources. However, they are remunerated only for the generation of energy and not for the other services they provide, such as storage, which is also important for the multiple uses of water such as irrigation and supply.

5.4 Power sector emission and the Brazilian NDC

Power generation expansion trend in Brazil is already based on renewable sources. The dominance of hydroelectricity results in a predominantly renewable energy mix, and thus presents lower GHG emissions than most other countries. This occurs even in 2021, when the renewables share in the power mix was marked by the fall in the supply of hydropower associated with water scarcity, which led to the activation of thermopower plants. The Brazilian electricity sector emitted 118.5 kgCO_2e/MWh in 2021, a very low rate when compared with countries of the European Union, the USA, and China (EPE, 2022).

The weight of the hydropower source in the electricity generation mix has been decreasing over the years, however, it still represented 63% of the generation capacity in 2020. The national grid GHG emission is very low and represents only 3%[6] of the total country emissions (Unterstell, La Rovere, et al. 2021). GHG emissions from power generation are expected to decrease further, from 49 MtCO_2e in 2020 to 26 MtCO_2e in CPS1 and to 47 Mt CO_2e in CPS2 in 2050. However, emissions are expected to increase after 2050 due to the resurgence of natural gas thermoelectricity, to offset the increased demand for electricity and the reduced share of hydroelectricity in the Brazilian energy mix (Figure 14).

[6] 49 MtCO2eq in 2020 out of 1,511 MtCO_2e

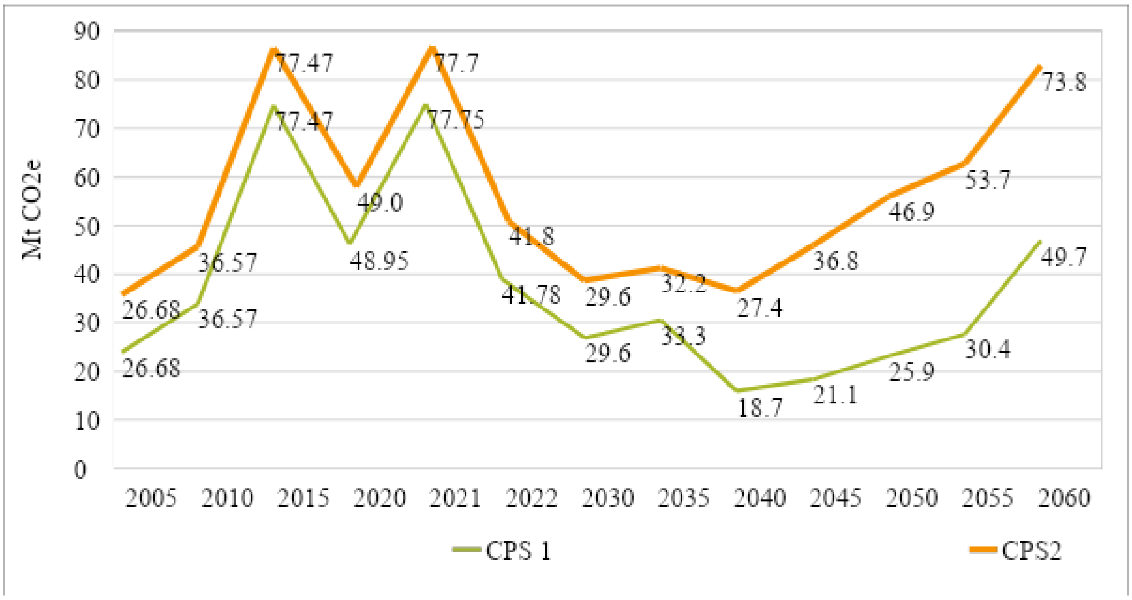

Figure 14 – Estimates of power sector emissions in CPS1 and CPS2 (2005-2060)
Source: Authors

It is important to highlight that increase in emissions, which occurs especially after 2040, is accompanied by a significantly greater expansion of the electricity supply in the analyzed period. Between 2020 and 2060, GHG emissions are expected to increase by 10% in CPS1 and 61% in CPS2, while electricity supply witnesses a notable increase of 112%.

Concerning the emission zeniths achieved in 2015 and 2017—amounting to 77 and 78 Mt CO_2e respectively—these instances were a result of a water crisis period. This crisis prompted a substantial decrease in hydroelectric generation, the primary energy source in the country, causing a notable increase in thermal generation.

The emission is higher in CPS2 because natural gas supplies the main backup to renewables in periods when they are not available, accounting for 10% of power generation in 2050 and 15% in 2060. As explained, the reason is that it is increasingly difficult to build new large hydropower plants as most of the potential to be tapped is located in environmentally sensitive areas in the Amazon region.

