BRAZILIAN CENTER FOR INTERNATIONAL RELATIONS

Empresa de Pesquisa Energética

cenergia

IDB

ENERGY

TRANSITION

PROGRAM

Carbon Neutrality 2050: Scenarios for an Efficient Transition in Brazil

Final Report of the technical cooperation
ATN/OC-17965-BR

February, 2023

EDITORIAL TEAM

Authors

André Bello
Breno Lyro
Gabriel Paiva
Gabriela Gonzalez
Gregório Araújo
Humberto Lima
Luciana Sampaio
Pedro Guimarães
Rafaela Guedes
Thiago Moraes
Yuri Telles
Cenergia: **Alexandre Szklo, Mariana Império, Matheus Poggio, Roberto Schaeffer**

Editorial coordination

Jorge Camargo
Vice President, CEBRI

Julia Dias Leite
President, CEBRI

Luciana Gama Muniz
Project Director, CEBRI

Giovani Machado
Director of Economic, Energy and Environmental Studies, EPE

Carlos J. Echevarría
Senior Regional Specialist for Energy, Energy Division, IDB

Léa Reichert
Project coordinator, CEBRI

Graphic design

Presto Design

The findings of the Energy Transition Program reflect Cenergia's efforts to build, develop and quantify exploratory scenarios which may not express the individual opinion of the entities that participated in the Program and may not consider other work said institutions are developing.

The decarbonization policies, studies and analyses developed by the competent sectoral or industry institutions/entities must be considered in relation to aspects and recommendations pertaining to each specific sector or industry. The sectoral and industry analyses and policy recommendations in this report are not exhaustive and are subject to review for validity and consistency with the regulatory, technical and policy frameworks of the sectors or industries involved and with those frameworks in the specific context of Brazil.

CEBRI

ENERGY PROGRAM

The Group researches the future of energy and global energy trends and seeks solutions to create a competitive and attractive investment environment in Brazil.

Jorge Camargo
Vice President at CEBRI

Rafaela Guedes
Senior Fellow at CEBRI

Gregório Araújo
Senior Rechearcher

CENTRO BRASILEIRO DE RELAÇÕES INTERNACIONAIS
Rua Marquês de São Vicente, 336 – Gávea
Rio de Janeiro / RJ - CEP: 22451-044
Tel + 55 21 2206-4400 - cebri@cebri.org.br
www.cebri.org

BRAZILIAN CENTER FOR INTERNATIONAL RELATIONS

Empresa de Pesquisa Energética

ENERGY TRANSITION

PROGRAM

Final Report of the technical cooperation
ATN/OC-17965-BR

Carbon Neutrality 2050:

Scenarios for an Efficient Transition in Brazil

Sponsorship:

Support:

ABOUT CEBRI

The Brazilian Center for International Relations (CEBRI) is an independent, non-partisan and multidisciplinary entity guided by excellence, ethics and transparency and that focuses on the creation and dissemination of high-quality content about the global scenario and about Brazil's international role. CEBRI maintains an open debate with government and non-government entities to influence the construction of an international agenda for Brazil and to support the formulation of forward-looking public policies that can make an impact.

In the course of its twenty-two year history, CEBRI has organized more than 500 events and produced more than 200 publications. CEBRI cooperates with more than 100 high-level entities on every continent, standing out for its intellectual capital, for its ability to bring together the multiple views of renowned specialists and for the heft of its Board of Trustees.

CEBRI uses its international connections to identify and analyze major international issues and to foster the interaction between the production of knowledge and political action. CEBRI operates as counterpart to strategic global institutions such as the Council on Foreign Relations in the US and Chatham House in the UK, as well as several other Councils on International Relations across the global arena.

CEBRI's international significance is also attested by the University of Pennsylvania's *Global Go to Think Tanks* survey, which found CEBRI to be one of the most important think tanks in the world.

CEBRI
BRAZILIAN CENTER FOR INTERNATIONAL RELATIONS

ABOUT THE IDB

The Inter-American Development Bank (IDB) is an international financial institution founded in 1959 and including 48 member countries. Its objective is to fund economic development projects in Latin America and the Caribbean and to provide technical assistance to governments and private institutions. Main IDB initiatives focus on reducing poverty and inequality, fostering regional and trade integration, competitiveness, productivity and innovation and enhancing the efficiency of government spending.

IDB

ABOUT EPE

The purpose of the Energy Research Company - EPE is to prepare studies and research for the Ministry of Mines and Energy (MME) in support of power industry planning, focusing on electricity, oil and natural gas and its by-products and biofuels. EPE is owned by Federal Government and funded by the Federal Budget.

EPE was created in satisfaction of the Federal Government's constitutional duty to foster the sustainable development of Brazil's energy infrastructure. EPE has since its creation become a key player in the process that begins with the definition by the CNPE – National Energy Policy Council and by the MME of the policies and guidelines used in the studies and research that will effectively steer the development of Brazil's energy sector.

EPE has since its inception actively participated in all major discussions concerning the Brazilian energy sector. EPE's participates in Brazil's energy planning process by preparing studies and engaging in research that culminate in the construction of an array of procedures and actions that lay the groundwork for policy to ensure an adequate energy supply. EPE's product portfolio includes the Ten-Year Energy Expansion Plan (PDE), the National Energy Plan (PNE), the National Energy Balance (BEN) and the Transmission Expansion Program (PET).

epe
Empresa de Pesquisa Energética

ABOUT CENERGIA

The Center for Energy and Environmental Economics (Cenergia Lab) was created in 2002 as a research arm of the Energy Planning Program (PPE) of the Federal University of Rio de Janeiro (UFRJ) Graduate School of Engineering (Coppe). Cenergia is a major energy planning think-tank for Latin American and global issues and develops innovative interdisciplinary knowledge on energy, economics and environmental sustainability through research and teaching activities, outreach initiatives and collaborative work with government and non-government organizations.

CenergiaLab is considered a center of international excellence in the application of integrated planning modeling tools to support energy and climate policymakers in understanding the synergies and paths of technological innovation for Brazil, Latin America and the world to transition to a low-carbon reality. Cenergia Lab has been working with integrated energy and environmental optimization models, in particular with the MESSAGE-Brazil model, since 2003, and more recently with the TIMES-Brasil and REMIX-CEM-B national models and with the COFFEE (Computable Integrated Framework for Energy and the Environment) and TEA (Total-Economy Integrated Assessment Model, a computable general equilibrium model) global models. CENERGIA modeled Brazil’s 2050 energy transition scenarios.

cenergia

SUMMARY

FIGURES

TABLES

CHARTS

Executive Summary

1

CARBON NEUTRALITY 2050:
SCENARIOS FOR AN EFFICIENT TRANSITION

The IDB-CEBRI-EPE Energy Transition Program (PTE) was established to assess the constraints and the potential of Brazil's energy transition and to offer an independent and open contribution to the formulation of public policies geared towards Brazil's energy mix in 2050. Particularly by involving discussions with and the participation of different stakeholders, the Program from the outset aimed to help build consensus by supporting the analysis of critical uncertainties and by exploring scenarios and sensitivities.

The evaluation of potential decarbonization paths and of their associated strategies is challenging because of the complexity surrounding climate change itself, social and economic change and the social, cultural and institutional context over the long term. Furthermore, estimates that span long time horizons are highly dependent on assumptions about how public policies and social consensuses evolve, how companies and consumers behave and how new technologies are developed and disseminated.

Scenarios are a useful guide for this analytical exercise, providing a plausible narrative to anchor the data and hypotheses included in the model and thus helping identify consistent institutional and technological strategic options for the energy system, for industrial transformation and for land use (forestry, agriculture and cattle ranching).

We used our decarbonization scenarios to explore different emission mitigation options to achieve a given climate outcome associated with temperature increase thresholds. Three different scenarios were prepared that converge on Brazil reaching zero net greenhouse gas (GHG) emissions in 2050, to wit: (i) Brazil Transition (BT); (ii) Alternative Transition (AT) and (iii) Global Transition (GT).

The Brazil Transition scenario (BT): was shaped to reflect Brazil's commitments under its Nationally Determined Contribution (NDC) to find the optimal cost-efficient path (based on Brazil's resources, knowledge base and future cost expectations) to reach net carbon neutrality by 2050. In this scenario, Brazil achieves neutrality regardless of the ambitions and commitments of other countries and once again offering large-scale and attractive capital allocation opportunities.

The Alternative Transition (AT): scenario presents an alternative technological route for Brazil to achieve neutrality by 2050 considering the impacts of climate change itself on the energy sector and the uncertainties of new technologies. It is a variant of the Brazil Transition scenario, with greater restrictions to limit or induce the choice of technological routes through which the transition process will take shape.

The Global Transition scenario (GT): focuses on Brazil's contribution in a world that seeks to limit average increase in global surface temperature to 1.5°C in 2100 in reference to pre-industrial levels. The minimal global cost allocation among countries of a 400 $GtCO_2$ global carbon budget gives Brazil a 13.2 $GtCO_2$ carbon budget for 2010-2050.

