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

ICAT Brazil Project phase 3

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

Output 3 – Report on VRE and biomass expansion under the deep decarbonization scenario

July 2024

Initiative for Climate Action Transparency – ICAT
Report on VRE and biomass expansion under the deep decarbonization scenario

Deliverable #3

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List of abbreviations

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
CAPEX	Capital Expenditures
CBC	Brazil Climate Centre
CBios	Biofuel Emission Certificates
CCC	Copenhagen Climate Centre
CCEAR	Energy Trading Contracts in a Regulated Environment
CCEE	Electric Energy Trading Chamber
CEOs	Chief Executive Officer
CEPEL	Electric Energy Research Center
CGE	Computable General Equilibrium Model
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
HEV	Hybrid Eletric Vehicle
HGV	Heavy Goods Vehicles
HPP	Hydroelectric Power Plant
IBGE	Brazilian Institute of Geography and Statistics
IASA	International Institute for Applied System Analysis (IASA)
ICAT	Initiative for Climate Action Transparency
ICE	Internal Combustion Engines
iCS	The Institute for Climate and Society
IDDRI	Institute for Sustainable Development and International Relations
IEPM	Integrated Energy Planning Model
IKI/BMU	International Climate Initiative / Nuclear Safety
IMACLIM	General equilibrium model of the economy
IMAGINE	Insights from Modelling and Analysis for Global Interactions and National Engagement

iNDC	Intended Nationally Determined Contribution
IRENA	International Renewable Energy Agency
LCV	Light Commercial Vehicles
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
LULUCF	Land use change and forestry sector
MATRIZ	Brazilian Energy Mix Model
MME	Ministry of Mines and Energy
MRV	Measurement, Reporting, and Verification
NAMAs	Nationally Appropriate Mitigation Actions
NGPS	New Government Policy Scenario
NDC	Nationally Determined Contribution
OPEX	Operational Expenditure
PDE	Ten-Year Energy Expansion Plan
PERS	Social Renewable Energy Program PERS
PLANDEP	Petroleum Refining Study Model
PNE	National Energy Plan
PNMC	National Policy on Climate Change
PPE	Energy Planning Program
ProGD	Power Generation Development Program
Proinfa	Incentive Program for Alternative Sources of Electric Energy
REN	Aneel Normative Resolution
RenovaBio	National Biofuels Policy
SAM	Social Accounting Matrix
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

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Forewords

This report is part of the ICAT Brazil Project phase 3, henceforth 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 ICAT project embodies a robust initiative for advancing climate transparency in Brazil.

The previous phases of the ICAT project were dedicated to fortifying the transparency framework in Brazil. This endeavour included the development of MRV indicators to assess climate policies and actions at both the national (1st phase) and subnational (2nd phase) levels. These phases developed mitigation scenarios that provide critical insight for policy development at the national and sub-national levels, and proposed MRV indicators for monitoring the implementation of the Brazilian NDC.

The third phase of the ICAT Brazil project, builds off insight gained from the first two phases, by providing a detailed analysis of the electricity sector in Brazil. This phase delves deeply into the analysis of Brazil's electricity sector, assessing the potential expansion of the power sector via variable renewable energies (wind and solar photovoltaic) and biomass. Furthermore, it assesses the sustainable development impacts of sectoral policies by employing the ICAT's Sustainable Development Methodology and actively contributes to the strategic planning for a Just Energy Transition in Brazil.

This document, constituting Output 3 of the ICAT project, is prepared by Centro Clima/COPPE/UFRJ. It unfolds a comprehensive Deep Decarbonisation Scenario (DDS) and meticulously analyses the expansion of Variable Renewable Energy (VRE) and biomass sources, incorporating additional measures to achieve an economy wide net zero GHG emissions by 2050. The primary objective of this report is to conduct a comparative analysis of scenario results pertaining to the electricity mix, its associated costs, and greenhouse gas (GHG) emissions. This analysis highlights the differences between the DDS and the 'current policies' scenario (CPS), particularly in terms of VRE penetration and GHG emissions.

1 Introduction

The IRENA's 1.5°C pathway positions electrification and efficiency as key drivers of the energy transition, enabled by renewable energies, hydrogen, and sustainable biomass. This pathway, which requires a massive shift in how societies produce and consume energy, would result in a reduction of almost 37 gigatonnes of annual CO2 emissions from energy by 2050 (IRENA, 2022). Therefore, the ICAT 3 scenarios exercise is key to assess the Brazilian perspectives regarding renewables.

In the context of this ICAT 3 project assessment focused on the potential for renewable energy implementation in Brazil, four electricity supply scenarios were developed extending to the year 2060[1]: CPS1, CPS2, DDS1, and DDS2, 'CPS' refers to Current Policy Scenario and follows the trend of ongoing mitigation actions. 'DDS' denotes Deep Decarbonization Scenario and follows a GHG emissions trajectory compatible with the global objective of 1.5ºC, achieving net-zero emissions in 2050. The project aims to estimate the maximum potential for increasing renewable energy sources for the Brazilian power sector, projecting its implications through 2060.

The four supply scenarios were designed to meet the demand projections generated in the scenario development exercise, undertaken as part of the IMAGINE Project, which was carried out by Centro Clima in collaboration with IDDRI. The ICAT 3 scenarios are the following (Figure 1).

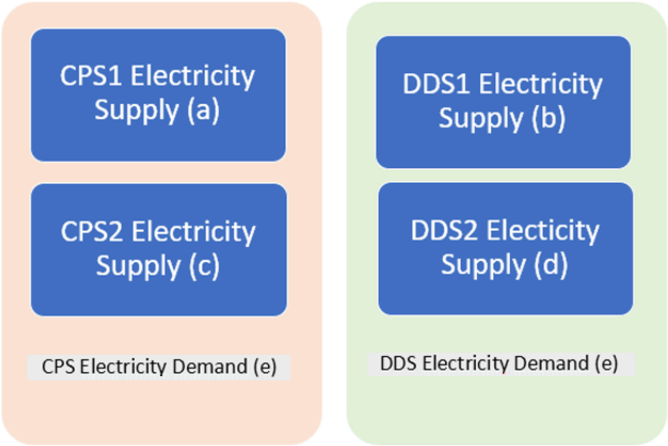

Figure 1 - ICAT electricity supply scenarios
Source: Prepared by the authors.

(a) This ICAT 3 Project scenario includes the total inventoried hydroelectric potential for Hydropower Plants (HPP) as detailed in the PNE 2050. For the expansion period, 52 GW of capacity is available within the MATRIZ model's subsystems. This includes 1.96 GW available up until 2031, according to the PDE 2031 (EPE, 2022b), with the remainder becoming available from 2032 onwards;

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[1] To illustrate how a net-zero Brazilian economy could continue to grow after 2050, maintaining a steady-state net-zero pattern, the time frame of the scenarios exercise was extended up to 2060.

(b) Same as (a) but with a carbon shadow price simulated;

(c) This ICAT 3 Project scenario, while maintaining the same assumptions as outlined in (a), specifically focus on HPPs that do not infringe upon protected areas (including conservation units, indigenous lands, and quilombola[2] territories). During the expansion period, there is 12 GW of capacity available within the MATRIZ model's subsystems, with 2.95 GW specifically allocated to the northern region. Of this, 1.96 GW is accessible up until 2031 as indicated in the PDE 2031 (EPE, 2022b), and the remaining capacity from 2032 onwards;

(d) Same as (c) but with a carbon shadow price simulated;

(e) Estimates from the Imagine Project are provided up to 2050, while for the ICAT 3 Project, the estimates extend up to 2060.

The CPS1 and CPS2 assumptions and results were presented in the previous ICAT Phase 3 project report (product 2 from August 2023). However, Centro Clima continuously updates its scenarios, aiming to reduce uncertainty regarding political risks tied to climate mitigation policies. The recent IMAGINE project brought about some changes to the Current Policy Scenarios (CPS called NGPS), including an extensive review and new data integration, particularly affecting the power sector. While the updated CPS electricity supply is presented along the DDS supply in the main text of this report, the updated CPS demand is detailed in Appendix 1. This report presents scenarios DDS 1 and DDS 2 and an update in CPS figures.

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[2] Quilombola communities are ethnic groups - predominantly composed of rural or urban black populations formed by descendants of runaway slaves during the time of slavery in Brazil - who self-define based on specific relationships with the land, kinship, territory, ancestry, traditions, and their own cultural practices.

2 Modelling approach

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 modelling. Given these considerations, more detailed modelling efforts have been 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 modelling 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 4where the methods for estimating electrical demand are presented (and they are also applied to fuel-related modelling). 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 ICAT3 project (also used in the IMAGINE 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 analysing 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 DDS for electricity demand and generation. A summary of the simulations of the Imagine Project which the simulations features are presented in Table 1.

Table 1 – Main features of the simulations of the Imagine Project

Estimate features	CPS – based on the current policies	DDS – based on policies and measures required to meet Net Zero in 2050
Residential	Estimates based on projections of energy per capita consumption.	Same values as CPS.
Transport	Estimates tailored to the CPS (sectoral GDP, infrastructure, fleets efficiency and energy source and technology penetration).	Estimates tailored to the DDS (sectoral GDP, infrastructure, fleets efficiency and energy source and technology penetration).
Industry	Estimates tailored to the CPS (sectoral GDP, and energy source/ technology penetration).	Estimates tailored to the DDS (sectoral GDP, and energy source/ technology penetration).
Service and Public	Estimates follow the CPS sectoral GDP estimates.	Estimates follow the DDS sectoral GDP estimates.
Agriculture Energy	Estimates follow the CPS sectoral GDP estimates.	Estimates follow the DDS sectoral GDP estimates.
AFOLU	Estimates tailored to the CPS (sectoral GDP, penetration of low carbon agriculture practices and forestry activities, and deforestation rates). The estimates are adjusted to meet the biomass demand from other sectors.	Estimates tailored to the DDS (sectoral GDP estimates, penetration of low carbon agriculture practices and forestry activities, and deforestation rates). Estimates are adjusted to meet the biomass demand from other sectors.
Waste	Estimates based on per capita waste generation, with assumptions for collection and treatment levels tailored to the CPS.	Estimates based on per capita waste generation, with assumptions for collection and treatment levels tailored to the DDS.
Energy supply	Estimates tailored to meet the sectoral energy demand from CPS. In the Power sector, focus on cleaner and renewable energy sources, such as hydro, wind (onshore), biomass, and solar power.	Estimates tailored to meet the sectoral energy demand from DDS. In the Power sector, focus on cleaner and renewable energy sources, such as hydro, biomass, wind (onshore and offshore), and solar power. Reduction of 32% in carbon intensity in the E&P segment by 2025 compared to 2015 (maintained until 2030) according to Petrobrás Sustainability report. Expanding to 57% by 2050 compared to 2015. Reduction of 16% in carbon intensity in the refine segment by 2025 compared to 2015, Expanding to 57% by 2050. Energy storage deployment.
Macroeconomics	We start by defining premises for the CPS and test them in the Computable General Equilibrium (CGE) Model for projections up to 2050. Initial forecasts, including GDP and other economic variables, are refined through an iterative process with sectoral models, which provide the final equilibrium for the CPS. This exchange ensures that the CGE model and sectorial models are aligned, reflecting both macroeconomic and sectoral trends. The result is	In the DDS scenario, the CGE model undergoes simultaneous shocks that include the implementation of a carbon price, crucial for achieving established environmental targets. This adjustment leads to the adoption of a new energy matrix, reflecting the transition induced by carbon pricing, alongside the integration of other mitigation policies and the necessary investments at each step to ensure an effective transition. An interactive process between the CGE model and sectoral models is employed to ensure consistency

	accurate economic indicators for strategic guidance.	and alignment. As a result, the CGE model produces vital macroeconomic and social indicators, such as GDP, trade balance, investment rate, unemployment, household income, and social inequality indices.

Source: Prepared by the authors.

2.1 Qualitative storyline and quantitative assumptions – approaches for scenario construction

The definition of the scenarios' assumptions was undertaken through a participatory process involving stakeholders during the 2020-2023 period (Appendix 2). Centro Clima collaborated with other projects in the field of the ICAT Brazil Project phase 3, such as: DDP BIICS; the ACT-DDP project; the Climate and Development Initiative; DecarBoost project; and the IMAGINE Project just released. These projects' designs considered quantitative modelling 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 stakeholders comprise experts from the government, private sector, academia, and civil society (Appendix 2), that discussed and validated assumptions concerning market trends, the performance of public policies and societal transformation, critically appraised to outline possible development pathways for the Brazilian economy.

2.2 MATRIZ Model

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

The MATRIZ model has been 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[3], 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

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

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 2).

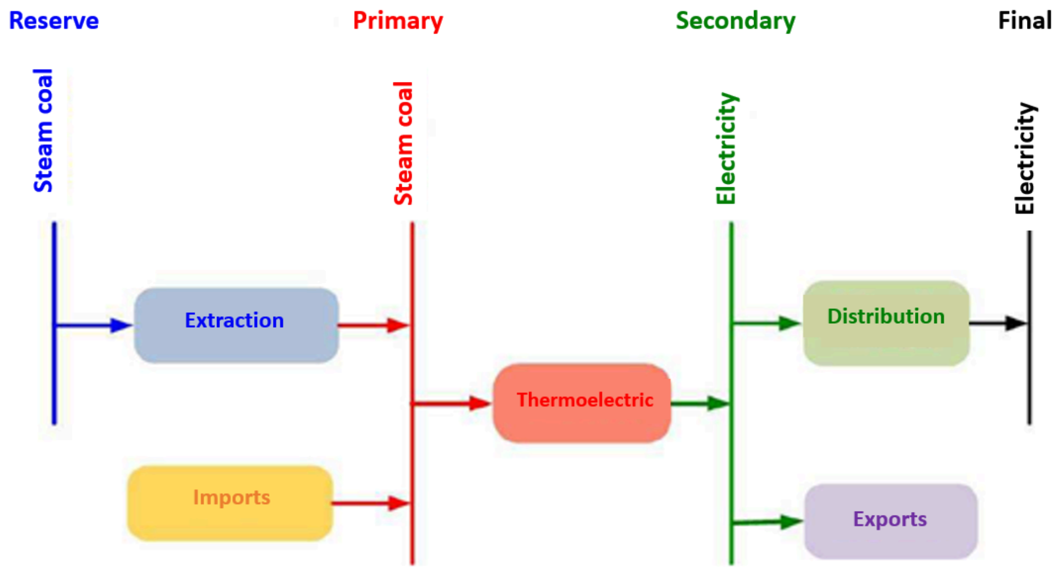

Figure 2 – Schematic diagram of the coal chain (simplified example)
Source: DEA/CEPEL (2016).

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. *et al.*, 2023).Each period is subdivided into four seasons of the year, and, in each season, there are eight levels (Figure 3). 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.