Brazil is on track to meet the target of the outdated first NDC of 23% of renewables other than hydro in the power generation mix by 2030. Besides the economy wide mitigation targets, it also had some sectoral goals, unlike the current version that eliminated them. It is worth mentioning that in both current policy scenarios, the share of renewables in supply – other than hydropower – increased to 39% by 2030 (wind, biomass and solar – including utility scale and distributed power generation).

6 PNE 2050 Scenarios

The National Energy Plan 2050 (PNE 2050), developed by the Energy Research Company, was approved by the Ministry of Mines and Energy in December 2020. This plan stands as a pivotal instrument, fostering the formulation of a comprehensive long-term blueprint for the expansion of the energy sector. Presenting a collection of key actions and recommendations, the PNE 2050 is a vital landmark within the energy policy realm. It evaluates trends in the production and use of energy and guides alternative strategies for the expansion of energy supply in the coming decades (EPE, 2020a).

Brazil's challenge is to strategically manage the abundance of energy resources due to the wide range of sources, containing a significant portion of renewables. Legal and regulatory frameworks, as well as public policies and technological innovations, are fundamental to harnessing the potential of the country's energy resources under a sustainable development pathway with a decarbonized electric mix, positioning Brazil as a model and reference in this theme.

The PNE 2050 presents two main scenarios called "Expansion Challenge" and "Stagnation". They dialogue with different possibilities and uncertainties due to their long-term vision and take into account constraints within energy policy as well as the costs and benefits associated with different options.

The elaboration of the PNE 2050 started from a "cone of uncertainties", which sought to encompass a great diversity of possible trajectories. These uncertainties stem from macroeconomic factors, encompassing energy demand, as well as the technologies and sources on the supply side, all within the framework of the global energy transition.

The Expansion Challenge scenario delimits the upper limit of the cone, in which the tonic is the pressure to expand the infrastructure and supply of energy, seeking to meet a relevant growth in demand. Delimiting the lower limit of the cone, there is the "Stagnation" scenario, which tests the implications of relative stagnation in per capita energy demand in Brazil (Figure 15). The PDE 2050 studies were preferably conducted in the Expansion Challenge scenario, as they point out how energy sector authorities need to deal with a significant expansion of energy demand when designing their strategy for the sector.

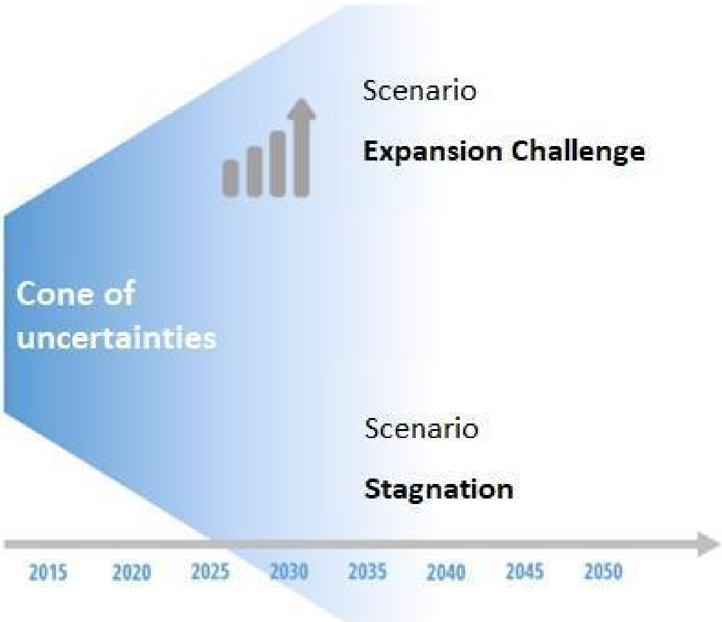

Figure 15 – Main Scenarios – Challenge of expansion and stagnation (PNE 2050)
Source: EPE, 2020a

6.1 Methodology

The studies in the development of PNE 2050 were divided into four main blocks, namely:

i) The macroeconomic module, which encompassed the contextualization of the entire work, including the formulation of the long-term scenario for the global and national economy;
ii) The demand module, which involved setting sectoral, demographic, technological, and energy efficiency assumptions, resulting in the projection of final energy consumption by source;
iii) The supply module, which encompassed the assessment of energy resources considering technological, price, and socio-environmental aspects, resulting in the definition of the strategy for expanding energy supply by source, as well as energy efficiency policies; and
iv) The consolidation module, where demand and supply studies were integrated, potentially leading to the revision of initial projections in light of political, strategic, institutional, and energy security considerations.