MAIN CHARACTERISTICS OF EACH SCENARIO

	TRANSITION **BRAZIL**	TRANSITION **ALTERNATIVE**	TRANSITION **GLOBAL**
Environment international	Limited cooperation ("regional blocks")		Global cooperation ("Global village")
National context	Transition process defined by the Brazilian context		Transition process included in a global context
Approach	Minimal cost for carbon neutrality	Minimal cost, with CCS and water availability restrictions and assuming hydrogen and nuclear production	Minimal cost for global 1.5° optimum
Global production chains	Production more regionally-oriented		Onshoring strategic segments in global value chains
Carbon Budget	24.3 GtCO2	24.9 GtCO2	15.3 GtCO2
Emission neutrality in Brazil	CO2 in 2040 GHG in 2050	CO2 in 2040 GHG in 2050	CO2 in 2035 GHG in ~2050

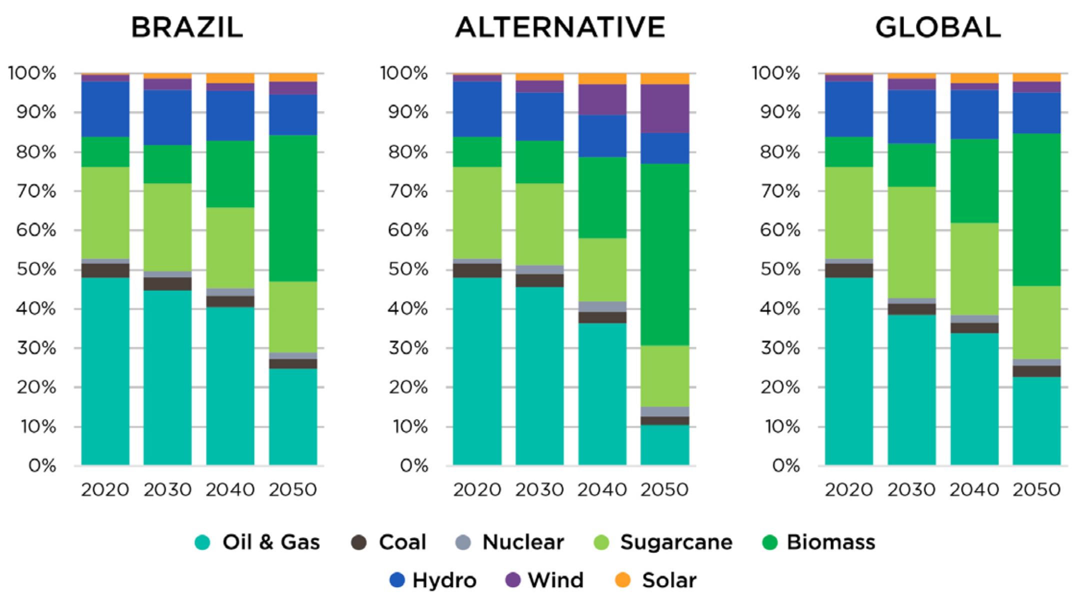
Energy Mix

Brazil is at an advanced stage of its energy transition process. Thanks to the significant share of modern renewable sources both in the power mix and in the fuel mix, the renewability level of Brazil's primary energy mix (49% in 2020) is almost triple the global average (14% in 2019) so that Brazil is uniquely poised to become a low-carbon economy. That said, our 30-year forward looking decarbonization scenarios require the dynamics of the energy mix to change in relation to its behavior in the preceding three decades. New energy instruments and guidelines will be necessary for Brazil to achieve its carbon neutrality ambition.

In our carbon neutrality scenarios primary energy demand grows in average 1.5% per annum to exceed 400 million toe by 2050. That is slightly more than half the growth rate seen in the last thirty years. Economic and population expansion are important drivers for the increase in demand for energy services, while efficiency gains operate to reduce demand.

The three scenarios examined present different primary energy mixes, both in terms of total supply and of the sources used. But all scenarios show decreased use of fossil fuels and increased use of renewable sources by 2050, with the latter exceeding 70% in all climate-neutral scenarios. This change is spearheaded by the growth in biomass, the source that will grow the most within Brazil's energy mix, followed by wind and solar power.

PRIMARY ENERGY USE BY SOURCE IN BRAZIL



Biomass plays a prominent role in the decarbonization of the transportation industry, especially in replacement of diesel oil and jet fuel, but also, in scenarios GT and BT, as a negative emission tool using BECCS (Bioenergy with Carbon Capture and Storage). The ongoing growth in installed generation capacity for wind and solar power will cause them to gain share within Brazil's mix.

Emissions

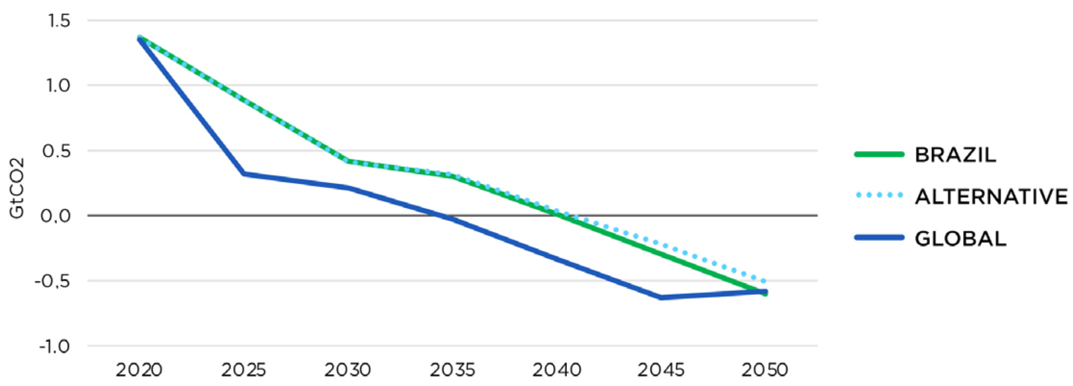
In 2020, Brazil emitted 2.16 billion tonnes of CO_2 equivalent (tCO_2eq), ranking among major annual global emitters. However, Brazil is considered a low-emission nation in per capita terms, with each Brazilian emitting, on average, 1.9 tCO_2eq. That corresponds to about 1/7 the emissions of a US citizen and 1/3 the emissions of an European or Chinese citizen.

Brazil's peculiarity is that its GHG generation is not strongly related to power generation but to changes in land use (deforestation) and to agriculture and livestock, which together represent 73% of Brazil's total emissions. While the energy sector is responsible for 76% of GHG emissions worldwide, in Brazil the energy mix answered for 18% of the country's gross GHG emissions in 2021 (SEEG, 2022).

The three decarbonization scenarios include structural changes in energy supply and demand. Scenarios BT and AT require saving some 30 billion tCO_2eq over the projection horizon for Brazil to reach zero net emissions by 2050. Scenario GT requires greater savings: some 40 billion tCO_2eq over the same time span.

For Brazil to become GHG-neutral by 2050, CO_2 neutrality must be achieved 10 years earlier, around 2035-2040. The fact that the three decarbonization scenarios (BT, AT and GT) involve around 500 million tonnes negative CO_2 shows how big the challenge is.

CO2 EMISSIONS, 2020-2050



Another significant finding given the need to have negative CO_2 emissions by 2040, is that if emissions from deforestation and from changes in land use cannot be eliminated, the energy sector will have to partially offset those emissions and at the same time address the remaining GHG emissions from hard-to-abate industries such as long-haul road freight transportation and carbon-intensive industrial processes. That will make the energy transition more costly and less competitive.

If illegal deforestation cannot be eliminated by 2028, it will be technically unfeasible for Brazil to reach net zero GHG emissions by 2050 even using immature technologies at later stages within the projection time horizon.

Agriculture, Forestry and Other Land Uses

The Agriculture, Forestry and Other Land Uses (AFOLU) sector accounts for most (73%) of Brazil's emissions and plays a key role in achieving carbon neutrality, offering an array of attractive low-cost mitigation options.

The AFOLU sector can use natural carbon removal options (nature-based solutions – NBS) that not only remove carbon but provide additional social and environmental benefits. Brazil shows great NBS potential (approximately 20% of global potential) and can reconcile food, energy and environmental objectives through the conversion of 61-85 million hectares of degraded pastures into native forests, planted energy forests and sustainable agriculture and cattle ranching areas.

Positive changes in land use, reforestation and forest restoration in particular, can have a very significant role in curbing emissions and in expanding the supply of energy. For example, degraded areas covering 3-6 million hectares are expected to be turned into planted forests (eucalyptus and pine) to meet the demand for biomass feedstock to produce cellulosic biofuels using the BTL route (biomass-to-liquids) to replace fossil fuels.

ENERGY SUPPLY

Power Generation

All scenarios projected show wind and solar sources as the main drivers of generation growth, which will push hydropower's share in the energy mix down to 30%-55%. This reflects, on the one hand, the restrictions to the construction of new hydropower projects with dams, because of their environmental and social impact, and, on the other hand, the very competitiveness of other renewable sources. The share of renewable sources in Brazil's power generation mix will continue to grow, surpassing 90%.

The flip side to power generation growth is the ensuing need to expand transmission lines within the National Interconnected System (SIN) to support the increased flow of power, with 181-221 GW growth until 2050. That expansion occurs both within subsystems and between them. We further assumed that new and more efficient transmission and distribution facilities will reduce transmission losses.

The high potential for wind and solar plants may seemingly indicate that the power industry will face no hurdle to contribute with Brazil's energy transition process. However, some challenges are intrinsically associated with the industry's modernization agenda. Modernization is necessary to change how the system is operated and how power is marketed. Those changes will help rearrange the source mix and will foster the introduction of new technologies and capacity at no additional cost or even reducing cost for consumers.

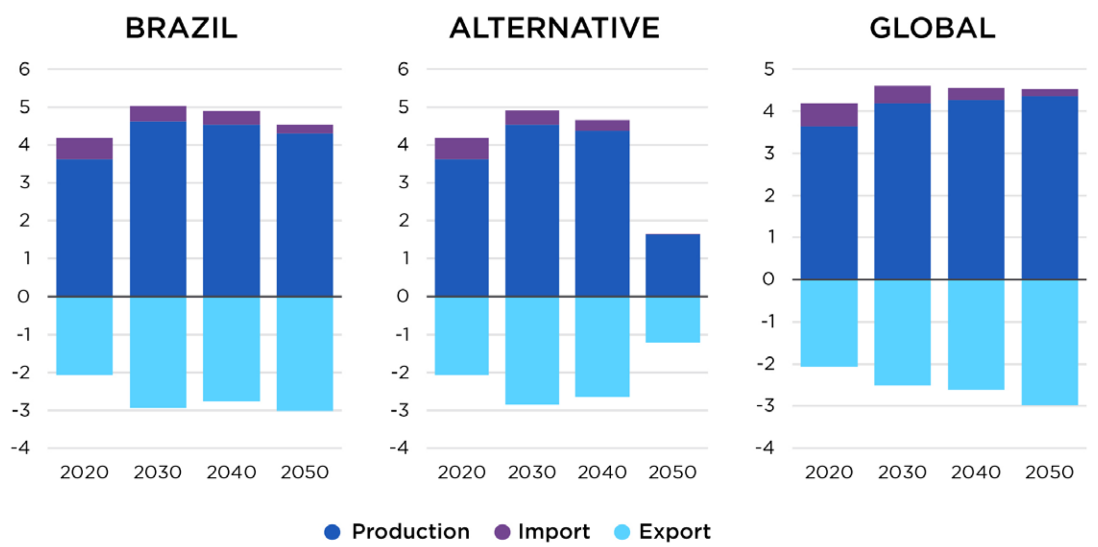
Oil, Natural Gas and Petroleum Products

Domestic demand for oil and natural gas declines over the projection time. Demand for petroleum products, in particular, contracts sharply in the long run as they are replaced by biofuels and as the vehicle fleet electrifies. Oil and natural gas will account for a smaller portion of Brazil's energy mix, around 10%-25% in 2050.