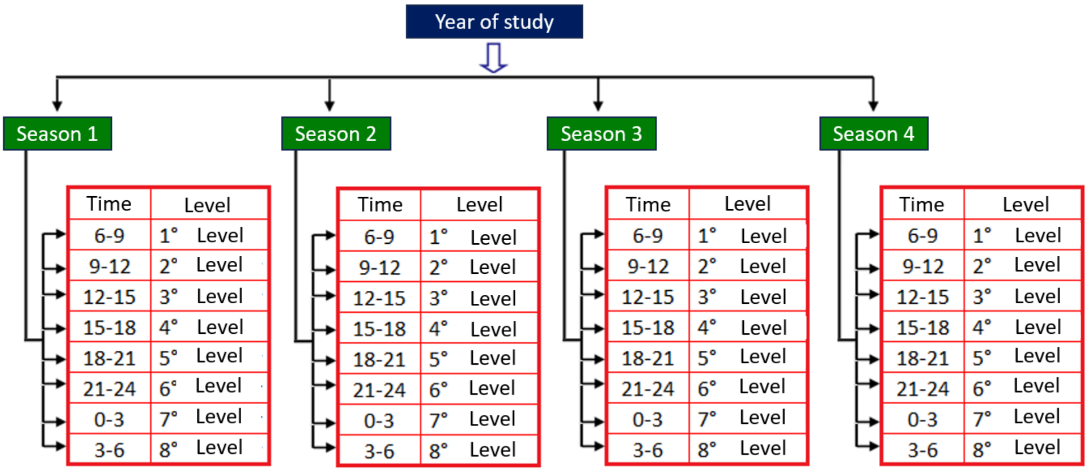

Figure 3 – Diurnal (up to 8 levels) and/or seasonal variations in the MATRIZ model.
Source: Prepared by the authors.
Note: In the example, the day is divided into 8 levels of 3 hours each, a total of 24 hours a day.

In other words, the new version of the MATRIZ model provides higher granularity in matching electricity demand with power generation dispatch, which is a key feature for assessing the potential contribution of VRE such as solar and wind energy to power generation. Given the complexity of the Brazilian electricity sector, the model considers nine operating subsystems with each analysis period detailed across four seasons and eight load levels. This detailed representation of the system in the model is essential for assessing energy security, ensuring that the system meets both seasonal and hourly-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 2060, 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.

2.3 General features of IMACLIM-S BR model and the marginal abatement cost curve

Utilizing IMACLIM-S, a hybrid CGE model specifically crafted for the comparative statics evaluation of medium- to long-term macroeconomic impacts arising from either aggregate price- or quantity-based policy, scenario analysis is conducted (GROTTERA *et al.*, 2020). This model operates on the foundation of a hybrid Social Accounting Matrix (SAM), an accounting framework that harmonizes economic, energy, and environmental databases to equilibrate economic and physical flows.

Within the model's projections, crucial determinants of economic growth are considered, encompassing demographics, labor and capital productivity, energy system prices, and the structure and efficiency of the system. These factors collectively contribute to estimating a trajectory for a specified time horizon.

IMACLIM-S BR has been employed for long-term assessments concerning mitigation strategies and carbon pricing mechanisms, as evidenced by Gupta, Ghersi, Vishwanathan, and Garg (2019), Lefèvre, Wills, and Hourcade(2018), La Rovere, Wills, Grottera, Dubeux, and Gesteira (2018), and La Rovere, Grottera, and Wills (2018). A detailed exposition of the IMACLIM-S BR model is available in Lefèvre (2016).

The key iteration of IMACLIM-S BR (hybrid CGE model) and sectoral bottom-up models for energy use and production are succinctly presented in Figure 4, as an integrated methodological framework.

The GHG emission scenarios are then compared with the expected abatement potential of the mitigation measures relative to the CPS. The CPS serves as a benchmark to ascertain the necessary increase in ambition and implementation of mitigation actions required to reach the Brazilian NDC targets in 2025 and 2030, ultimately leading to carbon neutrality by 2050.

The deployment of mitigation measures follows an incremental cost-based approach, with measures implemented in ascending order according to their cost until the essential abatement is achieved to meet the targets. The abatement potential (in $MtCO_2e$) and cost (in USD/tCO_2e avoided) for all mitigation measures are computed over distinct periods. Measures are ranked by ascending abatement cost, which may vary largely between periods due to increasing abatement potential over time and variations in costs assumptions. The model identifies costs by constructing Marginal Abatement Cost (MAC) curves, where the carbon cost is defined by the cost of the last measure adopted to meet the predefined target.

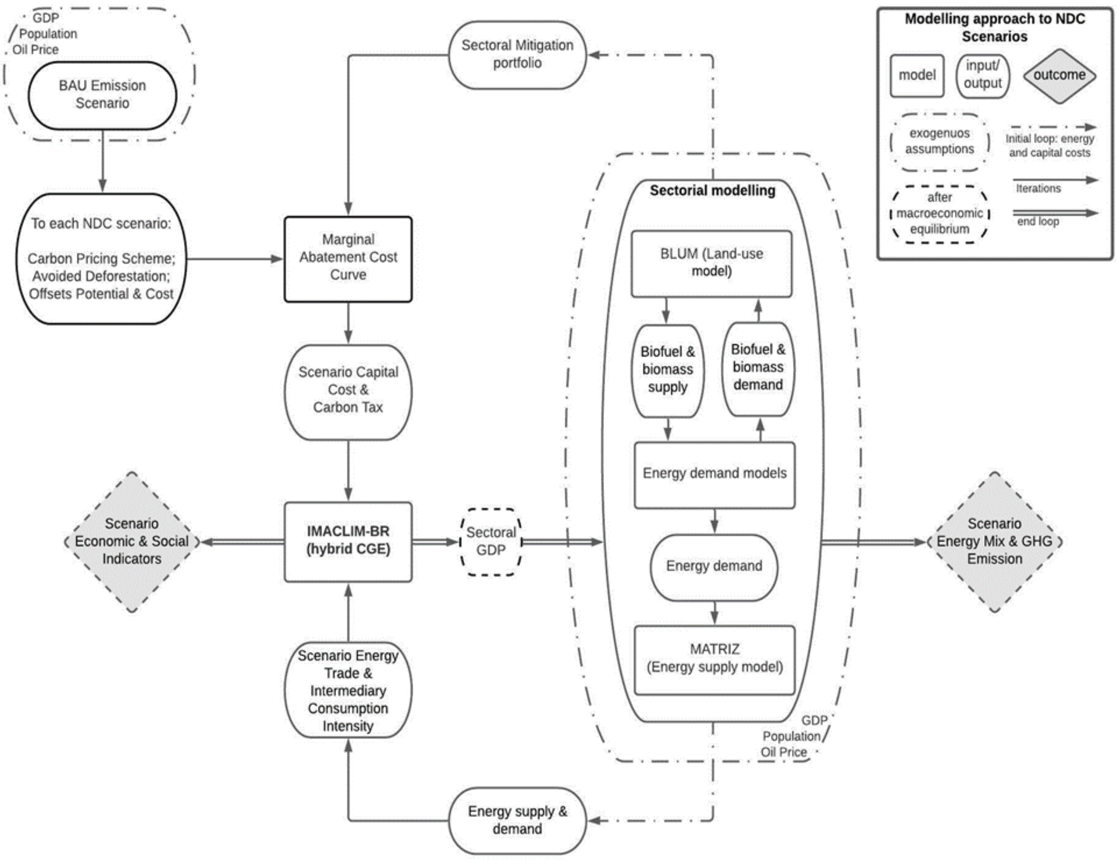

Figure 4 – Integrated modelling framework
Source: Adapted from GROTTERA *et al*. (2022).

3 Centro Clima Deep Decarbonization Scenario (DDS): long-term power supply simulation

Centro Clima simulated two GHG emissions scenarios in Brazil until 2050 for the IMAGINE Project (recent concluded), DDPBIICS (LA ROVERE *et al.*, 2021) among other studies. These exercises provide a framework for analysing economy-wide and sectoral indicators of a decarbonization pathway. The CPS follows the trend of ongoing mitigation actions. The DDS follows a GHG emissions trajectory compatible with the global objective of 1.5ºC of the Paris Agreement, achieving net-zero emissions in 2050.

For the ICAT3 project, the latest scenarios (IMAGINE Project) were extended to 2060, beyond the original estimation of 2050. Furthermore, the electricity supply simulations were divided into two subsets to address distinct environmental concerns (see section 5).

3.1 DDS General Assumptions

As previously pointed out, electricity demand is estimated based on simulations from various sectors, as well as consumption within the energy sector itself. This demand reflects the activity levels in each sector, and for the transport and industrial sectors, it also includes the effects of simulated mitigation measures. This section outlines the main general assumptions of the DDS pertaining to the sectors where mitigation actions occur and the energy sector itself. The energy sector's modelling differs from the CPS due to distinct assumptions and the mitigation efforts implemented in other sectors. In contrast, the agriculture, commercial, and public sectors vary from the CPS only regarding their activity levels. The assumptions for the residential sector remain unchanged.

In DDS scenario, a carbon tax of \$2/tCO_2e is implemented in 2030, increasing to \$31/ tCO_2e in 2040 and \$44/ tCO_2e (\$2020 prices) by 2050 and continuing up to 2060. This carbon tax incentivizes significant gains in both energy efficiency and the use of lower-carbon energy sources. The projected carbon price in Brazil until 2050 is lower than in Europe and other developed countries due to several unique characteristics of the country. Brazil already has an almost net-zero electricity sector and an energy sector with nearly 50% participation from renewable sources. Most of Brazilian emissions come from deforestation and agriculture. Additionally, the country has vast expanses of arable land, low-efficiency pastures, and areas degraded after deforestation.

A key part of Brazil's strategy to achieve net-zero involves getting to zero deforestation targets in 2030, promoting activities related to an ambitious reforestation program, and increasing carbon storage in the soil. This approach is the most cost-effective way for Brazil to reach net-zero, being a local and country-specific strategy, not directly comparable to those adopted by other countries, particularly developed ones. While this strategy is not permanent, it will allow Brazil to gain some time as new technologies mature and their prices become more affordable.

Passenger transportation main drivers:

(until 2030)

- The people's transport demand (pkm/cap) increases by 57% between 2020 and 2030. A significant portion of this increase is attributed to the low activity in 2020 due to the COVID-19 pandemic;
- Between 2020 and 2030, bus transportation will increase from 37% to 40%, while train transportation will increase from 1% to 1.6% (pkm);
- Air transportation will increase from 3% to 5% (pkm);
- Private car mobility will decrease from 55% to 48% (pkm);
- By 2030, non-motorized transportation will account for 5.4% of passenger activity (pkm);
- Liquid biofuel consumption will increase from 36% to 45% (EJ);
- Electricity will grow marginally, from 0.4% to 1.4% (EJ);
- Fossil fuels will decrease from 64% to 54% (EJ).

(2030-2050)

- Between 2030 and 2050, bus transportation will remain stable (~40%) (pkm);
- Air transportation will increase from 5% to 6% (pkm);
- Private car mobility will decrease from 48% to 44% (pkm);
- By 2030, non-motorized transportation will increase from 5.4% to 9.1% (pkm);
- Liquid biofuel consumption will remain stable, reaching 54%;
- Electricity will increase from 1.4% to 12.4% (EJ);
- Fossil fuels will decrease from 54% to 33% (EJ).

Freight transport main decarbonization drivers:

(until 2030)

- By 2030, the demand for freight transportation in ton-kilometers (tkm) and tons increases by 19% and 17%, respectively;
- The share of road transportation in the modal split reaches 45% (tkm), while rail transport represents 33%;
- Air transportation represents 0.11% (tkm), while pipelines and water transport remains with 2.8% and 19% (tkm);
- The average load factor of Heavy Goods Vehicles (HGV) increases by 6%, reaching 13 tons/veh;
- The share of agrofuels increases from 10% to 17%, primarily concentrated in Heavy Goods Vehicles (HGV);
- The share of electricity reaches 0.4%, primarily concentrated in Light Commercial Vehicles (LCV).

(2030-2050)

- Between 2030 and 2050, the demand for freight transportation in ton-kilometers (tkm) and tons increases by 42% and 74%, respectively;
- The share of road transportation in the modal split decreases from 45% to 42%, while rail transport mode remains with 34%;
- Air transportation achieves 0.2%, while water transport increases its share to 21% and pipelines share is reduced to 2%;
- The average load factor of Heavy Goods Vehicles (HGV) increases by 14%, reaching 14,8 tons/veh;
- The share of agrofuels increases from 17% to 33%, primarily concentrated in Heavy Goods Vehicles (HGV);

- The share of electricity increases from 0.4% to 5.7%, primarily concentrated in LCV and light-medium trucks.

3.1.1 Industry

- The industry's GDP share has been decreasing and in a state of crisis since the global economic downturn in 2008. However, it is expected to recovery from 2025 on;
- Energy efficiency and process optimization are key to emission reduction in the industry sector;
- Emissions will be lowered by switching from high-GWP fossil fuels to low-GWP alternatives, such as substituting fuel oil with natural gas;
- A further reduction in GHG emissions is achievable through a transition to renewable energy sources;
- Over time, adopting alternative processes (like steel production using the charcoal route or recycling) can significantly cut emissions;
- The decarbonization scenario intentionally excludes disruptive technologies as they are not necessary and to prevent excessive pressure on the Brazilian industry sector[4];
- Research indicates that net-zero emissions can be attained by focusing on energy efficiency, fuel switching, and new feedstocks in the industry;
- By 2050, the EEI (energy intensive industry) is projected to account for 68% of total industrial emissions.

3.1.2 Energy suply

- Offshore oil and gas production from the pre-salt layer increases steadily;
- Assumed oil price trajectory: 64 USD[5]/barrel from 2025-2060;
- Increasing shares of Brazilian oil production directed towards exports;

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[4] In the industrial sector, developing mitigation scenarios requires a thorough understanding of both the current state of the industry and the potential of emerging technologies. Direct reduction of steel using green hydrogen and carbon capture and storage (CCS) are critical technologies for global industrial decarbonization. However, both are expensive and necessitate complex infrastructure. The current state of the Brazilian industry is marked by ongoing crises, high debt levels, and idle capacity. Moreover, the adoption of these advanced technologies is not economically justified given the availability of more cost-effective emission reduction measures, such as enhancing energy efficiency and utilizing alternative fuels.

[5] The barrel price is sourced from the 'Announced Pledges' scenario of the International Energy Agency's World Energy Outlook 2022 (IEA, 2023b). The oil market experienced a dramatic fluctuation, with prices plummeting to $40.8 per barrel in 2020 from $62.5 in 2019, before surging to a peak of $98.2 per barrel in 2022. Prices are projected to adjust to $68.1 per barrel by 2030 and further decrease to $63.6 per barrel by 2050, same level before the COVID-19 crises.

- Hydro, wind energy (onshore and offshore), and photovoltaics are the main sources of power generation;
- Decommissioning of old thermopower plants and replacement with renewables;
- New Technologies: Offshore wind available for capacity expansion from 2030 onwards. Wind offshore cost assumptions for 2030, 2040 and 2050 were adjusted to ensure to maintain offshore wind penetration;
- Flexible Natural gas thermopower plays an important role in dispatchable power generation. Natural gas to provide greater flexibility and resilience to the electric system and thus mitigate the impact of the great variability of generation.

4 Electricity demand in DDS – ICAT Brazil Project phase 3

The DDS electricity demand estimates draw upon the latest data sourced from the National Energy Balance up to 2022. 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 the framework of the same underlying scenarios and narrative concepts. The aim is to ensure the accurate modelling of energy supply up to 2060.

4.1 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 2.3% was projected. For the 2031-2040 period, an annual GDP growth rate of 2.01% 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 2, Table 3, Table 4 and Table 5.

Table 2 – 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	2.37
2031 – 2040	2.01
2041 – 2050	2.00
2051 – 2060	1.75

Source: Prepared by the authors.
Note: Data until 2022

Table 3 – 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: Prepared by the authors.
Note: Data until 2020.