In each of these blocks, various simulation and quantification models were employed, developed with the aim of generating a coherent set of long-term projections for the variables of interest.

During the quantification of the national macroeconomic scenario, the consistency of the GDP evolution path was verified through the Long-Term Macroeconomic Consistency Model (LT-MCM), adapted by EPE from modeling proposed by the World Bank. In quantifying the demographic scenario, the Demographic Parameter Estimation Model (DEMO), developed at EPE from modeling proposed by IBGE, was applied. For projecting final energy consumption, a bottom-up type model named the Integrated Energy Planning Model (IEPM), developed at COPPE/UFRJ and enhanced at EPE, was employed. Specifically for residential electricity consumption projection, a similar bottom-up model developed at COPPE/UFRJ and refined at EPE, known as the Residential Energy Demand Projection Model (REDM), was used.

On the supply side, two specific models were employed to assess primary energy transformation: the Petroleum Refining Study Model (PLANDEPE), developed at EPE, enabling the scaling of petroleum refining expansion in relation to derivative demand evolution; and the Electric System Expansion Planning Model (ESEP), developed at EPE, which finds the optimal expansion solution for electricity supply, minimizing expansion and operation costs, taking into account investment costs in power plants and transmission lines connecting subsystems, the cost of fuels used in thermal generation, as well as various operational and environmental constraints.

The results of supply and demand studies were integrated and verified using the MATRIZ model, developed by Eletrobras/Cepel. As an outcome, the evolution of the domestic energy supply composition is obtained, allowing for the scenario analysis of the Brazilian energy mix for the next 40 years.

6.2 Electricity demand

The demand for electricity presents the scenarios of the evolution of energy consumption that envision the long-term horizon, to anticipate the possible innovations and events that may produce significant changes in society and its relationship with energy (EPE, 2020).

In the Expansion Challenge scenario, growth in the potential consumption of electric energy is projected, which is determined from the estimated consumption in the network, which corresponds to the result obtained from the potential consumption of electricity, minus the estimated portions of the contribution of energy efficiency, self-production and distributed generation. In the Stagnation scenario, the projected average growth rate of potential electricity consumption is 1% per year between 2015 and 2050. Considering the scenarios' outputs, on the horizon of the PNE 2050, the country's potential electricity consumption can reach up to three times the level of the base year (Figure 16).

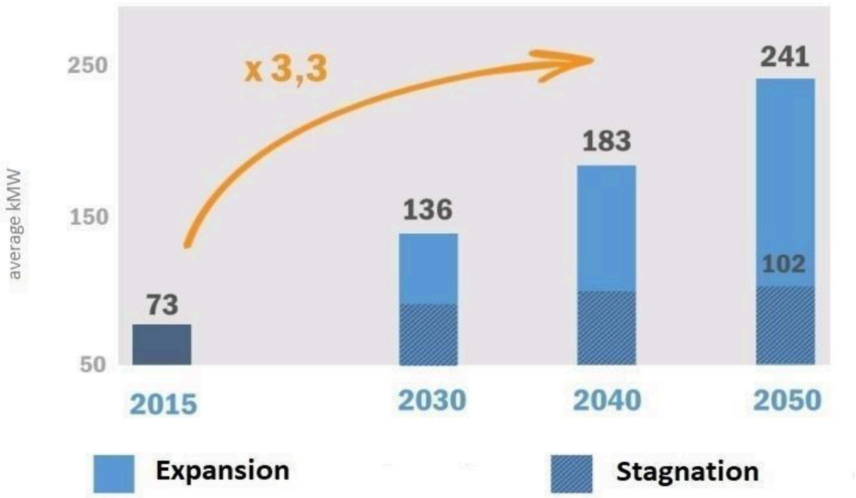

Figure 16 – Range of electricity demand (PNE 2050)
Source: EPE, 2020a

Brazil's potential electric energy consumption is projected to grow by an average of 3.5% annually from 2015 to 2050, reaching about 240,000 MW average (over 2,100 TWh) by 2050. Around 5% will come from distributed generation (nearly 11,000 MW average) and 7% from self-production (16,000 MW average). Energy efficiency will rise to 17% by 2050, equivalent to 40 GW average, or around 360 TWh. The analysis considers grid consumption minus estimated energy efficiency, self-production, and distributed generation.