Brazil's oil production is expected to hold firm throughout the projection horizon as robust exports pick up the slack in domestic consumption. That will be possible because Brazil's oil shows triple resilience (technical, economic and environmental). The world average carbon intensity of oil is 22 kilograms of CO_2 per barrel of oil equivalent produced ($KgCO_2/b$). Brazil's oil is one of the least carbon-intensive and oils from the pre-salt layer go below 10 kg CO_2eq/b. It is indeed important for Brazil that its oil reserves remain competitive.

Oil will remain in use throughout the energy transition to meet national energy security needs. In the long run, global carbon neutrality scenarios project a residual demand for oil to serve hard-to-abate industries and non-energy purposes. Brazilian oil helps mitigate global GHG emissions by displacing more carbon-intense oils traded in the global market. This will become more significant in coming years because of greater energy efficiency, electrification and carbon removal (CCUS and forestry offset).

BRAZIL'S OIL PRODUCTION, EXPORT AND IMPORT



Similarly to oil, natural gas production is expected to grow in all scenarios (the exception is the last decade in scenario AT). But there are marked differences. First, imports will become marginal, concentrated on imports through pipelines (i.e., from Bolivia) and LNG imports will be negligible. Second, the increase in production will be absorbed by the domestic market without any dependence on the foreign market. In other words, domestic production will meet the growing domestic demand for industrial and home uses.

Reduced domestic consumption of gasoline, diesel oil and other petroleum products will significantly affect refining assets. Indeed, the refinery use factor will have fallen by 2050. In addition, refineries can be converted into biorefineries or energy complexes following an asset redesign logic aligned with the energy transition. The introduction of vegetable oil, residual oil (UCOS) and pyrolysis oil co-processing in refineries equipped with HDT and FCC units will push up the use factor. Co-processing inputs are expected to have around 10% biomass content by 2050. Another trend noted is the increase in petrochemical yields in later years reflecting the behavior of the consumption of petroleum products (for non-fuel purposes) in a low-carbon economy.

Biofuels

In addition to ethanol and biodiesel, advanced biofuels produced following different technological routes emerge as potential substitutes for their fossil counterparts, e.g., green diesel, aviation biokerosene, green gasoline and biofuels for maritime use.

The use of advanced biofuels will grow for two major reasons: (i) decarbonization of hard-to-electrify transportation activities such as air, sea and road freight transportation; (ii) CO_2 capture and storage will reduce emissions from other industries.

Biofuels are key for Brazil because existing technological arrangements for biofuel production, such as eucalyptus or pine synthesis, provide negative emissions through the capture and storage of atmospheric CO_2 (designated BECCS). The key importance of BECCS for Brazil's carbon neutrality is evidenced by the volume of carbon captured, reaching 274 and 369 million tonnes of CO_2 in 2050 in scenarios BT and GT, respectively.

Advanced biofuels may (especially in association with CCS) give Brazil a competitive edge in the next three decades thanks to Brazil's plentiful land, favorable agricultural and livestock productivity and experience in the field. Advanced biofuels may come to be a strategic investment in the transition to a low-carbon economy for several activities (e.g., for industrial use) not only as an energy source but also as input to make petrochemicals.

Hydrogen and Biomethane

Hydrogen's versatility is a boon to the energy transition. Its application as a direct source of low-carbon energy in hard-to-abate industries or as vector for energy storage enables a greater input of renewable power.

We estimate that by 2050 Brazil may be producing 21 to 32 million tonnes. Most of that hydrogen volume will be obtained indirectly during the energy transformation process as an intermediate vector for other applications such as the production of syngas for end-use synthetic fuels and in biofuel-powered batteries.

Direct hydrogen production for domestic use, obtained mainly through natural gas reform, ranges from 0.6 to 1 million tonnes in all scenarios. Scenario AT includes hydrogen production from renewable energy and some 4 million tonnes in green hydrogen exports (obtained through electrolysis using electricity from renewable sources) by 2050.

Biomethane is another gaseous fuel with an important role to play in energy transition scenarios. Demand is expected to reach 15-18 million m3/day by 2050. Biomethane enhances the value of thermal plants and gas pipelines because it “decarbonizes” natural gas and keeps the existing infrastructure in use.

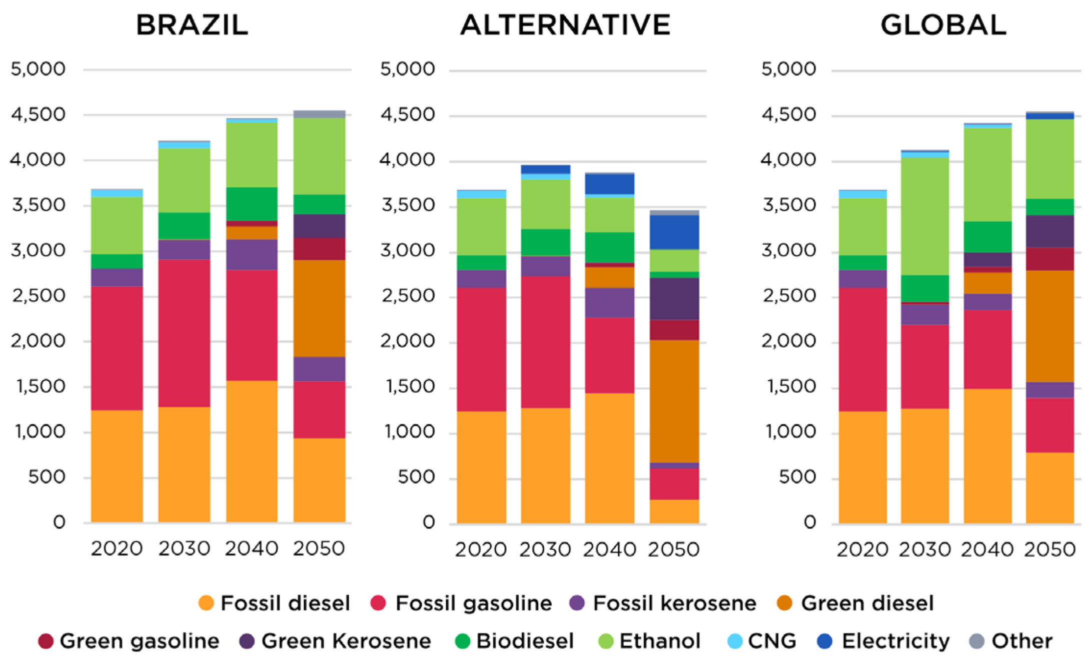
Energy demand by industry

Emissions from energy use correspond to only 18% of Brazil’s total emissions and transportation, industrial and residential uses answer for 3/4 of that percentage. The decarbonization of those activities faces at least three major challenges: (1) the expected growth in demand for energy services reflecting population and economic expansion. Even if some potential energy efficiency gains do come to fruition, emissions will likely increase and not decrease; (2) the technological solutions available to mitigate emissions for some applications need further development and scale; and (3) implementation costs remain high and funding and incentive mechanisms are incipient.

Brazil’s transportation industry is noteworthy because 25% of the energy used comes from renewable sources (biofuels), in comparison to a global average of less than 5%. Brazil has adopted decarbonization solutions that predate by many years electrification efforts that have been gaining traction elsewhere in the world. Its consolidated decades-old biofuel industry combined with a nationwide supply network and a significant fleet of flexfuel vehicles give Brazil a competitive edge.

Biofuels (advanced ones as of 2040 in particular) will be the main driver to decarbonize Brazil’s transportation industry. That said, the global automotive industry’s movements and strategies increasingly point to the introduction of electrification in their major markets so that the electrification of market niches is included in all scenarios and takes greater significance in scenario AT. Our scenarios point toward a number of electrification alternatives for the transportation industry (not only battery-powered vehicles) so that Brazil must find national solutions that can be included in the global automotive industry value chain such as, for example, the development of electric vehicles powered by ethanol-based fuel cells and the dissemination of hybrid flex technology to other markets.

ENERGY MIX OF THE TRANSPORTATION INDUSTRY (EJ)



Manufacturing adds to Brazil's total emissions both by burning fossil fuels and through industrial production processes. Efficiency gains and greater penetration of natural gas and biomass are the main decarbonization drivers in our scenarios. The biggest challenge for this sector lies in finding disruptive decarbonization technologies applicable to its greatest emitters, the metallurgy and cement industries, whose emissions are intrinsic to their production processes.

The energy demand of the residential and services sector is expected to grow by approximately 60% because of higher average income, wider equipment ownership and activity digitization and the increase in the number of consumer units. Electricity is the favored source to cater to that growth while reducing emissions. Our scenarios further project that liquefied petroleum gas (LPG) will be widely replaced by natural gas for cooking and heating applications, so that the sector's demand for natural gas soars 10-fold between 2020 and 2050.

Introduction

2

The IDB-CEBRI-EPE Energy Transition Program (PTE) was established to assess the constraints and the potential of Brazil's energy transition and to offer an independent and open contribution to the formulation of public policies geared towards Brazil's energy mix in 2050. Particularly by involving discussions with and the participation of different stakeholders, the Program from the outset aimed to help build consensus by supporting the analysis of critical uncertainties and by exploring scenarios and sensitivities. This report reflects the scenario construction process and the findings of their quantitative development (projections) and does not necessarily represent the opinion of the entities that participate in the Energy Transition Program.