Table 4 – 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	675	2.777	7.312	10.763
2030	771	3.161	8.368	12.300
2035	860	3.462	9.228	13.550
2040	965	3.814	10.236	15.015
2045	1.088	4.108	11.334	16.530
2050	1.235	4.448	12.620	18.303
2055	1.364	4.670	13.928	19.962
2060	1.505	4.904	15.361	21.770

Source: Prepared by the authors.
Note: Data until 2020.

The study used historical population 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 (2023).

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

Year	Population (hab.)
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: Prepared by the authors based on IBGE (2020) and IBGE (2023).
Note: data until 2020.

4.2 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, the average household consumption increased from 153 kWh/month to 179 [6]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.

4.3 Transport sector electricity demand

Brazil's advancement in standards, regulations, concession models, training programs, financing options, and business models from 2030 onwards mirrors the pace of electromobility adoption seen in leading regions such as Europe, the United States, and China. The emergence of new local manufacturers specializing in electric vehicles and components for buses reshapes the industry landscape, resulting in price reductions and increased accessibility.

Moreover, the diminishing relationship between battery price and energy density makes electric vehicles more economically viable, negating the necessity for government incentives. Credit facilities aimed at financing electric vehicles, particularly for intensively used vehicles like those in e-hailing applications, further drive adoption.

Despite the dominance of internal combustion engines (ICE+HEV) in HGV sales (63%), electromobility gains traction in urban freight transport, with 100% of LCV projected to be electric. Operational enhancements in road freight transport drive a 18% increase in energy efficiency by 2050, bolstered by sustainable logistics programs, such as the Programa de Logística Verde Brasil (PLVB/IBTS - Green Logistics Program Brazil) and Despoluir (Environmental Transport Program, an initiative by SEST SENAT and the National Confederation of Transport - CNT).

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

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[6] We conducted a cross-section analysis using data from some countries and cities to estimate future electricity demand in Brazil. This sensitivity analysis revealed that the values from Italy provided the best fit for our per capita electricity demand curve, based on per capita data since 2000.

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.

4.4 Industry sector electricity demand

The electricity demand of the industrial sector was based on the IMAGINE project results, that used an ASIF methodology approach to estimate energy demand until 2050[7]. 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.

4.5 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.

4.6 Electricity demand from other sectors

To estimate the energy demand from the commercial, public, and agricultural sector, the study employed linear functions that correlated historical data on energy demand with the sectoral GDP from 1995 to 2013. These years were selected for the econometric analysis because Brazil experienced negative GDP variations in 2014 and 2015 had and subsequent years showed inconsistent correlations between electricity demand and 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.

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

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[7] The ASIF methodology used to estimate energy demand stands for Activity, Structure, Intensity, and Fuel.

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.

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

4.7 Results of electricity demand estimates

In DDS, the aggregate electricity consumption experiences an increase of almost 103 % from 2020 to 2060, reaching 1,111 TWh (Table 6). Examined by sector, there is the following percentage growth in electricity consumption in this period: residential (62 %); transport (5.365%); industry (48%); public sector (93%); commercial sector (159%); agriculture (159%); and energy sector (110%).

Table 6 – Estimates of electricity demand in DDS (TWh)

Year	Residential	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	3.1	220.2	46.1	94.9	32.2	40.7	601.7
2030	178.7	9.6	234.9	50.8	111.2	37.5	55.5	678.4
2035	192.2	19.3	247.2	54.8	124.6	42.9	59.6	740.5
2040	204.7	33.4	259.5	59.3	140.2	49.2	57.4	803.8
2045	216.1	58.6	269.5	64.4	157.2	56.7	75.2	897.7
2050	226.1	85.0	279.6	70.2	177.3	65.8	77.5	981.5
2055	234.7	98.3	287.2	76.3	197.6	74.5	79.9	1048.5
2060	241.7	107.3	294.5	82.9	220.0	84.3	80.6	1111.3

Source: Prepared by the authors.
Note: Data until 2020.

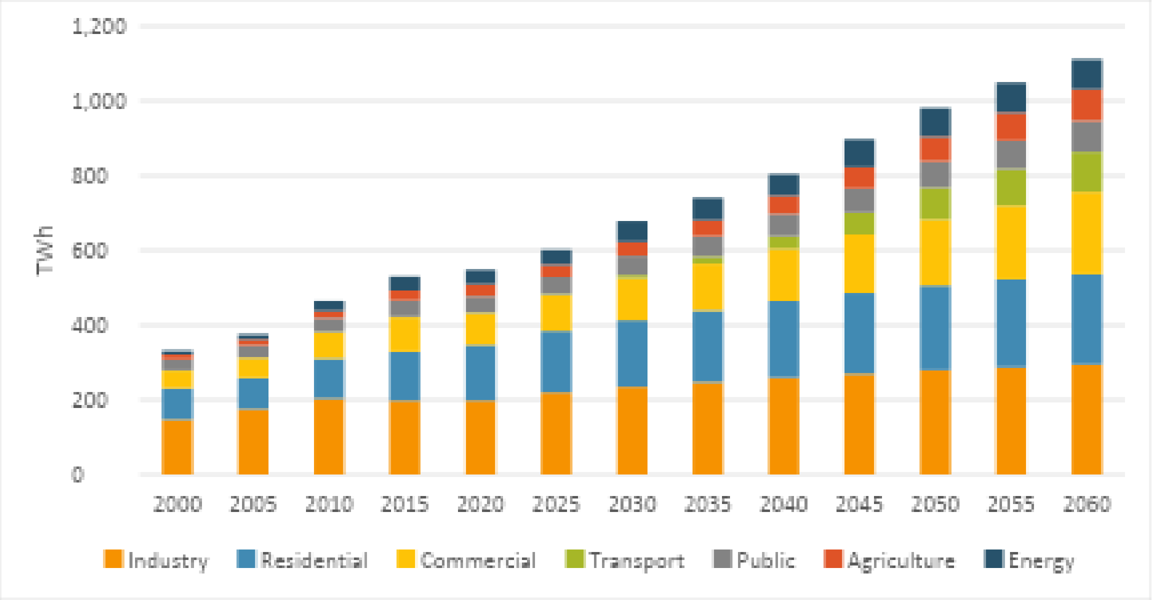

Figure 5 – Estimates of sectoral electricity demand in the DDS (TWh, 2000 – 2060)
Source: Prepared by the authors.

4.8 Evolution in electrical intensity across demand sectors in the DDS

In Brazil, per capita electricity consumption is notably low. However, with the expected growth of GDP, an increase in the electricity intensity of the residential sector is also expected. This indicates that as the economy expands, the power demand in households will also rise. Table 7 illustrates the electricity intensity per capita in the residential sector.

Table 7 – 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	1.60	1.67

Source: Prepared by the authors.

In the industrial sector, a decrease in electricity intensity relative to industrial GDP is anticipated, owing to the implementation of target energy efficiency measures. These actions are expected to lead to a more efficient electricity usage within the industrial sector as detailed in Table 8.

Table 8 – 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)	1.00	1.06	1.01	0.95	0.91	0.87	0.84	0.80	0.78	0.76

Source: Prepared by the authors.

In the commercial sector, electricity intensity is increasing, albeit at a modest rate. Conversely, in the public sector, a slight decrease is observed. These trends mirror the dynamics seen in previous years, reflecting the outcomes of public policies and autonomous technical progress, Table 9 shows the figures.

Table 9 – 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)	1.00	0.95	0.90	0.92	0.94	0.95	0.96	0.98	0.99	0.99
Public (kwh/GDP)	1.00	1.01	0.92	0.89	0.87	0.85	0.83	0.81	0.80	0.79

Source: Prepared by the authors.

In the agricultural sector, electricity intensity is increasing, driven by a higher rate of electrification and significant sector-specific tariff subsidies. Table 10 presents the figures.

Table 10 – 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)	1.00	1.11	0.94	0.95	0.98	1.00	1.02	1.04	1.07	1.10

Source: Prepared by the authors.

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

Year	2015	2020	2025	2030	2035	2040	2045	2050	2055	2060
Total (kwh/GDP)	1.00	1.06	1.00	0.98	0.97	0.95	0.96	0.95	0.93	0.90
Total (kwh/hab.)	1.00	1.01	1.08	1.18	1.26	1.35	1.50	1.65	1.77	1.90

Source: Prepared by the authors.

5 Electricity supply in DDS – ICAT Brazil Project phase 3

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, 2020). 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 and traditional local communities (EPE, 2021).

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 DDS1 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 DDS 2. Therefore, two deep decarbonization scenarios were developed and are described below:

- DDS 1 — total HPP potential –the DDS has additional mitigation actions in all sectors getting to net zero GHG emissions by 2050 (economy wide), using available technologies only (no CCS, just EOR, increasing share of oil&gas production to exports). 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, 2022) and the remaining from 2032;
- DDS 2 is based on the same assumptions as DDS 1 but considers only HPPs that do not interfere with protected areas. 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, 2022) and the remaining from 2032.

For each of these scenarios, the electric system expansion plan was derived using the MATRIZ model. The model establishes the optimal expansion of the system that minimizes the present value of the system's costs (investment and operation), while ensuring the fulfillment of the total load and adhering to system constraints.

5.1 Scenarios assumptions

In the context of the ICAT 3 project focused on the potential for renewable energy implementation in Brazil, four electricity supply scenarios were developed extending to the year 2060, two for CPS and two for DDS (CPS1, CPS2, DDS1, and DDS2).

In the current policy scenarios (CPS 1 and 2), mitigation measures are implemented through command-and-control instruments, with no carbon pricing scheme in force The deep decarbonization scenarios (DDS 1 and 2) implement a carbon pricing scheme (combining a cap-and-trade system in the industry with a carbon tax imposed on fossil fuels used in all other sectors). The carbon pricing policy is fiscally neutral, using the biggest share of the carbon tax proceeds to reduce labor taxes for employment incentive and compensate low-income households. Carbon prices are set at 2 $US\$_{2020}/tCO_2e$ in 2030, 31 $US\$_{2020}/tCO_2e$ in 2040 and 44 $US\$_{2020}/tCO_2e$ from 2050 on.

In the proposed electricity scenarios, there are several restrictions and premises that guide the expansion and development of different energy sources.

Starting with wind energy, we observe a uniform expansion both onshore and offshore. Onshore expansion is mainly concentrated in the Northeast (80%) and South (20%) regions. On the other hand, offshore expansion starting in 2030, is allowed along the entire coast except in the northern region, with a more pronounced reduction cost in the DDS compared to the CPS. Expert elicitation survey predicts 37% to 49% declines in wind energy costs by 2050 (WISER *et al.*, 2021).

Regarding solar energy, we have two distinct routes, the centralized and the distributed. The expansion of centralized solar energy is progressive and optimized in the Northeast, South, Southeast, and North regions.

Solar energy gains relevance through distributed generation, but the dynamics of distributed solar energy expansion in Brazil are influenced by various factors beyond technology costs. These factors include consumer preferences, population income, industrial growth, policies related to Transmission and Distribution Service Use Tariff rates (EPE, 2022) among others. The adoption of distributed generation systems is made by different individuals, whose decisions are not always strictly economic but also influenced by socio-cultural and environmental factors. The significant growth of distributed solar energy has a direct impact on expansion planning, requiring it to be properly represented in planning models (EPE, 2022). This is important to ensure accurate estimates because if planners underestimate distributed generation development, overinvestments in the centralized power grid may occur. On the other hand, if they overestimate distributed generation penetration and it does not materialize, the reliability of the electrical system may be compromised, and supply costs may increase. The CPS data is based on the extension until 2060 of information from EPE projections regarding distributed generation in Brazil within the scope of PLAN 2024-2028 studies (EPE, 2024).

Conversely, the DDS exhibits a faster expansion rate, growing annually at a rate 10% higher than that of the CPS. With these assumptions, the cumulative installed capacity of distributed generation reaches 59.2 GW in the CPS by 2050, and 65.1 GW in the DDS, showcasing its accelerated growth compared to the CPS (Figure 6).

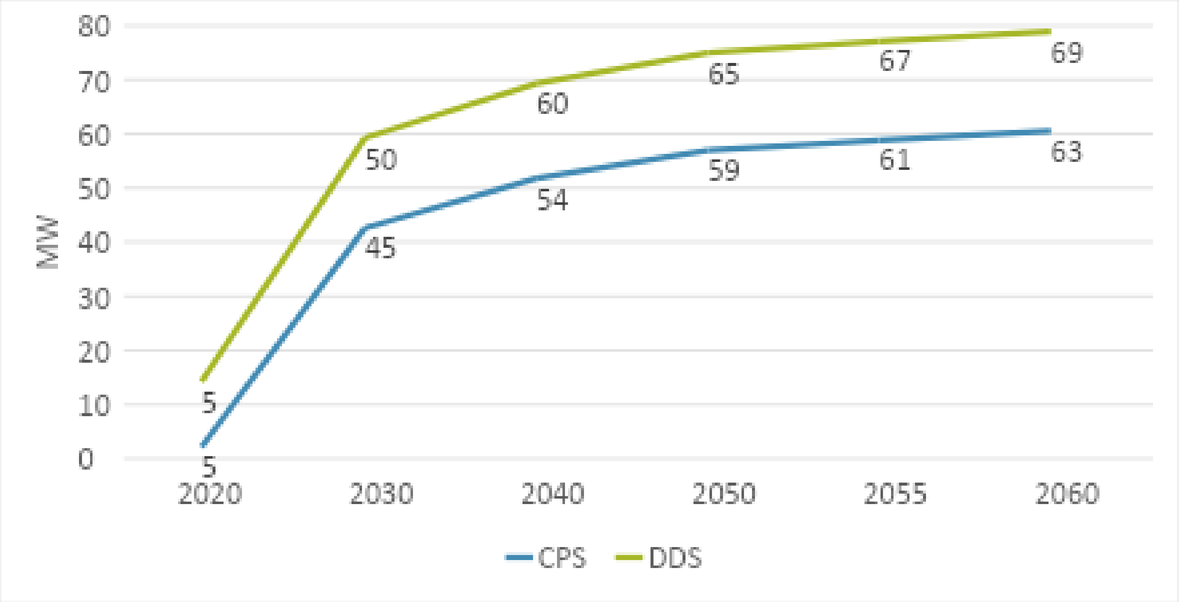

Figure 6 – Small scale solar power installed capacity in CPS and DDS
Source: Prepared by the authors.

In the context of biomass, there is a uniform expansion established, with specific minimum 80 MW/year and maximum 400 MW/year limits until 2040 (MME/EPE, 2021), followed by 3500 MW/year each five year onwards. As for natural gas, its expansion in the DDS focuses on flexible gas-fired power plants to complement renewable sources.

Nuclear energy is represented by the commissioning of Angra III in 2027, reaching 3.4 GW in 2030 with units I, II, and III in operation. In 2040, Angra I is decommissioned, leaving 2.7 GW with Angra II and III operational.

Regarding coal-fired power plants reach the end of their useful life by 2040, operating with partial flexibility (take or pay contracts) in the CPS until that period and becoming irrelevant from 2030 onwards in the DDS as more economical generation options become available.

Energy storage is allowed in all scenarios at 2 GW between 2040 and 2050, and an additional 2 GW by 2060, reflecting the importance of storage strategies to address the intermittency of renewable sources[8]. These guidelines aim to ensure a balanced electricity expansion planning, considering aspects such as cost, sustainability, and electric supply reliability.