In the Stagnation scenario, potential electric energy consumption grows at an average of 1% per year to around 100,000 MW average (under 870 TWh) by 2050. Self-production increases to 14% (13,000 MW average), distributed generation contributes with 7% (almost 6,000 MW average), and energy efficiency reaches 10% by 2050 (around 10,000 MW average).

The demand for electricity through centralized generation reaches about 172,000 average MW in the Expansion Challenge scenario, which is equivalent to about 2.5 times the consumption observed in 2015. By 2050, this level represents 70% of the total energy requirement of the Brazilian economy. If the prospects of faster expansion of DG, self-production, solar thermal energy, and energy efficiency in this scenario do not materialize, this growth may be even more pronounced.

The perspective in the Stagnation scenario is that centralized generation will continue in the range between 65,000 and 70,000 average MW, a level that represents approximately 2/3 of the total energy requirement in 2050, not only due to the more modest growth associated with this scenario but also to an increase in the relative share of Self-production and DG, whose determinants are not restricted only to the evolution of domestic economic activity (Figure 17).

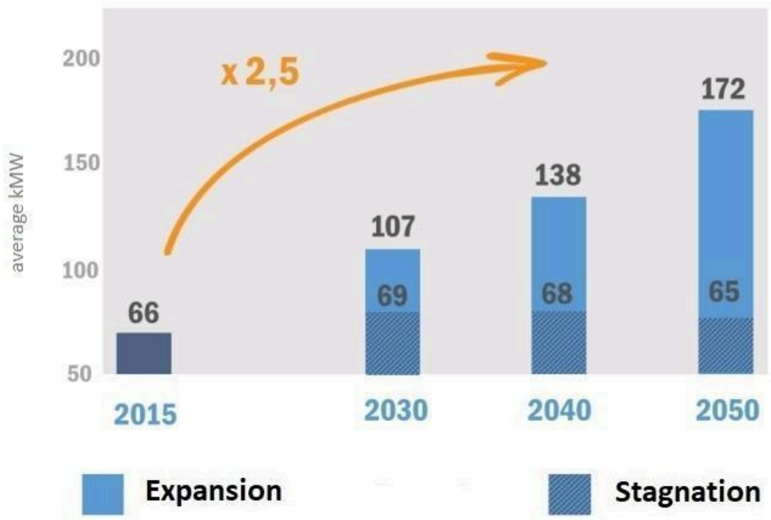

Figure 17 – Range of electricity demand to be met by centralized generation (PNE 2050)
Source: EPE, 2020a

The scenario of the Expansion Challenge presents an average growth rate of 2.2% per year, arriving in 2050 with just over double the final consumption of 2015, with faster growth in the first fifteen years, with an average rate of more than 2.5% per year.

6.3 Electricity supply

The quantitative exercise carried out in the PNE generates an indicative expansion of the offer based on the investment decision model (EPE, 2018), which defines an optimal expansion of the system by minimizing the expected total cost of investment and operation. This optimization process operates on a quarterly basis, factoring in the primary operational limitations of the service. These limitations encompass energy demand (with a single threshold) and the highest instantaneous power demand projected up to the year 2050.

Within the findings, the outcomes imply that the extent of sustainability within Brazil's electricity framework will remain high throughout the study's time frame. Assuming an entirely renewable power complementation, Figure 18 illustrates the forecasted proportion of renewable energy sources within the electricity framework by 2050. This proportion remains substantial across various simulated scenarios, regardless of whether it's evaluated in terms of average period generation or installed capacity.