Led by the Brazilian Center for International Relations (CEBRI), the Inter-American Development Bank (IDB), the Energy Research Company (EPE) and the Center for Energy and Environmental Economics (CENERGIA), this innovative program was divided into three phases (diagnosis, convergence and scenario development) in order to situate Brazil in the process of global society's understanding of the consequences of climate change and of progress in the development of sustainable energy technologies.

PHASE 1

The purpose of the **diagnosis phase**, in the 1st half of 2021, was to map major trends and critical uncertainties through a series of virtual debates with experts, the public at large and stakeholders. It resulted in the publication, in December 2021, of a white paper consolidating the insights obtained.

The phase 1 guiding questions were:

A.

What are the structural effects of the pandemic on the global energy sector and what are their consequences for Brazil?

B.

What technologies and energy sources make the most sense for Brazil in its effort to comply with climate agreements?

C.

Which alternatives bring the greatest benefits to Brazil? What is each industry's contribution to this process?

PHASE 2

The **convergence phase** began in the 2nd half of 2021 and sought to consolidate a vision of the future for the main explanatory variables identified in the preceding phase.

PHASE 3

Scenario development phase where future scenarios were modeled based on the methodology used by Cenergia/PPE/COPPE/UFRJ. The findings for each scenario will be described in this report.

3

Energy Transition Scenarios for Brazil

The purpose of the Energy Transition Program is to identify paths for Brazil to reach carbon neutrality. Three different scenarios were prepared that converge on Brazil reaching zero net greenhouse gas (GHG) emissions in 2050, to wit: (i) Brazil Transition (BT); (ii) Alternative Transition (AT) and (iii) Global Transition (GT).

In scenarios BT and AT, net zero emissions for all greenhouse gases are achieved in 2050, which implies zero CO_2 emission around 2040. In scenario GT, the emission reduction path is associated with the global carbon budget (400 Gt CO_2eq) available to meet the 1.5°C global temperature increase ceiling. Using a minimal cost global allocation gives Brazil a 13.2 GtCO_2eq carbon for 2010-2050, which means net zero emissions for all greenhouse gases will be achieved a few years after 2050 but that CO_2 emissions must drop to zero just before 2040.

We shall see that for Brazil to achieve its carbon neutrality goal it is imperative to change course in certain aspects and to foster and/or develop technologies that can drive decarbonization at the proper pace.

TABLE 1. MAIN CHARACTERISTICS OF EACH SCENARIO

	TRANSITION **BRAZIL**	TRANSITION **ALTERNATIVE**	TRANSITION **GLOBAL**
Environment international	Limited cooperation ("regional blocks")		Global cooperation ("Global village")
National context	Transition process defined by the Brazilian context		Transition process included in a global context
Approach	Minimal cost for carbon neutrality	Minimal cost, with CCS and water availability restrictions and assuming hydrogen and nuclear production	Minimal cost for global 1.5° optimum
Global production chains	Production more regionally-oriented		Onshoring strategic segments in global value chains
Carbon Budget	24.3 GtCO2	24.9 GtCO2	15.3 GtCO2
Emission neutrality in Brazil	CO2 in 2040 GHG in 2050	CO2 in 2040 GHG in 2050	CO2 in 2035 GHG in ~2050

To quantify our policy recommendations and to calculate the magnitude of private investment for each of the three carbon-neutrality scenarios, we created a Business As Usual (BAU) trend based on current policies and actions related to the energy system and to change in land use, such as:

i. Current and committed installed capacities for power generation sources, refineries, distilleries, power transmission and distribution assets;

ii. Completion of the Angra 3 nuclear power plant between 2025 and 2030;

iii. Continued operation of the Jorge Lacerda coal-fired power plant until 2040;

iv. Implementation of a mandatory 20% biodiesel mixture (volume-based, B20) as of 2028;

v. Decarbonization goals of the International Maritime Organization (IMO) and of the International Air Transport Association (IATA) with 50% emission reduction targets in 2050 in relation to 2008 and 2005 emissions levels, respectively;

vi. Current agricultural production technologies and adherence to the Low Carbon Agriculture Plan (ABC Plan);

vii. Reduction of illegal deforestation to the minimum historical level of 400,000 hectares/year, both in the Cerrado and in the Amazon biomes, starting in 2028 and until the end of the projection period.

3.1. Brazil Transition Scenario (BT)

The Brazil Transition scenario was shaped to reflect Brazil's commitments under its Nationally Determined Contribution (NDC) to find the optimal cost-efficient path (based on Brazil's resources, knowledge base and future cost expectations) to reach net carbon neutrality by 2050.

In this scenario, Brazil achieves neutrality regardless of the ambitions and commitments of other nations. Indeed, in a world where the lack of cooperation and global governance for energy transition prevails, Brazil emerges as a green power on the international arena, significantly improving its image with foreign investors and once again offering large-scale and attractive capital allocation opportunities.

International multilateral agreements for the transition to a low-carbon economy, including COP, struggle to align interests and to coordinate the actions needed to maintain the goals agreed to during COP21. Discussions and engagement never cease but energy transition funding issues and conflicts between Western and Eastern blocs make it difficult to build consensus and to take decisions in global forums.

In a world where the lack of cooperation and global governance for energy transition prevails, Brazil emerges as a green power on the international arena, significantly improving its image with foreign investors.

This scenario is marked by significant setbacks with regard to the global environmental and climate agenda. There is no consensus around what a fair transition will look like from the point of view of the distribution of responsibilities and efforts to achieve the commitments and goals stipulated in the Paris Agreement. With the degradation of global coordination, some regional leaders see the opportunity to boost their economic growth rates by harnessing the potential in low-carbon industries. Brazil may become one such leader by putting energy and environmental policy at the core of the discussion around how to spark economic growth.

Many nations choose their domestic transition strategies focusing on national solutions and betting on the best technological routes for their capabilities and resources. This is Brazil's case, whose goal is to achieve emissions neutrality by 2050. Although Brazil continues to participate in international forums, the path is chosen domestically based on the target the Brazilian government defined and announced in 2022. The choice for a national path stems from Brazilian society's understanding that Brazil must position itself as an energy transition leader through a strategy and choices based on its skills and resources so that its energy advantages will bear fruit as opportunities that spark economic growth, technological modernization, more investments, jobs and income. Generally speaking, that Brazilian transition involves the formation of convergences, robust articulation between government and non-government players, policy coordination, a long-term roadmap and investment. Public opinion strengthens consensus in favor of the transition strategy and the financial sector supports a cost-efficient transition path.

Brazilian society is going through a far-reaching transformation process that puts energy transition within a social and human development paradigm. Public resources, including those originating from income created by the oil and gas industry, are earmarked to fund education, technological transformation and the creation of an environment that is conducive to innovation and to a low-carbon economy.

Political leaders from across the ideological and party spectrum converge on the potential gains that investments in renewable sources will provide for Brazil's economy and society. Government budget discussions, for example, prioritize tax and fiscal actions that can foster the development of Brazil's green economy. This scenario requires the large-scale involvement of civil society in environmental and climate issues through the realization of the benefits to be acquired if Brazil is seen as a world leader in the development of a low carbon economy.

That context encourages different economic groups to align in defense of an economic model driven by decarbonization investments. From a public policy management perspective, the officials who define government incentives use a cost-benefit approach to encourage those industries and technologies that are better suited to the Brazilian reality.

Convergence around a growth model based on the decarbonization of the economy is key to minimize Brazil's political and institutional instabilities. That creates a business environment that is very conducive to investments that can consolidate the green infrastructure needed to meet Brazil's economic needs.

The path towards net zero GHG emissions by 2050 requires:

i. That aggregate GHG emissions from all sources and industries, i.e., all remaining emissions in Brazil, be offset by technologies or methods to remove GHG from the atmosphere, such as reforestation/afforestation and carbon capture and storage (carbon capture and use or storage – CCUS);

ii. Curbing GHG emissions through technological innovations and disruptions, as a way for Brazil to become emissions-neutral by 2050; and

iii. Achieving zero deforestation as of 2028 and the IMO and IATA decarbonization goals as of 2023.

3.2. Alternative Transition Scenario (AT)

The Alternative Transition (AT) scenario presents an alternative technological route for Brazil to achieve neutrality by 2050 considering the impacts of climate change itself on the energy sector and the uncertainties of new technologies. It is a variant of the Brazil Transition scenario, with greater restrictions to limit or induce the choice of technological routes through which the transition process will take shape.

This scenario simulates an alternative path affected by: (i) lower hydropower generation; (ii) greater nuclear power generation capacity; (iii) economic unfeasibility of carbon capture and storage solutions; (iv) increased use of biomethane; (v) greater electrification of the fleet of light and heavy passenger and freight vehicles.

In this scenario, Brazil again achieves net emissions neutrality by 2050. As in scenario BT, this path is supported by consensus around a transition strategy that aligns carbon neutrality with economic development. But some organized groups from specific industries take the front seat in the consensus creation process seeking to induce investments in certain decarbonization solutions. We indicate an alternative path that can tackle the technological risks and uncertainties inherent to the energy transition process.

In this scenario, Brazil again achieves net emissions neutrality by 2050.

Because those technological routes were not chosen (or were less favored) in the original optimization exercise (scenario BT), greater participation will require additional restrictions and further inducement through public policies to, for example, foster vehicle fleet electrification, the production of hydrogen for export and nuclear power generation. Legislation, tax incentives and government investments will be associated with certain technologies. The Government acts to co-create and co-develop markets, aligning the instruments available such as government procurement and taxation.

The perception is that, thanks to its natural resources, Brazil should take the lead in the active development of certain technologies so as to appropriate the income generated by the energy transition business. That leadership will contribute to leverage Brazil's development. In this scenario, traditional industries lose ground and the oil and gas industry, in particular, has a smaller role in the transition process.

The AT scenario's key differences are climate or technological constraints and energy and technological policy choices such as:

a. Reduction in hydropower generation potential (less hydropower availability for dispatch) due to societal opposition to new plants with large dams/reservoirs, to their environmental costs and, mainly, to more droughts in consequence of climate change or of mesoclimatic alterations underway in Brazil or of conflicts over the multiple use of water. That restriction causes the capacity factor of hydropower plants to drop in average by 17% for small plants and by 32% for large ones, varying between regions in Brazil[1].