Finally, in the analyzed scenarios, no disruptive technology was assumed, either in the demand or supply sectors. The decarbonization scenario intentionally excludes disruptive technologies to avoid undue pressure on the Brazilian industrial sector, including technologies such as CCS and hydrogen.

Globally, hydrogen plays a crucial role in the energy transition. It enables large-scale integration of renewable energy, acts as an energy storage medium, facilitates decentralized energy generation, and decarbonizes hard-to-abate sectors, including zero-emission transportation, industrial and residential sectors producing heat and electricity, and as a clean feedstock for industry (HYDROGEN COUNCIL, MCKINSEY & COMPANY, 2021) (MME/EPE, 2022). However, for Brazil, it is more profitable to export hydrogen or sell it to industrial sectors, such as steel and fertilizers (ammonia, urea), rather than converting it into electricity (MACEDO, PEYERL, 2022). While exporting hydrogen can be an immediate strategy to enter the market, the true value lies in a holistic approach that includes capacity building across the value chain, expanding business opportunities, and fostering higher-value industrialization through integrated sectoral assessments to generate value within Brazil. The applications of green hydrogen are still limited by technological challenges, production and equipment costs, transportation and storage difficulties, and the need for institutional, legal, and regulatory frameworks (market design, standardization) (EPE, 2021a). Broader use of hydrogen energy projects will require substantial investments in research, development, and innovation to establish Brazil as a significant player in the emerging hydrogen economy.

5.2 DDS results

The installed capacity is an important indicator to understand a country's energy infrastructure and its ability to supply electricity reliably and sustainably. In both scenarios, DDS1 and DDS2, 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 12). The increasing expansion of wind and solar sources has reinforced their role as complementary sources, guaranteeing the safety of the system's operation.

In 2005, the installed capacity of hydroelectricity was 71.1 GW, growing gradually to 109.3 GW in 2020. In Scenario DDS1 (2030-2060) hydroelectric installed capacity relatively stabilizes at 111 GW until 2030, then moderately increases to 126 GW by 2040, reaching 145 GW by 2060. DDS2

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[8] Our scenarios do not account for the effects of climate change and interannual water availability, as the data is based on the average flow of each basin. However, it is important to highlight that climate change impacts can significantly alter the renewable energy landscape in Brazil, emphasizing the need for adaptive strategies to ensure energy security and sustainability in the face of changing climatic conditions, such as energy storage and grid flexibility.

(2030-2060) starts with the same 111 GW capacity but growth is lower due to restrictions in environmental protected areas. By 2040, capacity is projected at 122 GW, rising to 131 GW by 2060.

When examining historical data of wind energy, we note that in 2005, the installed capacity of wind energy in Brazil was zero. In the following years, there was a remarkable growth, reaching 17.1 GW in 2020.

Both scenarios, DDS1 and DDS2, show substantial growth in installed capacity of wind energy, reflecting the country's commitment to renewable energies. The DDS1 projects robust growth in wind energy installed capacity, reaching 28 GW in 2030, 47 GW in 2040, 79 GW in 2050, and 107 GW in 2060. DDS1 results expanded exclusively onshore wind energy, while DDS2 incorporates offshore wind energy from 2030 onwards. The inclusion of offshore wind energy in DDS2 represents diversification and expansion of the energy portfolio, offering potential for increased generation of clean energy and complement wind and solar contributions. In DDS2, there is a similar growth trajectory, but with some significant differences. The installed capacity in 2030 is slightly higher, reaching 29 GW. The major distinction is the introduction of offshore wind energy from 2030 onwards, with 1 GW, increasing to 3 GW in 2040, 10 GW in 2050, and 12 GW in 2060.

Table 12 – Estimates of installed capacity, by sources, in DDS1 and DDS2 (2030-2060)

Installed capacity (GW)	**Historical**				**DDS1-total HPP potential**				**DDS2- Without interference in protected areas**			
	2005	**2010**	**2015**	**2020**	**2030**	**2040**	**2050**	**2060**	**2030**	**2040**	**2050**	**2060**
Hydroelectric (HPP and SHPP)	71.1	80.7	91.7	109.3	111	126	144	145	111	122	128	131
Wind	0.0	0.9	7.6	17.1	28	47	79	107	29	50	90	123
Onshore	0.0	0.9	7.6	17.1	28	47	79	107	28	47	80	111
Offshore	0.0	0.0	0.0	0.0	0	0	0	0	1	3	10	12
Solar	0.0	0.0	0.0	7.9	62	78	89	100	62	78	89	100
Distributed (Small scale)	0.0	0.0	0.0	4.6	50	60	65	69	50	60	65	69
Centralized	0.0	0.0	0.0	3.3	13	18	24	31	13	18	24	31
Biomass	3.3	7.7	12.9	14.8	17	22	27	32	17	22	28	30
Bagasse	2.3	6.2	10.6	11.7	13	17	21	25	13	17	20	21
Other Biomass (Firewood-Wood and Black-Liquor)	1.0	1.5	2.3	3.1	4	5	6	7	4	5	7	9
Natural Gas	9.6	11.3	12.4	14.9	22	9	0	0	22	9	4	4
Nuclear	2.0	2.0	2.0	2.0	3.4	2.8	2.8	2.8	3.4	2.8	2.8	2.8
Coal	1.4	1.9	3.4	3.2	3	1	0	0	3	1	0	0
Petroleum Derivatives (Liquids) and Other Non-Renewable	4.8	7.2	9.1	8.0	2	1	1	1	2	1	1	1

Total	**92.2**	**111.7**	**139.2**	**177.3**	**249**	**286**	**343**	**388**	**250**	**286**	**343**	**392**

Source: Prepared by the authors**.**

As mentioned, solar power technology in the model encompasses both centralized (utility-scale) and distributed (small-scale) photovoltaic energy generation. Distributed solar capacity is projected to reach 69 GW by 2060 in both scenarios. 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 until 2045 for systems with approved access up to January 6, 2023. This provision has continued to fuel the race for new installations. Notably, 8.33 GW of small distributed solar capacity were added in 2023. The momentum continued in the first four months of 2024, with an additional 2.4 GW of small distributed solar capacity being integrated (EPE, 2023a).

For wind energy, onshore technology remains the primary source until 2029 in both DDS scenarios. Offshore wind, available for expansion from 2030 onward, was not competitive in DDS1, as all hydro potential was utilized. Although the DDS2 reached 12 GW of offshore wind deployment in 2060, technical-economic and regulatory developments remain necessary in Brazil. These factors could modify competitiveness and unlock even more the utilization of this technology.

With rising VRE integration and stagnant dispatchable sources alongside reduced hydroelectric reservoir utilization, storage systems, like batteries or hydro power pumps are increasingly vital. This is important to facilitate the management of fluctuating renewable energy and uphold grid stability. By entering 2 GW of installed storage capacity by 2045 in both scenarios, the capacity expands to 2.5 GW in 2060 for DDS1 and 4 GW for DDS2, driven by constraints in hydropower expansion.

Biomass, energy storage and flexible natural gas will replace hydropower role and complement wind and solar contributions. In 2060, the required installed capacity of hydropower is 145 GW in DDS 1 (130 GW of HPP and 15 GW of SHPP) and 131 GW in DDS2 (113 GW of HPP and 16 GW of SHPP). At the end of the analysed period, onshore wind capacity reaches 107 GW in DDS 1 and 111 GW in DDS2, and offshore wind capacity increased by 12 GW in DDS2. While photovoltaic systems (small and utility scale) account for 100 GW in both scenarios. Biomass reaches a higher level (32 GW) in DDS1 than in DDS2 (30 GW). Natural gas still plays a role in dispatchable power generation at a lower level in DDS2 (4 GW) due to hydro expansion restrictions.

Although Brazil has established an electrical generation infrastructure based on hydroelectricity potential, hydro power installed capacity share is decreasing. The contribution of hydroelectric plants diminishes from 62% in 2020 to 37% in DDS1 and 33% in DDS2 by 2060 (as shown in Table 13). This decline mirrors the growing competitiveness of other renewable sources in both scenarios. Wind, solar and bioelectricity sources together, will represent 62% in DDS1 and 65% in DDS2 of Brazilian installed capacity in 2060, a growth from the 22% that they represent in 2020.

Table 13 – Estimates of installed capacity, by sources, in DDS1 and DDS2 (%, 2030-2060)

Installed Capacity (%)	Historical				DDS1-total HPP potential				DDS2- Without interference in protected areas			
	2005	2010	2015	2020	2030	2040	2050	2060	2030	2040	2050	2060
Hydroelectric (HPP and SHPP)	77%	72%	66%	62%	45%	44%	42%	37%	44%	43%	37%	33%
Wind	0%	1%	5%	10%	11%	16%	23%	28%	11%	18%	26%	31%
Onshore	0%	1%	5%	10%	11%	16%	23%	28%	11%	17%	23%	28%
Offshore	0%	0%	0%	0%	0%	0%	0%	0%	0%	1%	3%	3%
Solar	0%	0%	0%	4%	25%	27%	26%	26%	25%	27%	26%	26%
Distributed (Small scale)	0%	0%	0%	3%	20%	21%	19%	18%	20%	21%	19%	18%
Centralized	0%	0%	0%	2%	5%	6%	7%	8%	5%	6%	7%	8%
Biomass	4%	7%	9%	8%	7%	8%	8%	8%	7%	8%	8%	8%
Bagasse	2%	6%	8%	7%	5%	6%	6%	6%	5%	6%	6%	5%
Other Biomass (Firewood-Wood and Black-Liquor)	1%	1%	2%	2%	2%	2%	2%	2%	2%	2%	2%	2%
Natural Gas	10%	10%	9%	8%	9%	3%	0%	0%	9%	3%	1%	1%
Nuclear	2%	2%	1%	1%	1%	1%	1%	1%	1%	1%	1%	1%
Coal	2%	2%	2%	2%	1%	1%	0%	0%	1%	1%	0%	0%
Petroleum Derivatives (Liquids) and Other Non-Renewable	5%	6%	7%	5%	1%	0%	0%	0%	1%	0%	0%	0%
Total	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%

Source: Prepared by the authors**.**

As expected, electricity generation more than doubles between 2020 and 2060, reaching around 1290 TWh (Table 14). In both scenarios, the share of hydroelectricity generation diminishes over the years from 64% in 2020 to 45% in DDS1 and 39% in DDS2) yet it remains the main source in the country by 2060 (Table 15). In DDS2, given the restriction of interference within protected areas, the contribution of hydroelectric plants to generation is 14% lower at the end of the period. This decrease is offset by other sources, particularly flexible natural gas, biomass, and storage.

Table 14 – Estimates of power generation, by sources, in DDS1 and DDS2 (TWh, 2030-2060)

Power Generation (TWh)	**Historical**				**DDS1-total HPP potential**				**DDS2- Without interference in protected areas**			
	2005	**2010**	**2015**	**2020**	**2030**	**2040**	**2050**	**2060**	**2030**	**2040**	**2050**	**2060**
Hydroelectric (HPP and SHPP)	337.5	403.3	359.7	396.4	421	478	568	585	419	462	497	501
Wind	0	2	22	57	107	171	294	386	110	188	337	465
Onshore	0	2	22	57	107	171	294	386	106	177	299	425
Offshore	0	0	0	0	0	0	0	0	4	11	38	40
Solar	0.0	0.0	0.1	15.5	100	128	157	179	100	128	157	183
Distributed (Small scale)	0,0	0,0	0,0	4,8	66	80	87	93	66	80	87	93
Centralized	0.0	0.0	0.1	10.7	34	48	70	86	34	48	70	90
Biomass	12.8	31.2	47.3	55.6	66	83	102	120	66	82	108	116
Bagasse	7.7	22.4	34.0	38.8	44	58	73	87	44	57	72	75
Other Biomass (Firewood-Wood and Black-Liquor)	5	9	13	17	22	25	29	33	21	25	36	42
Natural Gas	18.8	36.5	82.6	59.5	47	28	0	0	47	28	1	1
Nuclear	9.9	14.5	14.7	14.1	24	20	20	20	24	20	21	21
Coal	6.4	7.0	19.1	11.9	0	0	0	0	0	0	0	0
Petroleum Derivatives (Liquids) and Other Non-Renewable	10.6	13.8	27.2	9.0	0.0	0.5	0.4	0.3	0.0	0.0	0.0	0.0
Total	**395.9**	**508.5**	**572.4**	**619.0**	**766**	**908**	**1143**	**1290**	**766**	**908**	**1122**	**1287**

Source: Prepared by the authors.

By 2060, wind power experiences a substantial increase, emerging as the second largest generator, accounting for 30% of the total generation in DDS1 and 36% in DDS2. In both scenarios, solar energy occupies the third place with 14%, biomass the fourth place with 9% while natural gas remains at zero generation.

It's important to highlight the significant growth of solar energy, which increases 466% from 2020 to 2060. Nuclear energy follows the same pattern in both scenarios, representing 2% in 2060.

Petroleum liquids and other non-renewable sources do not contribute to electricity generation in either scenario. Finally, coal-fired power plants are also non-existent in both scenarios.

Table 15 – Estimates of power generation, by sources, in DDS1 and DDS2 (%, 2030-2060)

Power Generation (%)	**Historical**				**DDS1-total HPP potential**				**DDS2- Without interference in protected areas**			
	2005	**2010**	**2015**	**2020**	**2030**	**2040**	**2050**	**2060**	**2030**	**2040**	**2050**	**2060**
Hydroelectric (HPP and SHPP)	85%	79%	63%	64%	55%	53%	50%	45%	55%	51%	44%	39%
Wind	0%	0%	4%	9%	14%	19%	26%	30%	14%	21%	30%	36%
Onshore	0%	0%	4%	9%	14%	19%	26%	30%	14%	19%	27%	33%
Offshore	0%	0%	0%	0%	0%	0%	0%	0%	1%	1%	3%	3%
Solar	0%	0%	0%	3%	13%	14%	14%	14%	13%	14%	14%	14%
Distributed (Small scale)	0%	0%	0%	1%	9%	9%	8%	7%	9%	9%	8%	7%
Centralized	0%	0%	0%	2%	4%	5%	6%	7%	4%	5%	6%	7%
Biomass	3%	6%	8%	9%	9%	9%	9%	9%	9%	9%	10%	9%
Bagasse	2%	4%	6%	6%	6%	6%	6%	7%	6%	6%	6%	6%
Other Biomass (Firewood-Wood and Black-Liquor)	1%	2%	2%	3%	3%	3%	3%	3%	3%	3%	3%	3%
Natural Gas	5%	7%	14%	10%	6%	3%	0%	0%	6%	3%	0%	0%
Nuclear	2%	3%	3%	2%	3%	2%	2%	2%	3%	2%	2%	2%
Coal	2%	1%	3%	2%	0%	0%	0%	0%	0%	0%	0%	0%
Petroleum Derivatives (Liquids) and Other Non-Renewable	3%	3%	5%	1%	0%	0%	0%	0%	0%	0%	0%	0%
Total	**100%**	**100%**	**100%**	**100%**	**100%**	**100%**	**100%**	**100%**	**100%**	**100%**	**100%**	**100%**

Source: Prepared by the authors.