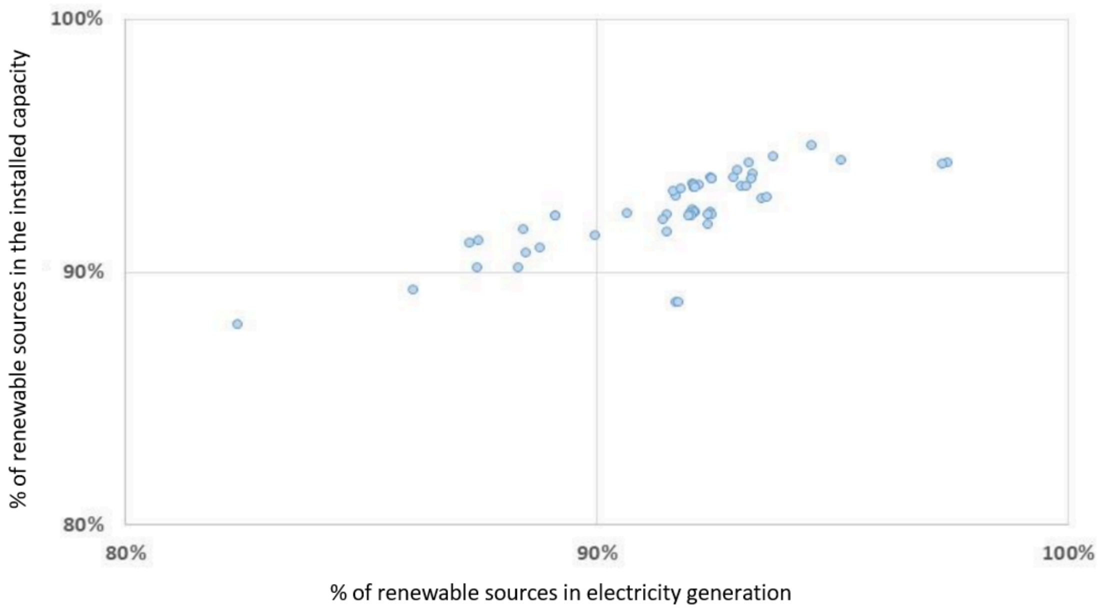

Figure 18 – Participation of renewable sources in the electricity mix by 2050 (PNE 2050)
Source: EPE, 2020a

The final inference remains materially consistent even if power complementation were to be exclusively non-renewable. In this hypothetical scenario, the graphical representation would undergo an average vertical shift of 12%. Nonetheless, the anticipated proportion of renewable sources within the installed capacity by 2050 would persist at over 75%.

To evaluate the feasibility of attaining a fully renewable electricity mix by 2050, the 64 total rounds were narrowed to exclusively encompass renewable projects within the expansion portfolio of the Expansion Challenge scenario. The outcome, depicted in

Figure 19, underscores the potential realization of an electricity mix that is nearly 100% renewable within the centralized system by 2050. Without the renewability restriction, the installed capacity varies between 451-473 GW and with a 100% renewable mix this capacity rises to 488-525 GW. This achievement hinges on the condition that even the power complementation, ranging from 77 GW to 85 GW of installed capacity by 2050, is sourced entirely from renewable origins. The fraction of the mix that remains non-renewable, accounting for roughly 0.5% of the installed capacity in 2050, is represented by the thermonuclear plants situated in the Angra complex. These plants would not have been fully phased out from the national power generation network throughout the analysis period.

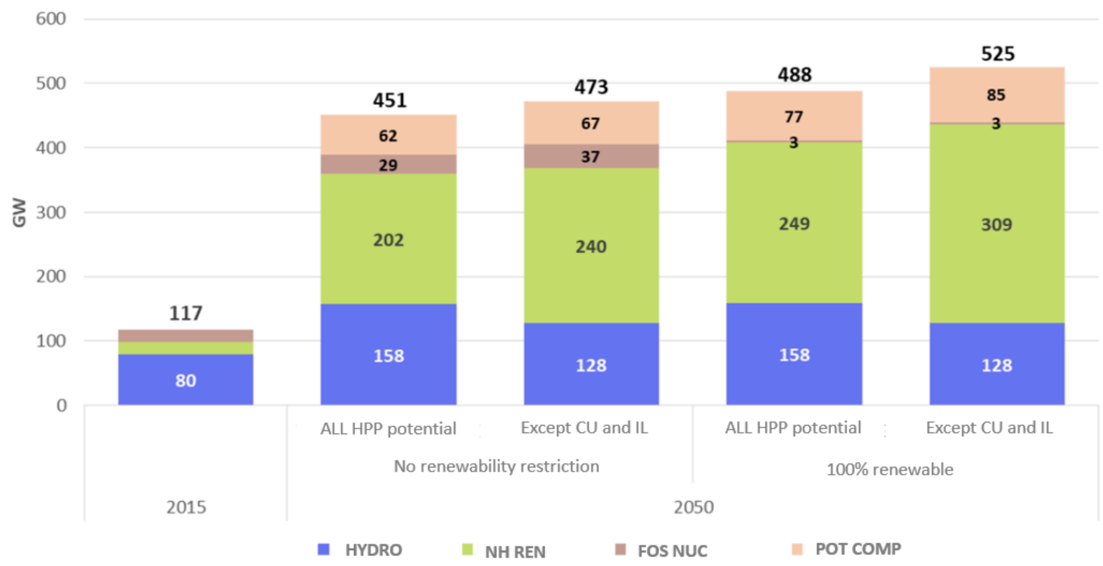

Figure 19 – Expansion of the installed capacity with reduced water availability and with and without emission restrictions by 2050 (PNE 2050)
Source: EPE, 2020a
Label: HYDRO – Hydroelectric; NH REN – Non-hydro renewable sources (Biomass, Wind and Solar); Except CU and IL – only HPPs without interference in areas of Conservation Units (CU) or Indigenous Lands or Quilombolas (IL); FOS – Fossil fuel thermal power plants; NUC – Thermonuclear Power Plant; POT COMP: Complementary Power.