1. Those reductions were based on Vasquez-Arroyo et al., (2020) and on Brazil's "Fourth National Communication to the United Nations Framework Convention on Climate Change" (MCTI, 2020).

TABLE 2. VARIATION IN CAPACITY FACTORS

	MEDIUM-SCALE HYDROPOWER		LARGE-SCALE HYDROPOWER	
	BT scenario	AT scenario	BT scenario	AT scenario
South	54%	53%	54%	49%
Southeast	54%	47%	59%	43%
Midwest	54%	47%	59%	45%
Northeast	54%	38%	54%	31%
North	54%	39%	49%	29%

b. Nuclear energy can significantly contribute to the reduction of GHG emissions, as well as increase the resilience of the robustness of the Brazil's power systems during the energy transition. This scenario projected that 4 GW installed capacity will be added, bringing Brazil's nuclear power generation capacity to 8 GW by 2050[2];

c. Competitive difficulties in adopting carbon capture and storage or use technologies, in order to find how the energy system will react to their unavailability;

d. Brazil will be competitive in low-carbon hydrogen and will answer for about 10% of the international market, exporting 4 million tonnes of hydrogen produced from water electrolysis in 2050[3];

e. Brazil will be competitive in biomethane and the domestic market will take 10 million Nm^3/day by 2030[4];

f. Electromobility assumptions aligned with the International Energy Agency's (IEA) report "Net Zero by 2050 A Roadmap for the Global Energy Sector" (IEA,2021). The values used in the IEA report were shifted by 10 years to account for the lag in the introduction of technologies in the domestic market in comparison with their global implementation speed.

2. We ran two exercises using PNE 2050 as reference, assuming 8 GW and 10 GW in new nuclear power generation. We simulated two cases: 1. 50% reduction in CAPEX and OPEX, which results in around 20GW by 2050; 2. Public policy put in place based on Brazilian Nuclear Policy (decree 9600/2018) to introduce 8GW to 10 GW in new nuclear power by 2050.

3. We used as reference for this assumption McKinsey's report " Hidrogênio verde: uma oportunidade de geração de riqueza com sustentabilidade, para o Brasil e o mundo". The report found that Brazil has the potential to competitively capture USD 1 to 2 billion in US and EU imports by 2030. Exports could reach USD 4 to 6 billion, or 2-4 million tonnes, by 2040. The AT scenario considered that Brazil's exports will get to 4 million tonnes in 2050 because reaching that figure will require fast-paced production growth. See https://www.mckinsey.com/br/our-insights/hidrogenio-verde-uma-oportunidade-de-geracao-de-riqueza-com-sustentabilidade-para-o-brasil-e-o-mundo

4. Our reference was the indication in PDE 2030 that Brazil potentially can produce 3.8 billion Nm^3 of biomethane in 2030 (equal to 10 M Nm^3/day) from vinasse and filter cake derived from the projections for ethanol and sugar production. See Ten-Year Energy Expansion Plan 2030 (PDE 2030), page 268. https://www.epe.gov.br/sites-pt/publicacoes-dados-abertos/publicacoes/PublicacoesArquivos/publicacao-490/PDE%202030_RevisaoPosCP_rv2.pdf

3.3. Global Transition Scenario (GT)

The Global Transition Scenario focuses on Brazil's contribution in a world that seeks to limit average increase in global surface temperature to 1.5°C in 2100 in reference to pre-industrial levels. This scenario assumes that Paris Agreement goals will not be achieved if GHG emissions are not immediately reduced and that Brazil is responsible for a portion of the global carbon budget. The minimal global cost allocation among countries of a 400 $GtCO_2$ global carbon budget gives Brazil a 13.2 $GtCO_2$ carbon budget for 2010-2050.

Brazil's energy transition process is integrated with and subordinated to the dynamics of international agreements. The COP is the major guiding entity for global action to reduce greenhouse gas emissions.

Led by China, the US and Europe, the international community reaches a consensus on how best to allocate the efforts required to achieve the goals set by the COP. From the point of view of international geopolitics, environmental and energy issues are a key pillar of a process of greater convergence between Western and Eastern powers.

The efforts to coordinate the environmental and climate actions of major powers help ease the current tension between the US and Western Europe, on the one hand, and China and Russia, on the other hand. International climate and energy authorities successfully show public policymakers in those countries that the fragmentation of the world and the reduction in trade and in technological collaboration to develop a low-carbon economy will delay the energy transition by decades and could trigger new social tensions and effectively jeopardize the survival of the planet.

From the point of view of international geopolitics, environmental and energy issues are a key pillar of a process of greater convergence between Western and Eastern powers.

In addition, the pandemic and the conflict between Ukraine and Russia show the importance of coordinating actions to push the transition process ahead. Investment must be encouraged and energy supply must be adapted so that the transition process will not cause energy inflation that will aggravate regional inequalities.

In summary, the decisive action of those stakeholders helps coordinate the balance of power between global powers to prevent a reversal in the dynamics of energy transition process in the medium term.

In Brazil, the scenario is marked by greater coordination between public policy makers in the economic, energy and environmental areas. Those players manage to put into practice the necessary action to reach the goals stipulated under global agreements. In that reality, Brazilian authorities effectively fight illegal deforestation in line with the desires and actions of the international community (negotiation of agreements, instruments and conditions for access to markets, trade or investment compensations, representation in multilateral entities, organizations or initiatives, etc.). Brazil adopts the cap-and-trade model as a reference for the implementation of its domestic carbon market.

In this scenario, the friendly welcome Brazil receives in the energy and environmental diplomatic arena puts the country in the international spotlight and leaves it well poised to attract from multiple countries significant foreign direct investment on the development of Brazil's renewable energy potential, low- carbon and carbon removal technologies.

Although achieving carbon neutrality in 2050 is not a requirement of the model for this scenario, considering current emissions volume and characteristics, Brazil does have to converge to carbon neutrality by 2050.

4 General Findings

4.1. Energy Mix

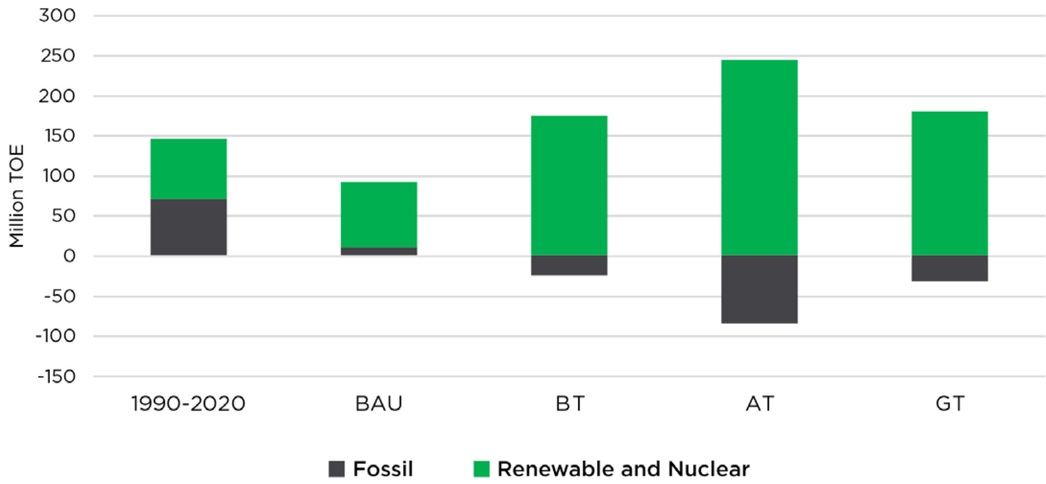
Brazil is at an advanced stage of its energy transition process. Thanks to the significant share of modern renewable sources both in the power mix and in the fuel mix, the renewability level of Brazil's primary energy mix (49% in 2020) is almost triple the global average (14% in 2019) so that Brazil is uniquely poised to become a low-carbon economy.

That said, our 30-year forward looking decarbonization scenarios require the dynamics of the energy mix to change in relation to its behavior in the preceding three decades and to current energy policies (BAU exercise). New energy instruments and guidelines will be necessary for Brazil to achieve its carbon neutrality ambition.

Between 1990-2020 Brazil's primary supply grew in average by 2% and the extra 146 million toe (tonnes of oil equivalent) were evenly supplied by fossil and renewable sources.

As the chart below shows, between 1990-2020 Brazil's primary supply grew in average by 2% and the extra 146 million toe (tonnes of oil equivalent) were evenly supplied by fossil and renewable sources. Primary supply will grow by 149-161 million toe until 2050 depending on the neutrality scenario and renewable sources need to account for all that growth and to displace 24-84 million toe from fossil sources.

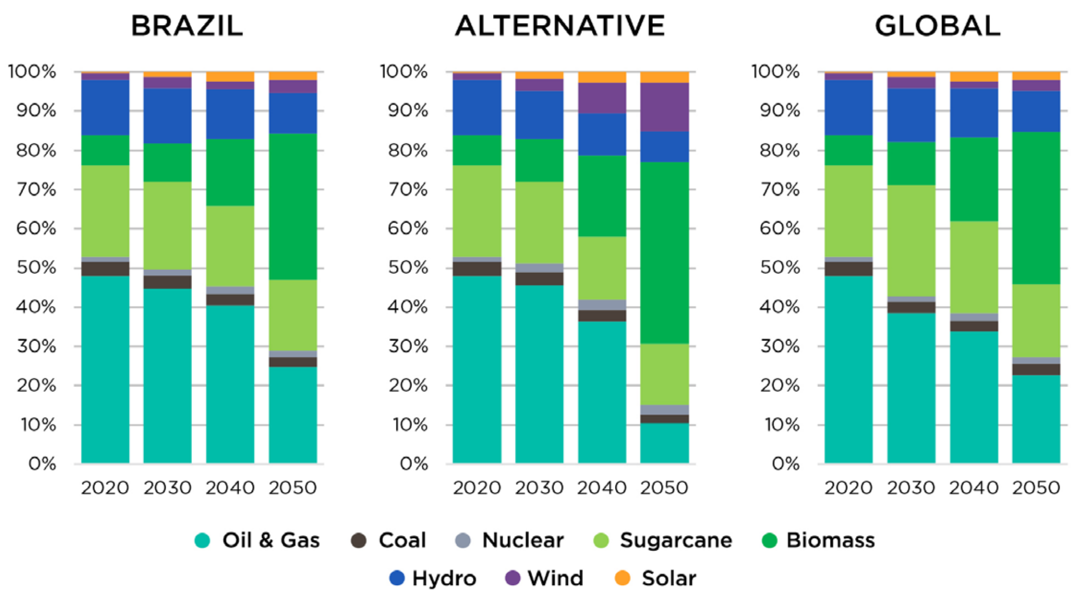
CHART 1 CHANGE IN PRIMARY ENERGY SUPPLY IN BRAZIL (2020-2050)



In our carbon neutrality scenarios primary energy demand grows in average 1.5% per annum to exceed 400 million toe by 2050. That is slightly more than half the growth rate seen in the last thirty years. Economic and population expansion are important drivers for the increase in the consumption of energy services, while efficiency gains operate to reduce demand.