5.3 Power sector emission in DDS

In the global context, variable renewable sources are at the center of economic decarbonization strategies. In Brazil, the increased in installed capacity of these sources in the power mix is foreseen in sectoral planning, including the PDE, PNE and consequently is already present in the CPS. In both DDS, the share of wind and solar sources in installed capacity should increase from 14% in 2020 to 36% in 2030. By 2050, in DDS1 they reach 49% while DDS2 54%. In the DDS2 this percentage is intensified due to hydropower expansion restriction.

Compared to many other nations, Brazil already has a very low carbon electricity content. Despite facing challenges such as water scarcity which affected hydropower supply in 2015 and 2021, leading to the use of thermopower plants, Brazil's electricity sector maintained a relatively low emission rates. The Brazilian electricity sector emitted 118.5 kgCO_2e/MWh in 2021, significantly lower than rates seen in the European Union, the USA, and China (EPE. 2022). Notably, in 2023, a favourable hydrological year, the National Interconnected System (SIN) recorded an emission of 38.5 kgCO_2e/MWh generated.

The weight of the hydropower source in the electricity generation mix has been decreasing over the years, although it still represented 64% of the generation capacity in 2020. The national grid GHG emission is very low and represents only 3%[9] of the total country emissions (UNTERSTELL & LA ROVERE, 2021) GHG emissions from power generation are expected to decrease further.

Both DDS 1 and 2 provide the similar emissions pathway until 2060. Until 2050 emissions are expected to decrease and afterwards, to stabilize, reaching 2.1 in DDS1 and 2.8 MtCO_2e in DDS2 in 2060 (Figure 7). From 2040 onwards new storage technologies will be needed to stabilize and reduce emissions from electrical generation, even in the DDS1 with the available total potential of hydro expansion. In the long-term future, new drops in emissions will only occur with an increase in the installed capacity of new storage technologies.

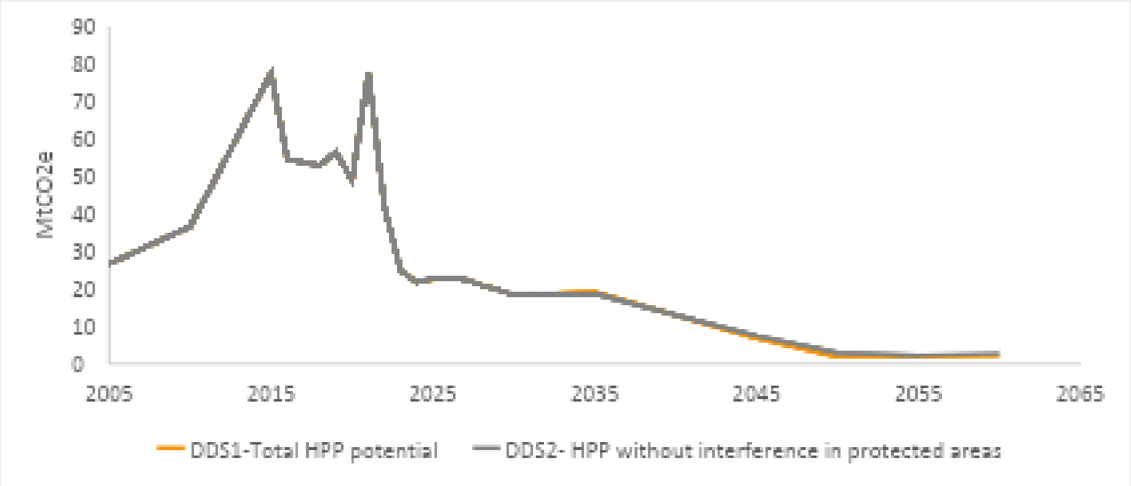

Figure 7 – Estimates of power sector emissions in DDS1 and DDS2 (2005-2060)
Source: Prepared by the authors.

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[9] 49 MtCO2eq in 2020 out of 1,511 MtCO_2e

5.4 Variable renewable energy (VRE) and bioelectricity

As mentioned, hydroelectricity share in the power mix is decreasing. The growth of renewable sources will be through wind, solar and bioenergy sources. As old thermopower plants reach the end of their useful lives, they will be decommissioned (end of their useful lives - we won't force them to dismantle and remove capacities within a certain period) and replaced by renewable power plants (wind, PV and biomass) due to lower costs.

This increase in other renewables than hydropower is the result of the combination of the large cost reduction observed in these sources in the last decade with the high Brazilian potential for wind and solar generation (as it presents strong, constant and unidirectional winds in most of its territory and a hight average annual irradiation) and bioenergy generation, which has a high degree of maturity in the country.

In the DDS wind offshore cost assumptions for 2030, 2040 and 2050 were adjusted to maintain some small-scale offshore wind penetration. A reduction in costs was identified when associating offshore wind with the production and decommissioning of oil and gas platforms (CARVALHO, 2019). These platforms are anticipated to function as central hubs for offshore wind farms, with the associated costs being distributed between electricity generation and the decommissioning expenses for oil companies. Furthermore, as onshore wind industries gradually deplete the best sites, challenges such as increased distances from manufacturing facilities and socio-environmental constraints are expected to result in rising onshore wind costs post-2045/2050.

Sustaining the DDS beyond 2050 becomes crucial. In the long term, there may arise a necessity to expand offshore wind generation when costs become more competitive, coupled with the establishment of a robust regulatory framework for this technology in Brazil.

The production capacities of the Brazilian electrical system are geographically diverse, with a significant portion of the country's power generation coming from hydropower plants, mainly located in the Amazon and central regions. Additionally, there are thermal power plants, wind farms (most in Northeast and South regions, including offshore wind capacity), and solar installations spread across different states. Major consumption sites are primarily concentrated in urban areas, such as São Paulo and Rio de Janeiro (Southeast region), where industrial and residential demand is high. The challenge lies in efficiently transmitting electricity from production centres to consumption hubs, often requiring extensive transmission lines for long-distance transfers.

One of the challenges of variable renewable energy is its intermittent nature, that poses challenges for maintaining a stable and reliable power supply. Integrating VRE into existing energy grids requires improvements in grid flexibility, energy storage and smart grid technologies. This ensures a smooth and stable transition to a more sustainable energy mix. Energy storage technologies solutions, such as batteries and pumped hydroelectric, can store excess energy generated during peak times for use when renewable resources are not actively producing electricity.

The Brazilian electrical system primarily relies on the main grid for power capacity. The development of transmission lines for the main grid is crucial to ensure grid reliability and meet growing demand. Thermal assets (flexible gas fired powerplants) continue to be significant, providing reliability during peak demand and as backup during hydropower shortages, contributing to grid stability and ensuring a continuous power supply.

From 2040 onwards, there is a need to incorporate energy storage options such as reversible hydroelectric plants (pumped storage hydropower) or batteries in the DDS scenarios. While natural gas provides the flexibility required to meet demand in the CPS, the DDS, with the introduction of a carbon tax, necessitates the inclusion of storage despite its high cost. In DDS1, due to the higher installed capacity of hydroelectricity, there is less demand for storage technologies compared to DDS2.

6 Comparative analysis (CPS x DDS)- Costs and emissions assessment

The change in the base scenario of the report delivered (Output 2), as mentioned in the introduction section, is justified by several reasons related to the evolution of the data and sectorial models' advancements. Initially, it is important to highlight that the CPS provided in the previous ICAT report (Output 2) was based on data from previous Centro Clima reports and not on the new modelling exercise described in section 2.3. This included adjustments to the demand, such as changes in GDP after a new round of IMACLIM-BR and population, reflecting a specific scenario vision. The recent scenarios, part of the IMAGINE Project, conducted by Centro Clima in collaboration with IDDRI projects, introduced a new comprehensive CPS round called NGPS.

The recent scenario's modifications were extensive, embracing a broader review of the data and modelling. The CPS presented in output 2 only included an update for the power sector demand, influencing the electricity demand of the energy sector for fuel production. This new CPS results involved a new round of IMACLIM, which brought changes in sector activity levels, industry modelling adjustments, and consequently, changes in electricity demand for the CPS.

Additionally, there was the disclosure of the DDS results from IMAGINE, which is being used as the electricity demand input for this ICAT report that is more detailed within the power sector. These results include not only the definition of the carbon tax but also a new perspective on post-MACC electricity demand.

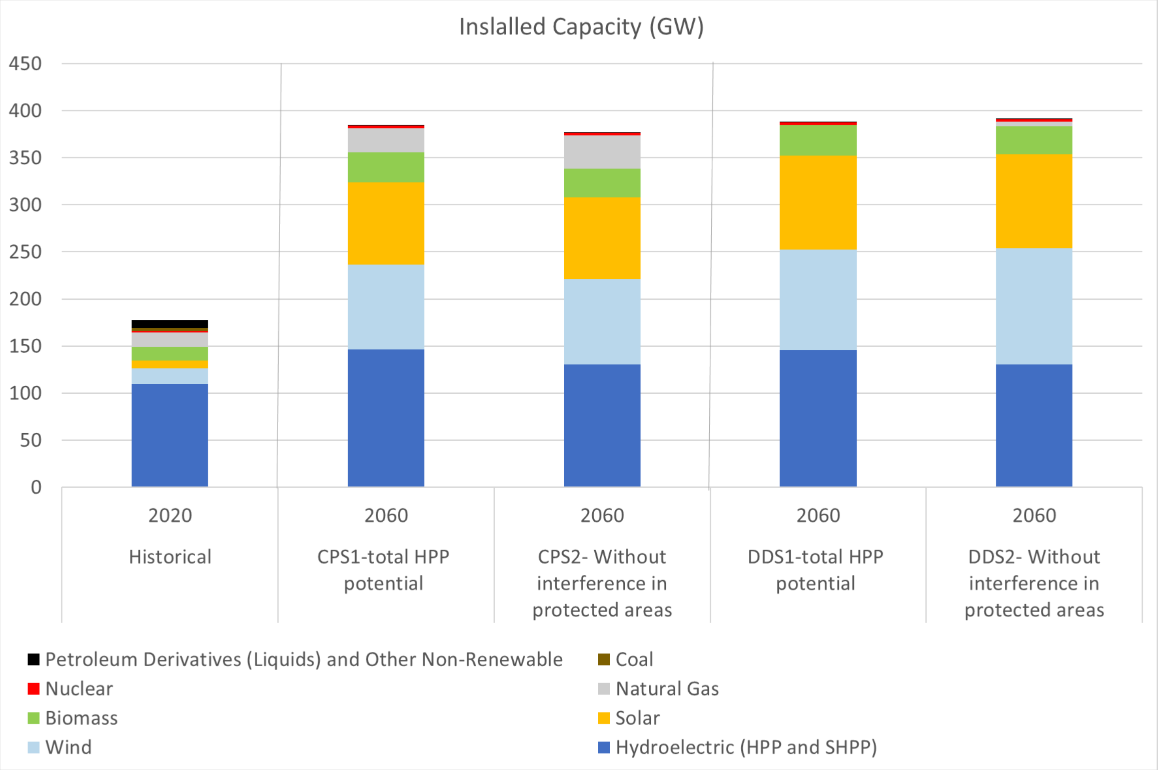
To ensure a proper and updated comparison, it is essential to incorporate this updated CPS information (the updated electricity demand is presented in Appendix 1) and results into the DDS analyses.

In summary, the change in the base scenario is necessary to ensure that the current ICAT report reflects the most recent and relevant information available, providing a more accurate and comprehensive analysis of mitigation scenarios and ongoing climate policies.

The charts below depict four scenarios related to CPS and DDS, with the total potential of hydroelectric power plants available for expansion (CPS1 and DDS1) and the scenarios that consider constraints on the HPP construction in protected areas (CPS2 and DDS2) (Figure 8 and Figure 9). The year of 2060 of these scenarios reflect a comprehensive view of electricity supply projections and the expected growth of renewable sources in the coming years.

Across all scenarios, Brazil power mix continues in 2060 with a high share of renewables, reaching 99% of renewable installed capacity in DDS1, the higher share scenario (with 65% of other renewable without hydro), and 90% in CPS2, the lower renewable share scenario (with 55% of other than hydro renewable) (Figure 8)[10]. Moreover, old thermopower plants are decommissioned and replaced by renewable power plants due to their lower costs in both scenarios.

While CPS 1 and 2 have a higher penetration of gas-fired power plants, DDS 1 and 2 focus on renewable sources. Global factors such as carbon pricing and technological advancements (cost reduction) play a crucial role in DDS 1 and 2 strategies. DDS 1 and 2 demonstrate a greater integration of variable renewable sources, with an emphasis on storage systems to ensure grid stability (as detailed in 5.2).



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[10] The values in table format are in the Appendix 1 for CPS 1 and 2 and section 5.2 for DDS 1 and 2.

Figure 8- Estimates of installed capacity in 2060, by sources, in CPS1, CPS2 and DDS1, DDS2 (GW)
Source: Prepared by the authors.

The electricity generation will continue with a high share of renewables. The lower renewable generation share of 89% occurs in CPS2, due to HPP construction constraints and the need to complement VRE with natural gas to meet the demand needs. In DDS 1 and 2, due to the domestic carbon tax, the competitiveness of natural gas-based power generation reduces, while new technology improvements can enable the competitiveness of renewables (like energy storage and offshore wind) (Figure 9)[11].

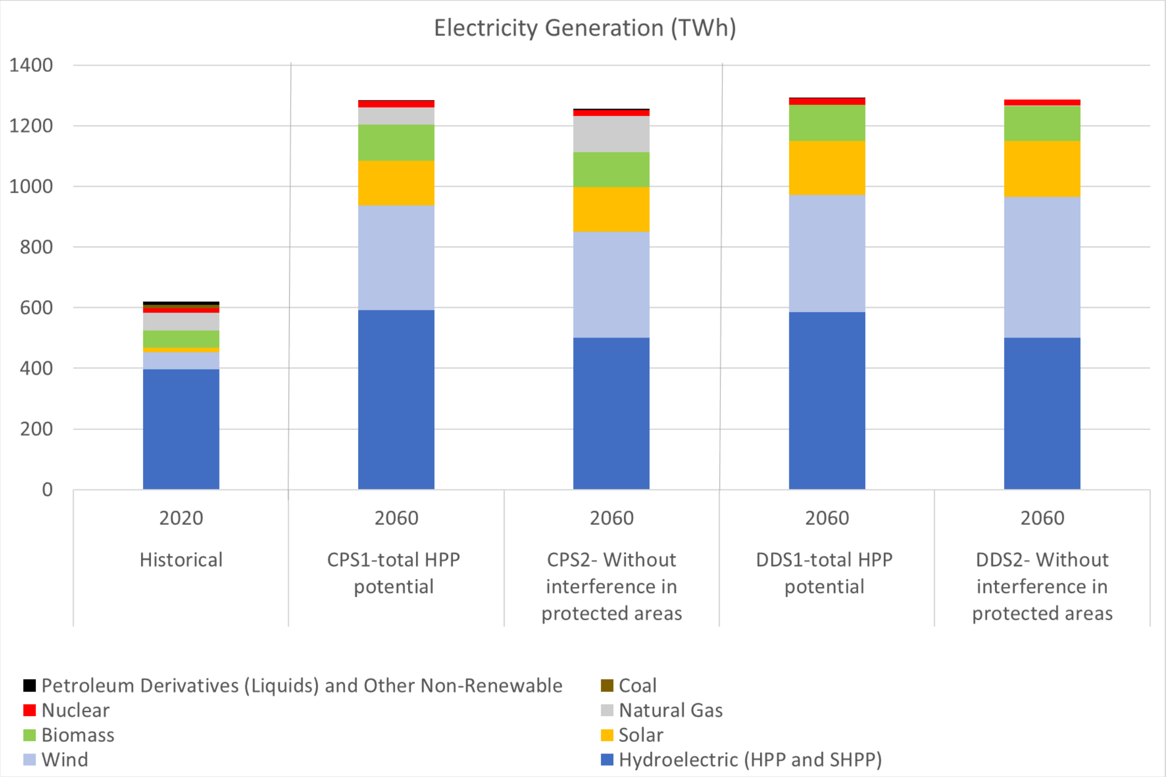

Figure 9- Estimates of power generation in 2060, in CPS1, CPS2 and DDS1, DDS2 (TWh)
Source: Prepared by the authors.