Regarding the cost implications of these four scenarios analyzed above, the net present value (NPV) of the total cost (at 2015 prices) of centralized generation in billions of reais would be R$ 723, R$742, R$ 767, and R$ 794, respectively (EPE, 2020a).

The PNE study also gives us an idea of how different sources might contribute to electricity generation by 2050, in the Challenge Scenario as shown in Figure 20. In that figure, we can see the possible ranges of participation for the sources displayed at the bottom of the figure (represented by the blue columns) and compare them with the historical data from 2015 (represented by the yellow dots). What stands out is that hydroelectric plants might contribute less, while wind and solar energy could play a bigger role. Other changes will depend on various factors like technical advancements, economic factors, and political decisions. The main factors that drive the maximum and the minimum percentage of each electricity source in the mix are explained in the figure in grey.

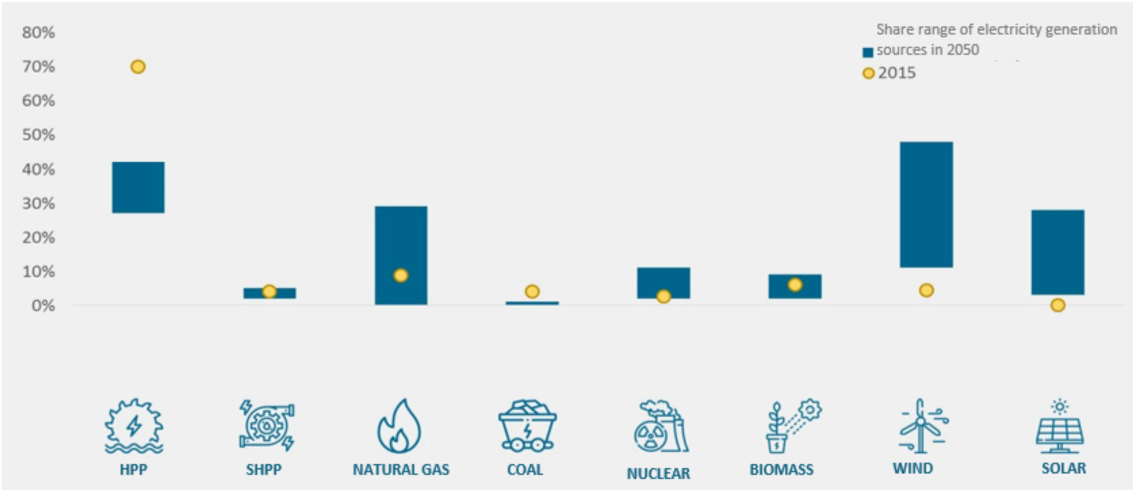

Figure 20 – Comparative analysis of source participation in electricity generation (2015) and projected percentage variation ranges by 2050, in the Challenging Scenario (PNE 2050)
Source: EPE, 2020b

Lastly, Figure 21 illustrates the potential range of change in installed capacity for energy sources up to 2050, under the Challenge Scenario. Notably, this figure highlights significant fluctuations in the potential capacity changes for natural gas, wind, and solar sources. These fluctuations largely hinge on the public policies adopted in the country leading up to 2050, and they represent some of the key factors influencing the outcomes outlined in the figure.