The three scenarios examined present different primary energy mixes, both in terms of total supply and of the sources used. But all scenarios show decreased use of fossil fuels and increased use of renewable sources by 2050.

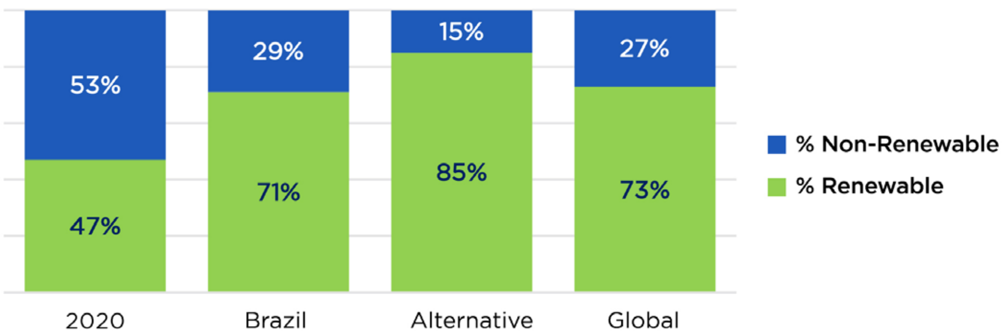
CHART 2 PRIMARY ENERGY USE BY SOURCE IN BRAZIL



The demand profile varies significantly over the projection horizon, with renewable sources exceeding 70% in all climate neutral scenarios, as illustrated in the chart below, Share of renewable sources in Brazil. This change is spearheaded by the growth in biomass, the source that will grow the most within Brazil's energy mix, followed by wind and solar power. Biomass plays a prominent role in the decarbonization of the transportation industry, especially in replacement of fossil-based diesel oil and jet fuel, but also, in scenarios GT and BT, as a negative emission tool using BECCS (Bioenergy with Carbon Capture and Storage) technologies, (see section Biofuels).

The use of biomass in those scenarios not only addresses the competitiveness of transportation technologies but also enhances the systemic optimization of the decarbonization of the economy. Demand for various liquid fuels, petrochemical naphtha and LPG has to be met while at the same time the GHG emissions from hard-to-abate industries such as aviation, maritime transportation and long-haul road freight transportation have to be offset[5]. Drop-in biofuels can be directly fed into vehicles and can be shipped and distributed using the current infrastructure. The fleet need not be renewed for technological reasons, fewer new power plants and transmission and distribution assets will be needed. The production of biofuels benefits from scope savings because green fuels can be produced jointly, that is, the production of green diesel will result in the production of green kerosene, gasoline and heavy oil. It follows that our model finds the decarbonization of all segments within the transportation industry to be cost-effective (see Müller-Casseres et al., 2021, 2022, Oliveira et al., 2021).

CHART 3 SHARE OF RENEWABLE SOURCES IN BRAZIL IN 2050



Wind and solar sources also play an important role in all decarbonization paths, more significantly in terms of installed capacity than of energy generation (see section Power Ìndustry). Wind power gains special significance in scenario AT to serve a more electrified transportation industry than in the other scenarios.

5. The model opts for the biofuel solution on routes where capture is easier (BTL and 2nd generation ethanol) in scenarios involving BECCS (GT and BT) in order to offset residual emissions (mainly from petroleum products). In the non-BECCS scenario (AT), the model needs the Fischer-Tropsch route (alternatively, the Alcohol-to-Jet and Alcohol-to-Diesel route) to produce fuels that manage to replace conventional jet fuel and mineral diesel earlier. The model needs some replacement - in the latter case, of petroleum products in hard-to-abate industries - to achieve zero net emissions.

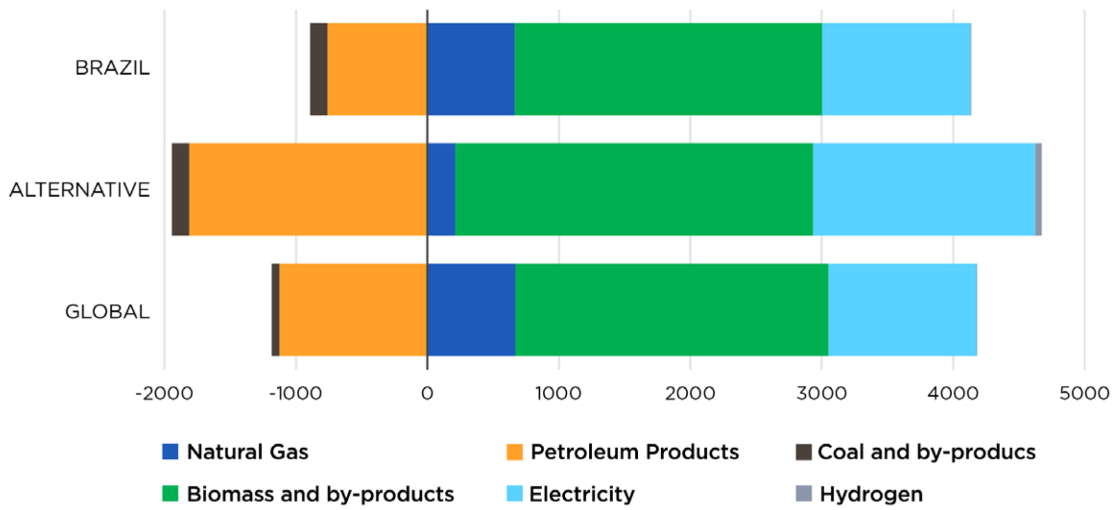
Oil is the source whose share in the energy mix drops the most in all scenarios, going as low as 5% by 2050 in scenario AT. That because the carbon capture and storage (CCS) technologies that enable negative emissions in other climate neutral scenarios face more competitiveness hurdles in scenario AT. The absence of CCS reduces the room for petroleum products, making it necessary to accelerate the implementation of cellulosic fuel production routes.

This is a clear sign that the consumption of fossil fuels must be reduced in energy transition scenarios through their replacement with renewable fuels. This indicates the importance of implementing robust national research and development strategies for cellulosic fuels and CCS. That is corroborated by the International Energy Agency's report Net Zero by 2050 (IEA, 2021), whose recommendation to cut by 80% current fossil energy consumption has considerable repercussions on oil refineries.

The "hydro" and "sugarcane products" sources, which currently give Brazil's energy mix its strongly renewable character, will begin to share their protagonism with other biomasses. Although those traditional sources lose share over time, they grow in absolute terms in all scenarios.

The chart below breaks down primary energy variation by source between 2020 and 2050 in toe.

CHART 4 ACCUMULATED VARIATION IN PRIMARY ENERGY (2020-2050)



4.2. Emissions

In 2020, Brazil emitted 2.16 billion tonnes of CO_2 equivalent (tCO_2eq), ranking among major annual global emitters. However, Brazil is considered a low-emission nation in per capita terms, with each Brazilian emitting, on average, 1.9 tCO_2eq. That corresponds to about 1/7 the emissions of a US citizen and 1/3 the emissions of an EU or Chinese citizen.

Brazil's peculiarity is that its GHG generation is not strongly related to power generation but to changes in land use (deforestation) and to agriculture and livestock, which together represent 73% of Brazil's total emissions. While the energy sector is responsible for 76% of GHG emissions worldwide, in Brazil the energy mix answered for 18% of the country's gross GHG emissions in 2021 (SEEG, 2022). That because almost half the Brazilian energy mix comes from renewable sources.

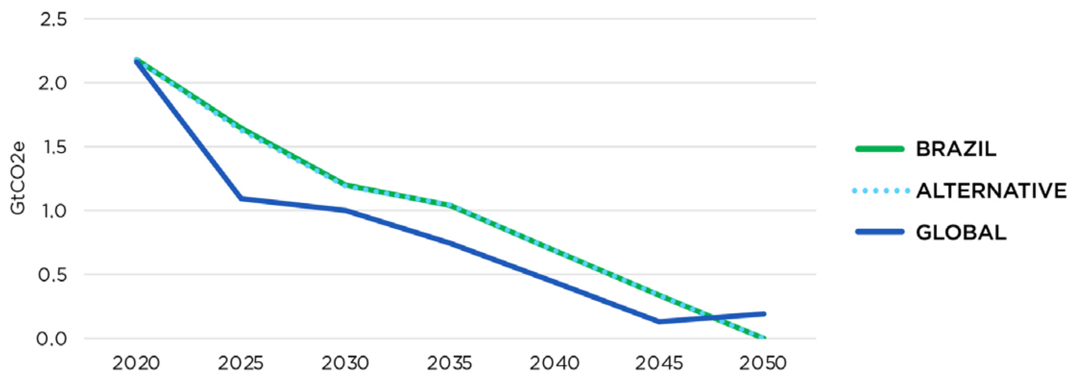
Brazil's energy-related emissions reached 393.7 million tCO_2eq in 2020 (SEEG, 2021). Breaking down energy-related emissions by industry will show how much each consumption group has to contribute to the success of climate targets. Transportation (47%), Fuel Production (18%), Power Generation (8%), and Manufacture (17%) account for almost 90% of Brazil's emissions from energy use.