6.1 CPS and DDS comparison

Brazil has a remarkable hydropower potential, standing out as one of the main sources of energy in the country. However, it is important to note that a significant portion of this potential is in areas of conservation units, indigenous lands, and quilombola territories. These areas play a crucial role in preserving biodiversity and protecting the rights and cultures of local communities, making them essential for environmental and social sustainability.

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[11] The values in table format are in the Appendix 1 for CPS 1 and 2 and section 5.2 for DDS 1 and 2

Given this scenario, the exploration of the remaining hydropower potential must be carefully planned and based on strategic environmental analyses. It is essential to adopt sustainable practices that minimize negative impacts on the environment and affected communities, ensuring the rational and responsible use of available water resources.

It is important to recognize that it is necessary to forgo a significant part of the hydropower potential in favor of protecting conservation areas. This balanced and conscientious approach is essential to reconcile energy development with environmental preservation and respect for the rights of traditional populations, contributing to a more sustainable and inclusive energy model in Brazil.

In this context, Table 16, Table 17, Table 18 and Table 19 will compare the results and represents the main technological features of CPS 2 and DDS 2 without interference in protected areas.

The CPS project a nearly 77% increase in demand from 2020 to 2050, slightly eclipsed by the DDS with a 79% rise in the same period. Across all scenarios, this extra electricity demand is primarily fulfilled through the expansion of wind and solar sources (both centralized and distributed), alongside modest growth in hydropower and biomass (See Table 16 and Table 17). Moreover, old thermopower plants are decommissioned and replaced by renewable power plants due to their lower costs in both scenarios.

While the CPS scenario anticipates a higher penetration of gas thermopower, the DDS foresees a reduction in this regard. Both scenarios integrate new offshore wind technology, albeit with differing deployment timelines; CPS2 estimates 1GW by 2060 due to cost competitiveness, whereas DDS2 plans an early deployment starting in 2030, scaling up to 12 GW by 2060.

Table 16 – Estimates of installed capacity, by sources, in CPS2 and DDS2 without interference in protected areas (2030-2060)

Installed Capacity (GW)	Historical				CPS2				DDS2			
	2005	2010	2015	2020	2030	2040	2050	2060	2030	2040	2050	2060
Hydroelectric (HPP and SHPP)	71.1	80.7	91.7	109.3	111	123	128	131	111	122	128	131
Wind	0.0	0.9	7.6	17.1	28	37	60	91	29	50	90	123
Onshore	0.0	0.9	7.6	17.1	28	37	60	90	28	47	80	111
Offshore	0.0	0.0	0.0	0.0	0	0	0	1	1	3	10	12
Solar	0.0	0.0	0.0	7.9	58	70	80	87	62	78	89	100
Distribute (Small scale)	0.0	0.0	0.0	4.6	45	54	59	63	50	60	65	69
Centralized	0.0	0.0	0.0	3.3	13	16	21	24	13	18	24	31
Biomass	3.3	7.7	12.9	14.8	17	22	28	30	17	22	28	30
Bagasse	2.3	6.2	10.6	11.7	13	17	20	21	13	17	20	21
Other Biomass (Firewood-Wood and Black-Liquor)	1.0	1.5	2.3	3.1	4	5	7	9	4	5	7	9
Natural Gas	9.6	11.3	12.4	14.9	22	18	27	36	22	9	4	4

Nuclear	2.0	2.0	2.0	2.0	3.4	2.8	2.8	2.8	3.4	2.8	2.8	2.8
Coal	1.4	1.9	3.4	3.2	3	1	0	0	3	1	0	0
Petroleum Derivatives (Liquids) and Other Non-Renewable	4,8	7,2	9,1	8,0	2	1	1	1	2	1	1	1
Total	**92.2**	**111.7**	**139.2**	**177.3**	**245**	**275**	**327**	**377**	**250**	**286**	**343**	**392**

Source: Prepared by the authors.

Carbon pricing and rapid advancements in renewable energy technologies, particularly solar and wind, are pivotal global factors driving change in Brazil's DDS power sector. A domestic carbon tax can reduce the competitiveness of natural gas-based power generation, while technology improvements and growing international experience of developers can enable the competitiveness of renewables. The entry of new fossil fuel thermal plants was not prohibited, but only entered the system those that have already been established at auctions and a small penetration of flexible gas power thermal plants to complement the variable renewable power mix.

The heightened integration of VRE sources in DDS2, coupled with a lack of growth in dispatchable sources and reduced utilization of hydroelectric reservoirs, underscores the need for adopting storage systems (batteries or hydro power pumps). These systems effectively manage fluctuating renewable energy output, ensuring grid stability. DDS2 plans to install 2 GW of storage capacity by 2045, expanding to 4 GW by 2060. Conversely, in the CPS2, where no carbon tax affects the competitiveness of natural gas, this technology still plays an important role in the dispatchable power generation for grid stability.

In the global context, variable renewable sources are at the center of economic decarbonization strategies. In Brazil, the increased in installed capacity of these sources in the power mix is foreseen in sectoral planning, included in the PDE, PNE and consequently is already present in the CPS (Table 16). In the CPS2, the share of wind and solar sources in installed capacity should increase from 20% in 2020 to 35% in 2030, 43% in 2050 and reaching to 47% in 2060. In the DDS2 this percentage is intensified to 52% in 2050 and 57% in 2060 (Table 17).

Table 17 – Estimates of installed capacity, by sources, in CPS2 and DDS2 without interference in protected areas (%, 2030-2060)

Installed capacity (%)	**Histórico**				**CPS2**				**DDS2**			
	2005	**2010**	**2015**	**2020**	**2030**	**2040**	**2050**	**2060**	**2030**	**2040**	**2050**	**2060**
Hydroelectric (HPP and SHPP)	77%	72%	66%	62%	45%	45%	39%	35%	44%	43%	37%	33%
Wind	0%	1%	5%	10%	11%	13%	18%	24%	11%	18%	26%	31%
Onshore	0%	1%	5%	10%	11%	13%	18%	24%	11%	17%	23%	28%
Offshore	0%	0%	0%	0%	0%	0%	0%	0%	0%	1%	3%	3%

Solar	0%	0%	0%	4%	24%	25%	25%	23%	25%	27%	26%	26%
Distributed (Small scale)	0%	0%	0%	3%	18%	20%	18%	17%	20%	21%	19%	18%
Centralized	0%	0%	0%	2%	5%	6%	6%	6%	5%	6%	7%	8%
Biomass	4%	7%	9%	8%	7%	8%	9%	8%	7%	8%	8%	8%
Bagasse	2%	6%	8%	7%	5%	6%	6%	6%	5%	6%	6%	5%
Other Biomass (Firewood-Wood and Black-Liquor)	1%	1%	2%	2%	2%	2%	2%	2%	2%	2%	2%	2%
Natural Gas	10%	10%	9%	8%	9%	6%	8%	9%	9%	3%	1%	1%
Nuclear	2%	2%	1%	1%	1%	1%	1%	1%	1%	1%	1%	1%
Coal	2%	2%	2%	2%	1%	1%	0%	0%	1%	1%	0%	0%
Petroleum Derivatives (Liquids) and Other Non-Renewable	5%	6%	7%	5%	1%	0%	0%	0%	1%	0%	0%	0%
Total	**100%**	**100%**	**100%**	**100%**	**100%**	**100%**	**100%**	**100%**	**100%**	**100%**	**100%**	**100%**

Source: Prepared by the authors**.**

The DDS2 allows a greater share of zero emission power generation. In 2050, the resulting system is 98% renewable and 1% nuclear, with a 99% zero emission power generation.

Upon analysing power generation estimates without interference in protected areas, significant patterns, and interesting projections for the CPS2 and DDS2 scenarios regarding hydroelectricity become apparent.

The estimates for the CPS2 scenario predict a steady increase in hydroelectric generation over time. By 2030, it is expected that generation will reach 416 TWh, a modest increase compared to the 2020 estimate. This gradual increase continues until 2060, reaching 501 TWh. Projections for the DDS2 scenario also indicate growth in hydroelectric generation, albeit with some nuances. It is forecasted that by 2030, generation will reach 419 TWh, slightly higher than the estimate for CPS2 and the same level projected for CPS2 in 2060.

There has been a remarkable rise in wind energy production over time. In 2005, generation was non-existent, but by 2020, it had reached 57 TWh, indicating significant growth in this sector.

For the CPS2 scenario, projections indicate a continuous increase in wind energy generation. By 2030, it is expected to reach 107 TWh, doubling compared to 2020. This growth persists until 2060, reaching 349 TWh. For the DDS2 scenario, projections are even more ambitious, with a significant increase in wind energy generation. By 2030, generation will reach 110 TWh, slightly above the estimate for CPS2. However, the introduction of offshore wind energy is estimated to contribute 4

TWh in 2030, increasing to 40 TWh in 2060. This further boosts the total wind energy generation in the DDS2 scenario, which reaches 465 TWh by 2060.

Comparing the CPS2 and DDS2 scenarios, both foresee a substantial increase in wind energy generation over the coming decades. However, DDS2 stands out for the inclusion of offshore wind energy, providing an additional boost to total wind energy production.

Solar energy has emerged as an increasingly significant source of energy over the past decades, showing remarkable growth in its contribution to power generation. In the estimated series of power generation, we observe an impressive progression. In 2005 solar generation was non-existent, but this energy source had a modest beginning but grew steadily, reaching 15.5 TWh in 2020.

In the CPS2 scenario, projections indicate a substantial increase in solar energy generation over the next decades. By 2030, generation is expected to reach 94 TWh, a significant increase compared to previous years. This growth continues consistently until 2060, reaching 147 TWh. On the other hand, estimates for the DDS2 scenario are even more ambitious, foreseeing even greater growth in solar energy generation. In 2030, generation is estimated at 100 TWh, surpassing CPS2 projections. This growth trend persists over the following decades, reaching 183 TWh in 2060.

Table 18 – Estimates of power generation, by sources, in CPS2 and DDS2 without interference in protected areas (TWh, 2030-2060)

Power Generation (TWh)	Historical				CPS2-Without interference				DDS2-Without interference			
	2005	2010	2015	2020	2030	2040	2050	2060	2030	2040	2050	2060
Hydroelectric (HPP and SHPP)	337.5	403.3	359.7	396.4	416	487	497	501	419	462	497	501
Wind	0	2	22	57	107	136	225	349	110	188	337	465
Onshore	0	2	22	57	107	136	225	347	106	177	299	425
Offshore	0	0	0	0	0	0	0	2	4	11	38	40
Solar	0.0	0.0	0.1	15.5	94	115	135	147	100	128	157	183
Distributed (Small scale)	0.0	0.0	0.0	4.8	60	72	79	84	66	80	87	93
Centralized	0.0	0.0	0.1	10.7	34	42	55	63	34	48	70	90
Biomass	12.8	31.2	47.3	55.6	66	84	108	116	66	82	108	116
Bagasse	7.7	22.4	34.0	38.8	44	58	72	75	44	57	72	75
Other Biomass (Firewood-Wood and Black-Liquor)	5	9	13	17	21	26	36	42	21	25	36	42
Natural Gas	18.8	36.5	82.6	59.5	47	55	88	118	47	28	1	1
Nuclear	9.9	14.5	14.7	14.1	24	21	21	21	24	20	21	21
Coal	6.4	7.0	19.1	11.9	14	7	0	0	0	0	0	0
Petroleum Derivatives (Liquids) and Other Non-Renewable	10.6	13.8	27.2	9.0	0.0	2.0	3.5	4.2	0.0	0.0	0.0	0.0

Total	**395.9**	**508.5**	**572.4**	**619.0**	**768**	**907**	**1077**	**1257**	**766**	**908**	**1122**	**1287**

Source: Prepared by the authors.

In Table 19, the participation of sources in power generation becomes even clearer. Hydroelectricity, which occupies the first place in 2020, continues to hold the top spot in both CPS2 and DDS2 in 2060, but with lower share. In 2020, it has a 64% share, and in 2060, approximate 40% for CPS2 and 39% for DDS2.

The wind and solar sources show significant growth in both CPS2 and DDS2 scenarios. Wind energy goes from 9% in 2020 to an estimated 28% in CPS2 and 33% in DDS2. Meanwhile, solar energy, which represented 3% in 2020, is estimated to have a share of 12% in CPS2 and 14% in DDS2.

Biomass shows no fluctuation in the power generation share. The 9% in 2020 remains the same for both CPS2 and DDS2. In 2020, nuclear energy accounts for only 2%, and it maintains the same share in both scenarios until 2060 (CPS2 and DDS2). Natural gas, which has a 10% share in the 2020 estimate, appears with 9% in 2060 for the CPS2 scenario, whereas for the DDS2 scenario in 2060, the participation of natural gas almost null.

Table 19 – Estimates of power generation, by sources, in CPS2 and DDS2 without interference in protected areas (%, 2030-2060)

Power Generation (%)	Historical				CPS2-Without interference				DDS2-Without interference			
	2005	2010	2015	2020	2030	2040	2050	2060	2030	2040	2050	2060
Hydroelectric (HPP and SHPP)	85%	79%	63%	64%	54%	54%	46%	40%	55%	51%	44%	39%
Wind	0%	0%	4%	9%	14%	15%	21%	28%	14%	21%	30%	36%
Onshore	0%	0%	4%	9%	14%	15%	21%	28%	14%	19%	27%	33%
Offshore	0%	0%	0%	0%	0%	0%	0%	0%	1%	1%	3%	3%
Solar	0%	0%	0%	3%	12%	13%	12%	12%	13%	14%	14%	14%
Distributed (Small scale)	0%	0%	0%	1%	8%	8%	7%	7%	9%	9%	8%	7%
Centralized	0%	0%	0%	2%	4%	5%	5%	5%	4%	5%	6%	7%
Biomass	3%	6%	8%	9%	9%	9%	10%	9%	9%	9%	10%	9%
Bagasse	2%	4%	6%	6%	6%	6%	7%	6%	6%	6%	6%	6%
Other Biomass (Firewood-Wood and Black-Liquor)	1%	2%	2%	3%	3%	3%	3%	3%	3%	3%	3%	3%
Natural Gas	5%	7%	14%	10%	6%	6%	8%	9%	6%	3%	0%	0%
Nuclear	2%	3%	3%	2%	3%	2%	2%	2%	3%	2%	2%	2%
Coal	2%	1%	3%	2%	2%	1%	0%	0%	0%	0%	0%	0%

Petroleum Derivatives (Liquids) and Other Non-Renewable	3%	3%	5%	1%	0,0%	0,2%	0,3%	0,3%	0,0%	0,0%	0,0%	0,0%
Total	**100 %**	**100 %**	**100 %**	**100 %**	**100 %**	**100 %**	**100 %**	**100 %**	**100 %**	**100 %**	**100 %**	**100 %**

Source: Prepared by the authors**.**

6.2 Power sector emission and the Brazilian Nationally Determined Contribution (NDC) pledge

The Brazilian emission profile differs significantly from the rest of the world. In Brazil, unlike the global average pattern of GHG emissions, the energy sector is not the primary contributor to emissions (Figure 10). Historically, emissions are mainly concentrated in the land use change and forestry sector (LULUCF), specifically related to deforestation, reaching its peak in 2004. However, with the progressive decline in deforestation rates, other sectors, particularly agriculture and energy, have gained prominence in percentage terms. Nevertheless, the emission profile remains substantially different from the global pattern.