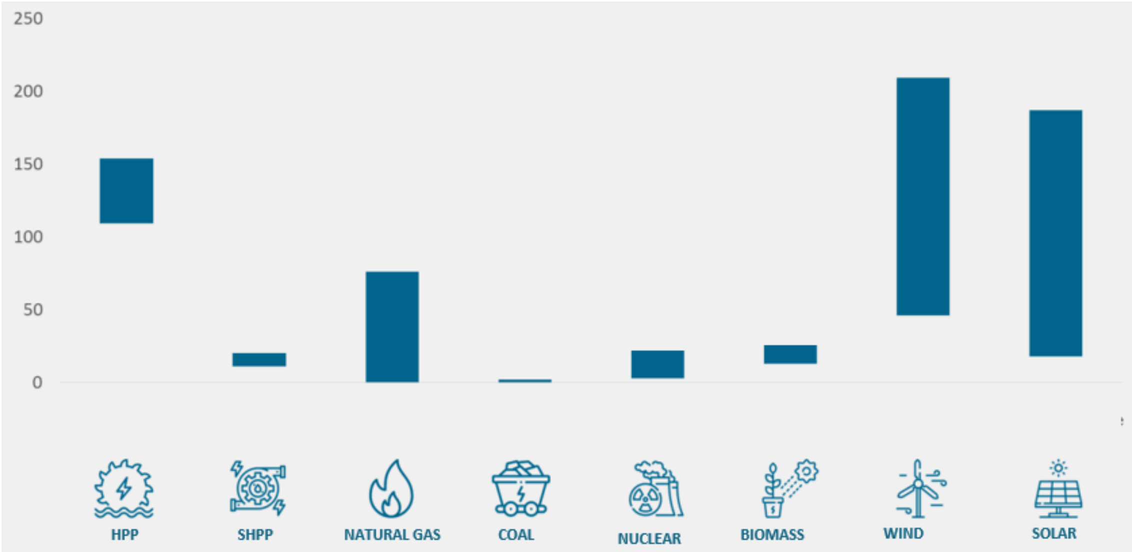

Figure 21 – Installed capacity variation range (GW) of sources by 2050, in the Challenging Scenario (PNE 2050)
Source: EPE, 2020b

7 Comparative analysis (PNE 2050 x CPS 2050)

The PNE 2050 is a set of studies that support the design of the government's long-term strategy regarding the expansion of the energy sector. This report focuses on the electricity sector and specifically on the opportunities and challenges of expanding variable renewable energies and biomass in relation to current policies.

Both base their analyses on scenario exercises, which is a decision support methodology. Elaborating scenarios is not an exercise of prediction, but rather an effort to make plausible and consistent descriptions of possible future situations, presenting the path between the current situation and each future scenario, highlighting the factors relevant to the decisions that need to be made (Wright and Spers, 2006). In an uncertain context, the objective is to explore future alternatives to improve the decision-making process in energy policies (EPE, 2020a).

The PNE 2050 and ICAT Brazil Project phase 3 scenarios are based on different assumptions and hypotheses for the future (Table 19). In addition, this study uses more recent data than the PNE 2050, launched in 2020.

Table 19 – Main data comparison between PNE 2050 and CPS

Indicators	PNE 2050		ICAT phase 3
	Stagnation Scenarios	Expansion Challenge Scenarios	CPS 1 and 2
Study publication year	2020		2023

Indicators	PNE 2050		ICAT phase 3
	Stagnation Scenarios	Expansion Challenge Scenarios	CPS 1 and 2
Population in 2050	226 million (after a pic of 228 million in 2040)		215 million (after a pic of 220 million in 2047)
Domestic oil production in 2030	3.6 million barrel/day	5.5 million barrel/day	5.3 million barrel/day[1]
Domestic oil production in 2050	3.6 million barrel/day	6.1 million barrel/day	5.3 million barrel/day[2]
Oil price in 2050	Around 60 USD_{2015}/barrel	Around 90 USD_{2015}/barrel	63.9 USD_{2022}/barrel [3] (51.46 USD_{2015}/barrel)
GDP (average annual growth rate, 2015-2050)	1.6%	3.1%	1.72%
Per capita GDP (average annual growth rate, 2015-2050)	1.3%	2.8%	1.4%
Electricity demand in 2050	102 average thousand MW[7] (894 TWh)	241 average thousand MW (2,111TWh)	970 TWh

[1]Source PDE 2032 EPE/MME (2023)
[2] Source PNE 2050 EPE/MME (2020)
[3] International Energy Agency | World Energy Outlook 2022. "Announced Pledges" Scenario

Although numerically different, the reports show similar future story scenarios. Both show that Brazil is abundant in a wide range of energy sources and a significant portion is made up of renewable resources. Thus, the expansions of energy supply and consumption will be made in a sustainable way, with the maintenance of renewable indicators in the electricity generation mix. As can be seen in Figure 22, the CPS 1 and CPS 2 values are within the set of scenarios of PNE 2050. The figure compares, in 2050, the share of sources in electricity generation (%) in CPS 1 and CPS2 (orange and green dots) with the range of variation of the share of each source in all the Expansion Challenge scenarios of the PNE 2050 (blue).

[7] The volume in MW- average is obtained by dividing the volume in MWh by the amount of hours of the period (in this case 1 year, 8760 hours). The PNE uses this unit because it allows a better comparison between volumes associated with different duration periods.