The decarbonization of those activities faces at least three major challenges. The first is the expected growth in their demand for energy services. In other words, everything remaining the same, emissions will likely increase and not decrease. Second, the technological solutions available for some applications need to be further developed and scaled and, last but not least, their implementation costs are high and funding and incentive mechanisms still fall short of expected needs.

The energy transition needed for Brazil to achieve climate neutrality during the 2050s must include structural changes in energy supply and demand in all three scenarios. Brazil's GHG emissions reach the desired reduction if mitigation efforts succeed. That will save some 30 billion tonnes of CO_2 equivalent over the projection horizon and will lead to zero net emissions by 2050 in scenarios BT and AT. See chart Greenhouse Gas (GHG) Emissions, below. In the GT scenario, Brazilian emissions are part of a coordinated global effort to limit temperature increase to 1.5°C by 2100. That will require a greater emission mitigation effort, about 40 billion tonnes of CO_2 equivalent over the same time horizon, although net zero emissions are reached during the 2050s.

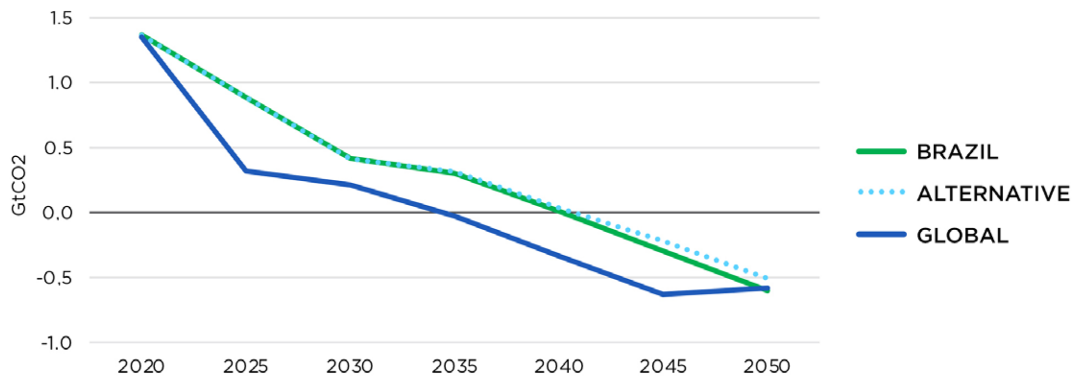
The energy transition needed for Brazil to achieve climate neutrality during the 2050s must include structural changes in energy supply and demand in all three scenarios.

CHART 5 GREENHOUSE GAS (GHG) EMISSIONS, 2020-2050



Our decarbonization scenarios assume that carbon neutrality includes zero net emissions for all GHGs. For Brazil to become GHG neutral by 2050, CO_2 neutrality must be achieved 10 years earlier, around 2040. The chart below shows CO_2 emissions to be negative by around 500 million tonnes in 2050 in all three decarbonization scenarios (BT, AT and GT).

CHART 6 CO2 EMISSIONS, 2020-2050



The preceding charts illustrate the scale of the challenge and show there is much to be done for Brazil to become climate neutral. The emissions path projected in our decarbonization scenarios indicate that current policies (BAU, Business As Usual) are inadequate despite the expected increase in the share of renewable sources in Brazil's mix.

Another significant finding, given the need to have negative CO_2 emissions by 2040, is that if emissions from deforestation and from changes in land use cannot be eliminated, the energy sector will have to partially offset those emissions and at the same time address the remaining GHG emissions from hard-to-abate industries such as long-haul road freight transportation and carbon-intensive industrial processes. That will make the energy transition more costly and less competitive.

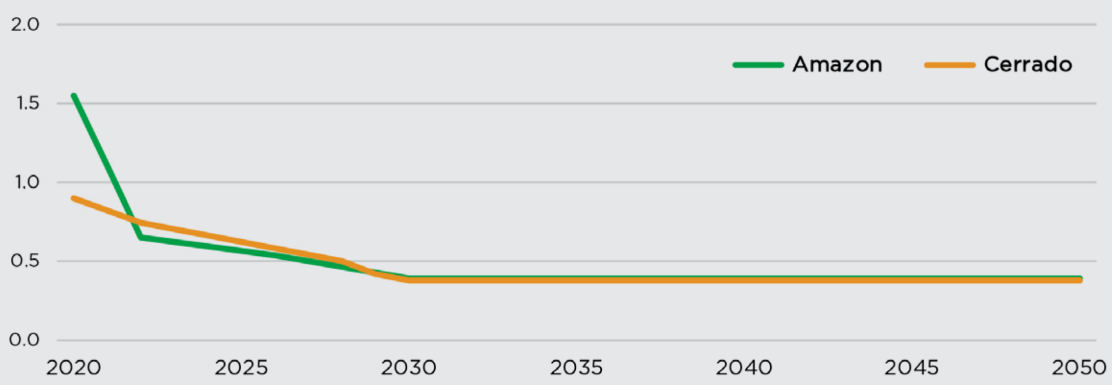
The conclusion is actually worse. If illegal deforestation cannot be eliminated by 2028, it will be technically unfeasible for Brazil to reach net zero GHG emissions by 2050 even using immature technologies at later stages within the projection time horizon (see box below).

Neutrality with deforestation is unfeasible

In order to test the impact emissions from deforestation and changes in land use have in achieving carbon neutrality, we ran a sensitivity analysis replicating the BT scenario with some level of deforestation and with no forest cover restoration and/or reforestation to offset those emissions. The sensitivity exercise considered that deforestation rates will be reduced until 2028 and will thereafter remain stable at 400,000 ha/year in the Amazon and Cerrado regions, the lowest historical level ever recorded in Brazil, until the end of the projection.

The fact that the sensitivity analysis could find no viable carbon neutrality paths means that continued deforestation contributes so much CO_2 emissions, around 220 million tCO_2 annually, or 11.5 billion tCO_2 in 2020-2050, as to make it impossible to find realistic solutions for the energy sector to offset those emissions. That occurs even in the face of a very ambitious array of disruptive technologies such as different hydrogen production alternatives, different renewable sources for power and fuels, electromobility (including fuel cells), and countless CO_2 capture possibilities, including direct air capture (DAC). Without those savings, achieving neutrality will require some US$ 3.4 trillion in offset costs at the carbon market for Brazil to comply with its NDC commitments.

CHART 7 ILLEGAL DEFORESTATION (THOUSAND HE/YEAR)



The sensitivity analysis shows that, even implementing all possible technologies by 2050, it is impossible to realistically offset in a time span of less than three decades the high emissions from deforestation.

For Brazil to fulfill its ambition, declared in the Glasgow COP, to become carbon neutral by 2050 without curbing deforestation, the associated positive emissions will have to be offset through the purchase of carbon credits at an additional cost of US$3.4 billion (assuming a carbon price of US$350/$tCO_2$ eq).

The pertinent cost can be calculated by comparing the difference in emissions between the BT scenario and the sensitivity analysis described in the Box above (BT with deforestation). Achieving climate neutrality by 2050 requires plugging a 761 million tCO_2 hole between the two scenarios in that year. Offsetting that much emissions through the acquisition of carbon credits will cost Brazil 53 to 266 billion dollars in 2050 considering carbon credits to be priced at between 70 and 350 dollars per tonne[6]. Assuming Brazil will gradually reduce emissions and purchase carbon credits in the course of the projection horizon, 9,764 million tCO_2 will have to be offset at a total cost of 683 billion to 3.4 trillion dollars.

4.3. Agriculture, Forestry and Other Land Uses

The "Agriculture, Forestry and Other Land Uses" (AFOLU) sector encompasses both the change in plant cover (land use change) and the implementation of different types of agricultural and livestock activities (land use). This sector uses different types of production mechanisms with or without climate mitigation efforts, which differ across Brazilian regions according to edaphoclimatic conditions and to labor intensity levels.

As discussed in the preceding section, the AFOLU sector accounts for most (73%) of Brazil's emissions and plays a key role in achieving neutrality, offering an array of attractive low-cost mitigation options. In other words, the greater the reduction in emissions in the AFOLU sector, the lesser the pressure on the energy sector for the early and costly introduction of solutions to reduce its emissions, favoring a lower-cost energy transition for Brazil.

The AFOLU sector includes natural carbon removal options (nature-based solutions – NBS[7]) that not only remove carbon but provide additional benefits such as: resilience of communities to the impacts of climate change; water security and promotion of biodiversity as the cornerstone of ecological balance; biological control of pests and diseases; as well as the maintenance of ecosystem services that benefit people and are vital for human well-being and for economic activities.

Indeed, NBS have the potential to deliver by 2030 at least one-third of the cost-effective CO_2 reduction needed to bring emissions in line with Paris Agreement targets (2°C target)[8]. The IPCC scenarios, which offer many pathways to net-zero emissions, show that NBS makes transition faster and less costly, whether by reducing emissions from land use changes (avoiding the degradation of ecosystems and managing agriculture) or by expanding natural sinks through restoration and reforestation, despite the risks associated with the permanence of stored carbon.

6. The carbon price values considered are in line with the uncertainty spectrum considered in the literature. See Bertram, et al., Energy system developments and investments in the decisive decade for the Paris Agreement goals. Environ. Res. Lett. 16 (2021).

7. Natural climate solutions or nature-based solutions (NBS) encompass the conservation, restoration and sustainable use of forests, pastures, mangroves, agricultural lands, wetlands and other ecosystems that increase carbon storage and/or avoid GHG emissions, focusing on mitigating climate change and increasing climate resilience.

8. According to Goodman and Herold (2014) "Why Maintaining Tropical Forests Is Essential and Urgent for a Stable Climate", tropical forests alone could reduce current global emissions by 24-30%.

A positive fact is that Brazil shows great NBS potential. The country accounts for approximately 20% of global potential and is uniquely positioned both in terms of volume and of cost-effectiveness[9].