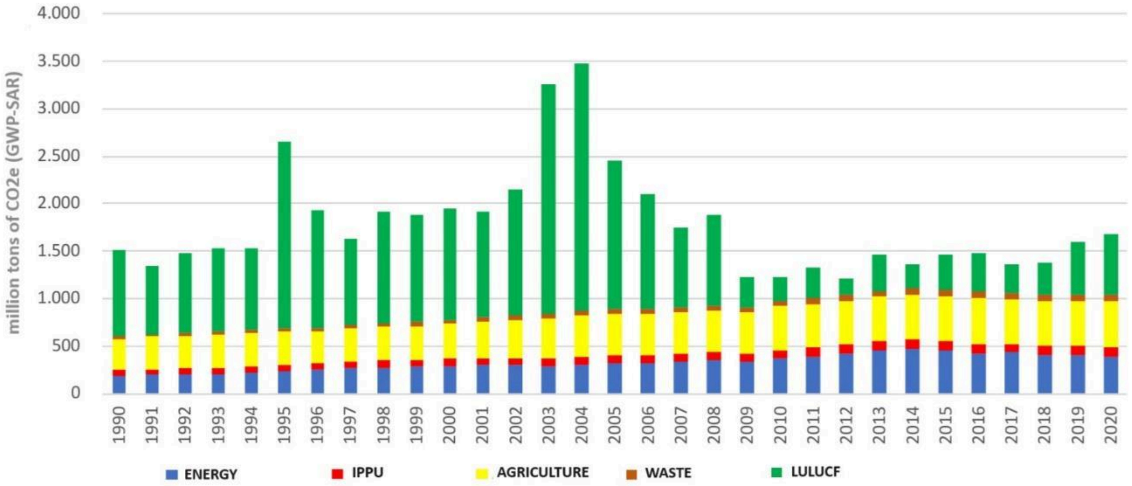

Figure 10 – Brazil's sectoral emissions, in CO_2e, from 1990 to 2020.
Source: BRASIL (2022).

The high renewable share of the national energy matrix (almost 50%) ensures the low significance of emissions from the energy sector in the overall national total. In the energy sector, fuel consumption in the transport and industry sectors is the major contributor to greenhouse gas emissions, accounting for 65% of the total (EPE, 2023a).

The electric power sector, where up to 90% of the energy generated comes from renewable sources (in favourable hydrological years), accounts for about 11% of the total emissions from the energy sector. In the national context, including all other sectors, this number drops to less than 3%. Therefore, achieving additional greenhouse gas mitigation in the electricity sector tends to be cost-ineffective and challenging.

Mitigation measures from the land-use sector reduce the reliance on costly, not-yet-mature engineered solutions from the energy sector. Brazil has the capability to maintain this characteristic of high renewable content in the electric and energy matrices in the medium and long term.

According to IMAGINE project results, short-term main measures that should be implemented are primarily those in the land use sector, due to their lower investment cost and significant impact on national emissions. Leveraging the Agriculture, Forestry, and Other Land Use (AFOLU) sector is essential to achieve net-zero emissions by 2050, as it can significantly reduce and capture emissions, thereby lowering overall costs for Brazil.

National policy packages and priorities for short-term climate action and sustainability must build upon successful past policies (2004-2012) that effectively reduced deforestation rates, employing a mix of command-and-control measures and economic instruments. Additionally, the development of smart financial mechanisms is crucial to fund investments in mitigation actions, particularly in forest cover restoration and low-carbon infrastructure. A robust carbon pricing strategy, featuring a well-structured cap-and-trade scheme for industry and a carbon tax on regulated sectors, provides a stable signal for choosing low-carbon technologies and can yield significant emissions reductions at low costs. This approach allows time for emerging technologies to become economically viable while meeting ambitious climate targets.

The Brazilian 2023 NDC pledge consists of an economy-wide, absolute mitigation target. The last update of Brazil's NDC to the Paris Agreement (in 2023)[12] stipulates the emission target of 1.32 $GtCO_2e$ (reduction of 48% in relation to 2005) by 2025 and 1.20 $GtCO_2e$ (reduction of 53% in relation to 2005) by 2030. Brazil's commitments also include a long-term objective to achieve climate neutrality by 2050. Achieving GHG neutrality by 2050 requires negative CO_2e emissions in other sectors, such as AFOLU.

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 years of water scarcity, which led to the activation of thermopower plants. For instance, the Brazilian electricity sector emitted 126 $kgCO_2e/MWh$ in 2015, a very low rate compared with the European Union countries, the USA, and

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[12] 2024: Brazil is conducting studies to define sectoral targets to be used in the carbon market currently under negotiation in Congress, but there is no indication from the government regarding the inclusion of sectoral targets in the next NDC

China. As mentioned above, in 2023, a favourable hydrological year, the GRID recorded an emission of 38.5 kgCO_2e per MWh generated.

In the context of GHG long term emission scenarios for the electricity sector, all projections show a decrease in sector emissions compared to 2020. Up to 2040, all four scenarios reduce the emissions of the sector (from 49 in 2020 to 28,6 MtCO_2e in CPS2, 18,5 MtCO_2e in CPS1 and to 13 MtCO_2e in DDS2 and DDS1) (Figure 11). Emissions from power generation are expected to decrease further to 2,8 MtCO_2e and 2,1 MtCO_2e in DD2 and DDS1, respectively nearly reaching net zero emissions by 2060. However, in CPS, emissions are expected to increase after 2040 due to the resurgence of natural gas thermoelectricity, aiming to offset the increased demand for electricity and the reduced share of hydroelectricity in the energy mix. It is important to highlight that the increase in emissions in CPS 1 and 2, is accompanied by a significantly greater expansion of the electricity supply during the analysed period. In CPS2, by the year 2060, emissions are projected to nearly match the levels of 2020, while electricity demand witnesses a notable increase of 103%.

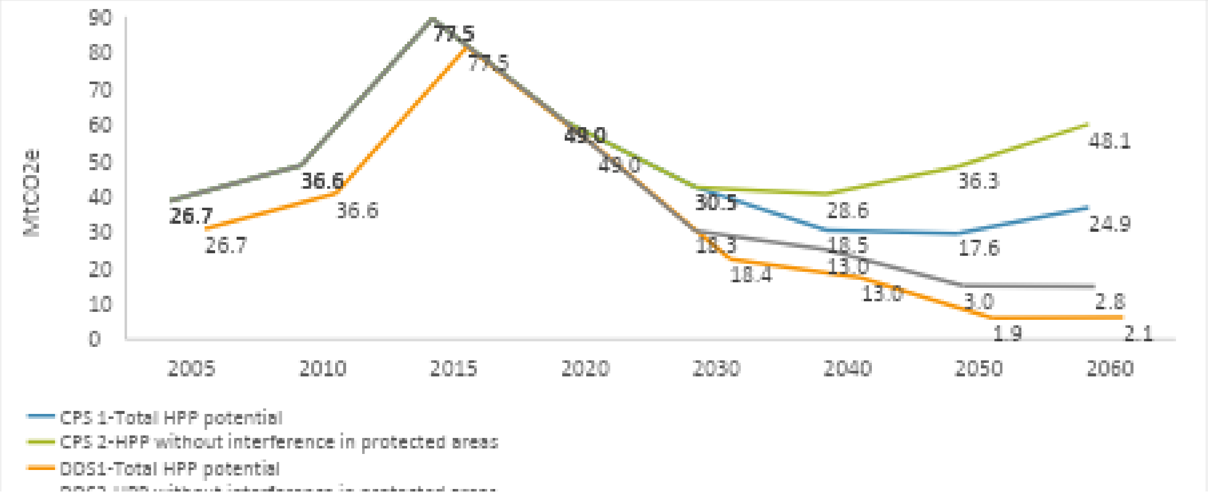

Figure 11 – Total electricity sector emissions (MtCO_2e - CPS 1, CPS2, DDS1, and DDS2)
Source: Prepared by the authors.

About the carbon content of the power generation, there is a reduction from 76 in 2020 to 29 and 2 kgCO_2eq/MWh, respectively, in the CPS2 and DDS2 and to 14 and 1 kgCO_2eq/MWh, respectively, in the CPS1 and DDS1 (Figure 12).

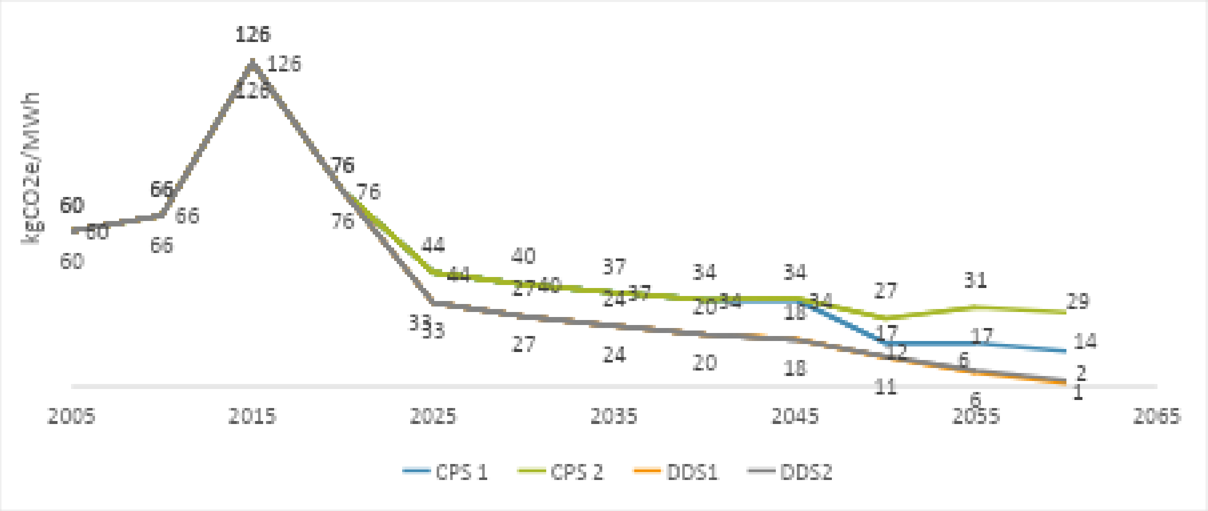

Figure 12 – GRID emissions factor - Generation (kgCO$_2$e/MWh- CPS 1, CPS2, DDS1, and DDS2)

Source: Prepared by the authors**.**

Besides the economy wide mitigation targets, the initial version of Brazil’s first NDC had additional targets such as achieving 23% of non-hydro renewables in the power generation mix by 2030. It is worth mentioning that in both CPS and DDS (all four scenarios), the share of renewables in supply – other than hydropower – increased to 42-43% by 2030 (wind, biomass and solar – including utility scale and distributed power generation), reaching 51% in CPS2 and 60% in DDS2, by 2060.

The DDS 1 and 2 allow a greater share of renewable power (wind, solar power - small and utility scale- and biomass). To compensate for the departure of these thermal plants with lifespan concluded, the model selected more onshore wind energy, given its high-capacity factor and seasonal complementarity with hydroelectric power plants. Additionally, in DDS2 offshore wind projects begin to enter 2030, when the technology becomes economically competitive according to the adopted assumptions adopted. In 2050, the resulting system is 98% renewable and 1% nuclear, with a 99% zero emission power generation. Emissions are close to zero, accounting only for emissions from biomass thermal plants (non-CO$_2$) and flexible gas thermopower plants.

6.3 Costs

The expansion of the electricity sector's infrastructure is critical for meeting growing energy demands, integrating renewable energy sources, enhancing grid resilience, and ensuring a reliable electricity supply to consumers. However, it involves significant investments in both capital expenditures (CAPEX- building new infrastructure) and operational expenditures (OPEX- operational costs). The total costs, comprising both CAPEX and OPEX, provide a holistic view of the financial implications and sustainability of grid expansion projects, guiding decision-makers in optimizing resources, improving cost-effectiveness, and determining the overall economic viability of the grid expansion projects.

Until 2030, there are no significant differences in the total costs between all four scenarios. This lack of divergence in costs can be primarily attributed to the fact that, by 2028/2029, the inputs from power plants that won energy generation auctions are already specified in the energy model. This means that the powerplants that will be added to the electrical infrastructure by that time are already under construction today. As a result, the costs associated with these new installations are already accounted for and spread over the construction and commissioning period, reflecting in the total costs of the scenarios relatively evenly until 2030.

Comparing the total costs of the two DDS scenarios, from 2035 to 2040, there is a higher cost in DDS2 due to the expansion of more expensive renewable sources than hydroelectric for meeting the growing demand (for example, offshore wind projects) (Table 20). Looking ahead to the period from 2045 to 2050, DDS1 continues to expand hydroelectric plants while DDS2 has already reached its full potential for expansion that does not affect protected areas. Furthermore, the total system cost for DDS1 by 2060 is higher than DDS2 due to the greater expansion of transmission lines from the hydropower plants in the North region to consumption centers.

When comparing the total costs of the two extreme scenarios, CPS1 and DDS2, distinct approaches become evident. CPS1 fully exploits hydroelectric potential, including HPP within protected areas, and supplements its power mix with gas-fired power plants. Conversely, DDS2 prioritizes the preservation of protected areas and places a greater emphasis on expanding renewable energy sources. It is noteworthy that from 2030 to 2035, there is a higher cost associated with DDS2 due to the expansion of more expensive renewable sources compared to hydroelectricity. However, after 2040, the total cost of the system for CPS1 exceeds that of DDS2 due to the increased consumption of natural gas. This comparison underscores the strategic and environmental considerations that significantly impact the total costs within the electricity sector.

Table 20 – Total DDS2 electricity expansion cost (CAPEX and OPEX) in relation to other scenarios (CPS1, CPS2 and DDS1)

Total DDS2 Cost in relation to other scenarios		DDS2	DDS2	DDS2	DDS2	DDS2	DDS2
		2035	2040	2045	2050	2055	2060
CPS1	2035	6%					
CPS1	2040		-2%				
CPS1	2045			-4%			
CPS1	2050				-5%		
CPS1	2055					-9%	
CPS1	2060						-12%
CPS2	2035	8%					
CPS2	2040		7%				
CPS2	2045			4%			
CPS2	2050				4%		
CPS2	2055					1%	

CPS2	2060						-3%
DDS1	2035	3%					
DDS1	2040		1%				
DDS1	2045			-1%			
DDS1	2050				0%		
DDS1	2055					1%	
DDS1	2060						-1%

Source: Prepared by the authors**.**

The total cost differences for the CPS2 and DDS2 scenarios without expansion of hydroelectric power plants in protected areas is presented in Table 21. Until 2030, the change in CAPEX is due to the higher penetration of solar distributed generation in the DDS, and in OPEX, there is a minimum coal generation to represent take or pay contracts in the CPS, while there is no such restriction in the DDS. The present value of the total cost is essentially the same in both scenarios until 2030 (average variation of 0.4% higher or lower). Apart from that, the model already includes auction data until 2029 and Angra III coming online in 2027.