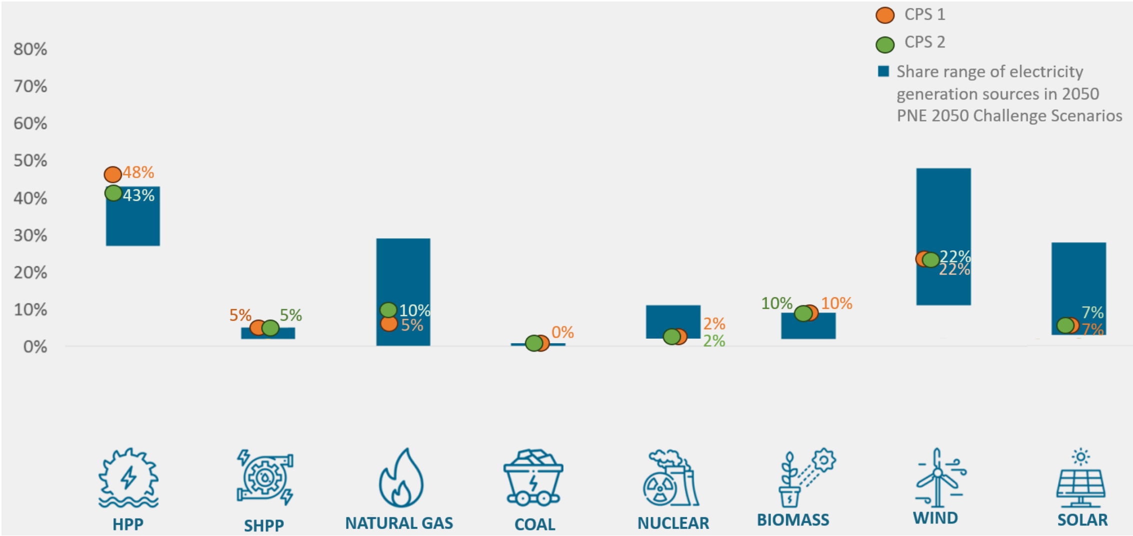

Figure 22 – Comparative analysis: share of electricity generation sources (%) in CPS1 and CPS2, and range of variation across all expansion challenge scenarios of PNE 2050

Source: Authors based on EPE (EPE, 2020a)

Scenarios are living instruments that dialogue with different possibilities and environments of uncertainty and that can serve as a guide for decision making (EPE, 2020b). In this sense, more important than the numbers themselves, is the debate and the process of reflection on the constraints of energy policy and the equation of costs and benefits in the medium and long term.

8 Conclusion

Brazil's electricity supply landscape is undergoing a significant transformation, with an increasing emphasis on variable renewable energy sources. The country's power generation mix is witnessing a shift towards wind and solar sources, which are playing a complementary role alongside the traditional dominance of hydroelectric power plants. As demonstrated in the scenarios presented, the expansion of wind and solar capacity is driving the reduction in the relative share of hydroelectricity. This transition is crucial for achieving the country's sustainable energy goals, as renewable sources become key contributors to the power generation mix.

Hydroelectric power, while historically central to Brazil's energy sector, is facing challenges due to socio-environmental considerations and the diminishing potential for large-scale projects. The intricate interplay between energy development and ecological conservation underscores the need for meticulous planning and comprehensive environmental impact assessments. Moreover, the role of hydroelectric plants extends beyond energy generation; their capacity for resource management, regulation, and ancillary services is increasingly vital for system stability and grid support.

As Brazil works towards its climate commitments, the importance of diversifying its electricity mix and valuing different attributes of energy sources becomes evident. The expansion of variable renewable electricity sources and bioelectricity offers promise but presents challenges related to supply variability and seasonality. The integration of these sources with hydroelectric power, along with investments in flexibility solutions, transmission/distribution, storage, and demand-side management, will be crucial for ensuring a stable and reliable energy supply. Furthermore, the evolution of regulatory frameworks and economic signals must align with the benefits and contributions of various energy sources to optimize the energy sector's growth and sustainability.

In the comparative analysis of the Power National Plan (PNE) 2050 and the Current Policy Scenarios, it is apparent that both reports envision a future where Brazil's energy mix continues to shift towards renewables. While numerical variations exist, the alignment of these scenarios underscores the significance of the ongoing dialogue surrounding energy policy and the dynamic trade-offs between costs and benefits. As Brazil progresses towards its NDC goals and endeavors to reduce greenhouse gas emissions, the integration of renewable sources, adaptation of hydroelectric plant roles, and strategic decision-making will shape the country's sustainable energy landscape in the years to come.

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