From 2035 to 2055, the DDS is higher due to the introduction of more expensive technologies, such as offshore wind, starting in 2030, and storage in 2040. The largest difference is 7,9% in 2035, and then the total cost decreases, with CPS becoming more expensive than DDS again in 2060.

Consequently, there is a reduction in the net present value of the total cost, indicating that if the cost perspectives[13] used in this study are confirmed, a low-carbon matrix is achieved in the 2060 at a lower cost, with various technologies in the expansion portfolio.

Table 21 – CAPEX and OPEX for the GRID in DDS 2 compared to CPS2.

Year	CAPEX DDS2 R$2020 compared to CPS2	OPEX DDS2 R$2020 values compared to CPS2	Total DDS2 R$2020 values compared to CPS2	Scenario
2023	-	-	-	-
2024	2.6%	-1.4%	0.4%	DDS2 Higher
2025	2.6%	-1.7%	0.3%	DDS2 Higher
2026	2.7%	-2.2%	0.1%	DDS2 Higher
2027	2.5%	-2.7%	-0.2%	CPS2 Higher
2028	2.6%	-3.0%	-0.2%	CPS2 Higher
2029	2.7%	-3.5%	-0.4%	CPS2 Higher

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[13] The investment costs and fixed operation and maintenance costs for electricity generation technologies in Brazil is based on information from PDE 2031 (MME/EPE,2022), along with cost reduction considerations for wind and solar power. Regarding fuel costs cost, coal is priced at 116-132 R$2020/MWh, natural gas costs are 262-390 $2020/MWh, nuclear is 47 R$2020/MWh, biomass 203 R$2020/MWh. Assumptions about oil price trajectories indicate an average of $64 per barrel from 2025 to 2060. The annual discount rate assumed is 8%, excluding any additional charges or taxes.

2030	4.6%	-2.9%	0.9%	DDS2 Higher
2035	15.3%	-1.7%	7.9%	DDS2 Higher
2040	20.9%	-18.0%	7.1%	DDS Higher
2045	25.6%	-33.8%	4.0%	DDS Higher
2050	25.8%	-38.2%	4.1%	DDS Higher
2055	19.5%	-39.7%	0.7%	DDS Higher
2060	16.5%	-43.0%	-3.0%	CPS Higher

Source: Prepared by the authors.

Substantial support from Annex I countries is vital to facilitate financial flows towards mitigation actions in non-Annex I countries. This includes leveraging climate finance tools within the UNFCCC, such as the Green Climate Fund and Sustainable Development Mechanism, as well as international financial initiatives to attract private capital to low-carbon investments. Such support is crucial in de-risking low-carbon projects and accelerating the transition to a more sustainable and climate-resilient future. Additionally, domestic sources like green bonds are becoming increasingly attractive, while innovative models like partial credit guarantees can incentivize local banks to participate.

7 Conclusion

The Brazilian electricity matrix stands as one of the world's most renewable, positioning the country advantageously in the race to reduce greenhouse gas emissions and align with global agreements addressing the planet's climate crisis. These economically viable and scalable options can effectively decarbonize not just the electricity sector but also potentially influence other economy sectors, such as transportation and industry through electrification.

Brazil's unique greenhouse gas emission profile highlights a distinct pattern compared to highly industrialized economies. The country's emissions are primarily from agriculture, forestry, and land use change (deforestation, agriculture practices, and livestock), with electricity generation accounting for a relatively small portion (approximately 3% of Brazil's greenhouse gas emissions in 2020).

The report underscores the criticality of ongoing expansion of Brazil's power mix with renewable energy to foster a decarbonized economy, mitigate climate change impacts, and foster sustainable development. Ensuring the security of energy supply while expanding renewable sources remains paramount. Smart integration of renewables is essential for guaranteeing a reliable and stable electricity supply while transitioning to a cleaner and more resilient energy future.

In analysing the four scenarios - CPS1, CPS2, DDS1, and DDS2 –, several differences and trends emerge. In terms of installed capacity, across all scenarios, Brazil power mix continues in 2060 with a high share of renewables, reaching 99% in DDS1, 98% in DDS2, 94% in CPS1 and 90% in CPS2. Moreover, old thermopower plants are decommissioned and replaced by renewable power plants due to their lower costs in both scenarios. While CPS 1 and 2 have a higher penetration of gas-fired power plants, DDS 1 and 2 focus on renewable sources with a greater integration of variable renewable sources, with an emphasis on storage systems to ensure grid stability.

Regarding total electricity generation, all scenarios will continue with a high share of renewables, especially wind and solar. The lower renewable generation share of 89% occurs in CPS2, due to hydro power plant construction constraints and the need to complement variable renewable electricity with natural gas to meet the demand needs. DDS1 and DDS2 lead in this aspect, reaching almost entirely renewable generation by 2060 (98%).

Emissions-wise, all projections show a decrease in electricity sector emissions compared to 2020. Up to 2040, all four scenarios reduce the emissions of the sector. CPS1 and CPS2 show a trend of increasing emissions post-2040 due to more natural gas use, while DDS1 and DDS2 continue reducing emissions towards nearly zero by 2060.

Regarding costs, until 2030, all scenarios show minimal differences due to pre-specified inputs from electricity auctions. Comparing CPS1 and DDS2, two extreme scenarios, showcases their different approaches, with CPS1 relying on hydro and gas, while DDS2 prioritizes renewables and preservation of protected areas. While DDS2 initially incurs higher costs, it becomes more cost-effective post-2040 compared to CPS1 due to reduced gas use.

The future of Brazil with the transition towards a secure and decarbonized electrical matrix lies in diversification. Embracing a diverse range of energy sources and technologies will not only enhance energy security but also contribute significantly to the country's efforts in mitigating climate change. By fostering a balanced and resilient power mix portfolio, Brazil can navigate the complexities of a rapidly evolving global energy landscape, ensuring sustainable development and a sustainable future.

The report examined deep decarbonization scenarios, DDS1 and DDS2, to illustrate Brazil's potential trajectory toward increased adoption of renewable energy and power supply emissions reduction. It emphasizes the shift towards variable renewable energy (VRE) sources like wind and solar, coupled with advancements in bioelectricity, grid flexibility, storage technologies, as key drivers in diversifying the energy mix and reducing dependence on fossil fuels. Comparing CPS and DDS scenarios highlights potential pathways to decarbonization, with DDS2 indicating a more aggressive transition towards renewable sources and significant emissions reductions over time. This transition is supported by carbon pricing mechanisms, renewable technology advancements, and strategic planning for energy infrastructure.

Brazil's abundant renewable resources provide a privileged position for advancing towards a more sustainable energy matrix. The government's opportunity lies in an energy transition plan, aligning with global trends favouring renewable sources and contributing positively to fulfilling its National Determined Contributions (NDC) targets. In essence, Brazil stands at a pivotal moment where strategic decisions can shape its energy future, not only in compliance with international commitments but also as a leader in sustainable energy practices.

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Appendix 1

This appendix provides an update on the electricity demand forecast from the ICAT Project 3 Current Policy Scenario (CPS), as presented in the previous report (Output 2) and the power supply. The figures presented here reflect the outcomes of the New Government Policy Scenario (NGPS, equivalent to CPS), which was developed for the recently concluded IMAGINE Project.

The aggregate electricity consumption experiences an increase of almost 107 % from 2020 to 2060, reaching 1,132 TWh (Table 22 and Figure 15). Examined by sector, the following percentage growth in electricity consumption in this period is observed: residential (62%); transport (3,761%); industry (84%); public sector (91%); commercial sector (155%); agriculture (156 %); and energy sector (69%).

Table 22 – Estimates of electricity demand in updated CPS (TWh)

Year	Households	Transport	Industry	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	2.8	223.8	46.0	94.3	32.1	40.9	604.3
2030	178.7	4.7	244.6	50.5	109.8	37.2	56.5	682.1
2035	192.2	7.9	266.0	54.3	123.0	42.5	57.9	743.8
2040	204.7	13.7	288.6	58.8	138.3	48.7	55.3	808.1
2045	216.1	24.8	308.9	63.7	155.0	56.1	58.6	883.2
2050	226.1	43.4	330.3	69.4	174.4	64.9	61.8	970.3
2055	234.7	64.3	347.5	75.4	194.4	73.5	63.5	1,053.3
2060	241.7	77.8	365.7	81.9	216.5	83.2	64.9	1,131.6

Source: Prepared by the authors.
Note: Data until 2020.

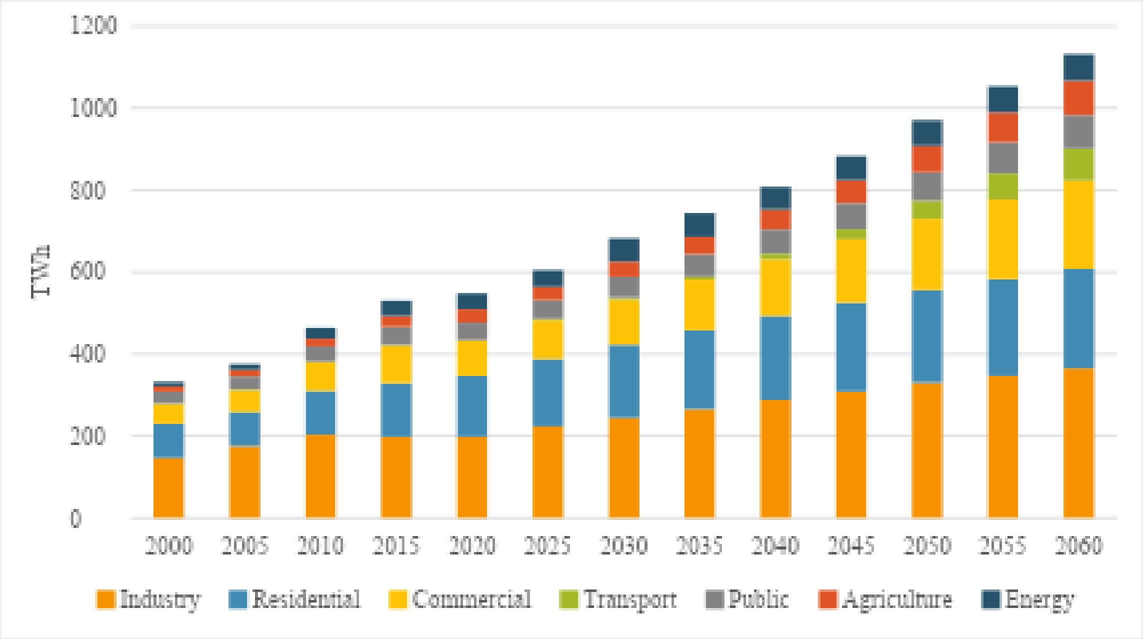

Figure 15 – Estimates of sectoral electricity demand in the CPS (TWh, 2000 – 2060)
Source: Prepared by the authors.

Table 23 – Estimates of installed capacity, by sources, in CPS1 and CPS2 (GW, 2030-2060)

	Historical				**CPS1-total HPP potential**				**CPS2-Without interference in protected areas**			
	2005	2010	2015	2020	2030	2040	2050	2060	2030	2040	2050	2060
Hydroelectric (HPP and SHPP)	71.1	80.7	91.7	109.3	111	134	145	147	111	123	128	131
Wind	0.0	0.9	7.6	17.1	28	37	60	90	28	37	60	91
Onshore	0.0	0.9	7.6	17.1	28	37	60	90	28	37	60	90
Offshore	0.0	0.0	0.0	0.0	0	0	0	0	0	0	0	1
Solar	0.0	0.0	0.0	7.92	58	70	80	87	58	70	80	87
Distributed (Small scale)	0.0	0.0	0.0	4.64	45	54	59	63	45	54	59	63
Centralized	0.0	0.0	0.0	3.29	13	16	21	24	13	16	21	24
Biomass	3.3	7.7	12.9	14.8	17	22	27	32	17	22	28	30
Bagasse	2.3	6.2	10.6	11.7	13	17	21	25	13	17	20	21
Other Biomass (Firewood-Wood and Black-Liquor)	1.0	1.5	2.3	3.1	4	5	6	7	4	5	7	9
Natural Gas	9.6	11.3	12.4	14.9	22	9	16	25	22	18	27	36
Nuclear	2.0	2.0	2.0	2.0	3	3	3	3	3	3	3	3
Coal	1.4	1.9	3.4	3.2	3	1	0	0	3	1	0	0
Petroleum Derivatives (Liquids) and Other Non-Renewable	4.8	7.2	9.1	8.0	2	1	1	1	2	1	1	1
Total	**92.2**	**111.7**	**139.2**	**177.3**	**245**	**277**	**333**	**385**	**245**	**275**	**327**	**377**

Source: Prepared by the authors.

Table 24- Estimates of power generation, by sources, in CPS1 and CPS2 (TWh, 2030-2060)

Power Generation (TWh)	**Historical**				**CPS1-total HPP potential**				**CPS2-Without interference in protected areas**			
	2005	**2010**	**2015**	**2020**	**2030**	**2040**	**2050**	**2060**	**2030**	**2040**	**2050**	**2060**
Hydroelectric (HPP and SHPP)	337.5	403.3	359.7	396.4	416	515	573	591	416	487	497	501
Wind	0.1	2.2	21.6	57.1	107	137	221	346	107	136	225	349
Onshore	0.1	2.2	21.6	57.1	106.9	137.4	221.1	345.6	106.9	135.8	225.1	347.1
Offshore	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	1.9
Solar	0.0	0.0	0.1	15.5	94	115	135	148	94	115	135	147
Distributed (Small scale)	0.0	0.0	0.0	4.8	60	72	79	84	60	72	79	84
Centralized	0.0	0.0	0.1	10.7	34	43	56	64	34	42	55	63
Biomass	12.8	31.2	47.3	55.6	66	83	102	120	66	84	108	116
Bagasse	7.7	22.4	34.0	38.8	44	58	73	87	44	58	72	75
Other Biomass (Firewood-Wood and Black-Liquor)	5.1	8.8	13.2	16.8	21	25	29	33	21	26	36	42
Natural Gas	18.8	36.5	82.6	59.5	47	29	39	55	47	55	88	118
Nuclear	9.9	14.5	14.7	14.1	24	20	21	21	24	21	21	21
Coal	6.4	7.0	19.1	11.9	14	7	0	0	14	7	0	0
Petroleum Derivatives (Liquids) and Other Non-Renewable	10.6	13.8	27.2	9.0	0.0	2.0	2.7	3.3	0.0	2.0	3.5	4.2
Total	**395.9**	**508.5**	**572.4**	**619.0**	**768**	**908**	**1093**	**1284**	**768**	**907**	**1077**	**1257**

Appendix 2

The Climate and Development Initiative and DecarBoost project was the result of the joint work of numerous organizations and individuals in building low-carbon future visions for the country. The reports were results from a solid ambition to action: cross-sectoral technical and scientific foundation, dialogues, and consultations with a wide spectrum of specialists and political leaders from across Brazilian society. The documents was prepared based on consultations with rounds by the Climate Policy Committee and with plenaries and thematic workshops of the Technical-Sectoral Committee.

Members of the Climate Policy Committee:

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