The findings of our decarbonization scenarios confirm that potential. All scenarios show growth in forest area through the combination of no deforestation with higher levels of reforestation. Scenario AT requires the reforestation and/or ecological restoration of 40 M ha for Brazil to meet the proposed goals. At the COP 26, in Glasgow, Brazil committed to restoring and reforesting 18 million hectares of forests by 2030.

Reforestation and ecological restoration not only contribute to lower emissions but can also create plentiful jobs. A recent report found that the ecosystem restoration chain can directly create 1 million to 2.5 million jobs if Brazil restores 12 million hectares by 2030, assuming that the active restoration of 100 hectares has the potential to generate 42 jobs[10].

Reforestation and ecological restoration not only contribute to lower emissions but can also create plentiful jobs.

The recovery of degraded pastures and the conservation of forests can also significantly contribute to the emissions reduction effort. Our quantification exercises indicate that 29, 27 and 51 million hectares of pastures can be recovered in scenarios BT, AT and GT, respectively. The recovery process occurs because carbon storage below ground in recovered pastures (and also in good-quality ones) requires low investment and maintenance costs for this type of pasture land. Recovered pastures also offer better feeding conditions. Livestock will consume material of higher nutritional value and will see its "fattening rate" go up, generating more income for ranchers in a shorter time span. This reduction in degraded land acreage is important to ease the pressure the expansion of arable land for biofuel production puts on natural vegetation areas in all decarbonization scenarios.

Additionally, scenarios BT, AT and GT project Brazilian planted forests (eucalyptus and pine) will grow by approximately 3.3, 3.5 and 5.9 million hectares in 2050[11], respectively. This expansion is mainly due to the demand for biomass to produce cellulosic biofuels in the BTL (biomass-to-liquids) route, to replace fossil fuels with biofuels associated with CCS, such as biofuel kerosene and diesel biofuel.

Their low production cost and high rates of carbon capture during the plant development process until harvest make planted forests an excellent source of biomass. Planted eucalyptus or pine forests capture significant amounts of atmospheric CO_2 during the development process, part of which is stored underground and part in cellular materials. Subsequently, during the biofuel manufacturing process, process CO_2 is captured and stored in geological reservoirs, completing the so-called BECCS process (see section Biofuels). The model points to this type of bioinput creation process to produce bioenergetic materials associated with CCS as the only one able to obtain negative carbon emissions precisely because of it includes an agricultural phase. The association of CCS with fossil sources will at best still produce slightly

9. References taken from Griscom, et al. (2020) "National mitigation potential from natural climate solutions in the tropics".

10. Brancalion, Pedro HS, et al. "Ecosystem restoration job creation potential in Brazil." People and Nature (2022).

11. According to a WWF report (2021), "Potencial de produção sustentável de biocombustíveis no brasil – 2030", the increase in Brazil's livestock productivity can free up to 36 million ha for other uses without clearing any native forest areas.

positive emissions due to the technical efficiency thresholds for carbon dioxide (CO_2) capture in industrial processes.

Their low production cost and high rates of carbon capture during the plant development process until harvest make planted forests an excellent source of biomass.

The model also shows an increase in the participation of integrated crop-livestock (ICL) and agroforestry systems in 2050, taking up to 25 million hectares in scenario AT. This type of system is important because it allows growing different crops and raising different livestock in the same territory, which helps climate mitigation by storing carbon below and above ground and by integrating those planted forests into the production chain of advanced biofuels.

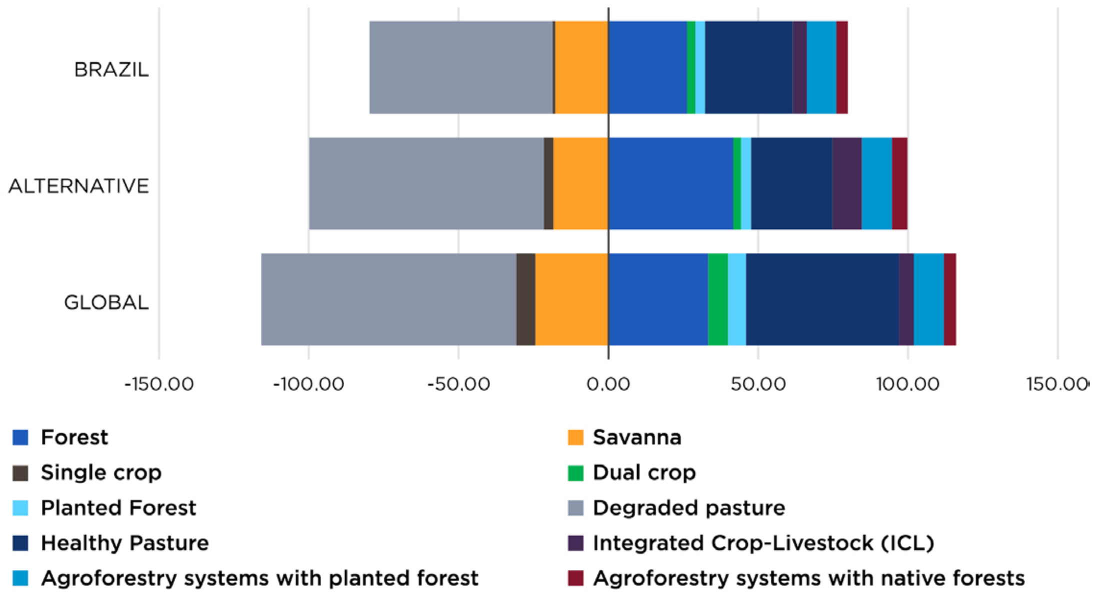
This section described how an optimal cost minimization strategy for Brazil to achieve carbon neutrality requires changes in land use to promote nature-based mitigation solutions.

The decarbonization solutions identified further point to the strong increase in agroforestry crops for bioenergy production, which are not expected to put pressure on biodiversity, food production and water security. Our model takes those objectives into account. The demand for food, for example, is external to the model and its satisfaction is a basic condition in all scenarios. Water availability is similarly assessed in all scenarios. The model factors in water demand for the technologies that make up the energy system[12] (for example, hydropower plants, refineries, biofuel production, thermal power plants, hydrogen production and others) and for agricultural processes, water restrictions for crop allocation within each mesoregion and other uses for water. This means that demands for food, energy services and water are always met, so that food, energy and water security are guaranteed. As shown in chart 8, which summarizes the cumulative changes in land use in Brazil in all scenarios, the paths to neutrality reconcile the agricultural, energy and environmental objectives. The main source of land for NBS is the conversion of degraded pastures into forests (native and planted), agroforestry systems and low-carbon agriculture, as shown in earlier studies. That will increase the supply of food, remove carbon and provide inputs for bioenergy generation with no significant impact on water usage and with no deforestation. On the contrary, the ensuing growth in forest cover benefits biodiversity.

Chart 8 also shows how important Agriculture, Cattle Ranching and Forestry activities are for carbon neutrality. Disruptive (and challenging) change in land use in relation to current trends is key for Brazil to achieve cost-efficient decarbonization.

12. Vásquez-Arroyo's doctoral dissertation (2018) gives details on the water module in the BLUES model. Angelkorte (2019) and Köberle (2018) explain the land use module.

CHART 8 LAND USE CHANGE IN 2050 IN RELATION TO 2020 (IN M HA)



4.4. Investment and Employment

Our scenarios showed different paths to GHG reduction and consequently involved different investment levels in each industry. The biggest differences between the scenarios occur in the following industries:

a. Power industry, because of the large expansion of wind power to meet electromobility needs and of bigger generation of low-carbon hydrogen (mostly green) in scenario AT;

b. Fuel industry, because of greater production of cellulosic biofuels, which gain heightened importance since no economically feasible CCS solution was found in scenario AT;

c. CCS: investment on the CO_2 transportation and injection infrastructure is needed in scenarios BT and GT.

The energy transition process is also a cultural process that involves the transformation of habits, usages and capabilities so that the investment made in each scenario affects how many jobs are created in each industry.

We estimated the number of jobs created in each industry in each scenario in order to gauge the effort required to meet the relevant energy transition requirements and to indicate what opportunities and challenges the educational system and the labor market will find to shape a workforce capable of responding to the new reality.

Our projection shown in the table below was based on the investments estimated for each scenario[13] and assumed an exchange rate of 5.00 BRL/USD.

TABLE 3. ANNUALIZED INVESTMENTS (2020-2050)

Million R$ @2020	BAU	BT	AT	GT
Land use	4,085	32,928	42,458	37,475
CCS	-	2,136	-	4,466
Buildings	35,861	35,905	37,376	35,770
Waste	4,283	5,034	6,442	4,352
Manufacture	18,191	18,529	18,277	22,499
Fuels (Fossil and Bio)	41,719	96,508	130,385	113,351
Power Industry	38,953	42,062	73,905	53,823
TOTAL	**143,093**	**233,102**	**308,844**	**271,737**

Based on those figures and so-called employment coefficients (job creation per unit of GDP), table 4 below shows the range of potential direct and indirect jobs created in each scenario. The figures shown below represent the average number of jobs maintained in each year in consequence of energy transition investments, so that they should not be added together. More investments take place and more jobs are created in scenarios that require more significant efforts to change infrastructure and the composition of energy supply and demand. Deeper transformation indeed requires more investment and more associated jobs.

TABLE 4. JOBS (ANNUAL AVERAGE IN MILLIONS)

BAU	BT	AT	GT
from 2.9 to 3.6	from 4.7 to 5.8	from 6.2 to 7.8	from 5.4 to 6.8

13. This exercise focuses only on how many jobs the relevant investment will create and not on total employment in the Brazilian economy in each scenario. Nor did we investigate if the additional investment will have any implication on the allocation of other economic aggregates, which could impact investment and consumption in other industries (displacement effect).

5 Energy supply

This session investigates how energy production changes to meet demand with respect to each scenario's climate targets. The Brazilian power industry already boasts a very significant participation of non-emitting sources and the ongoing growth in the share of wind and solar power in the mix is expected to continue.

In addition to traditional fuels, the transportation industry is expected to use biomass converted into by-products via gasification and Fisher-Tropsch synthesis as a major provider of low-emission fuels.

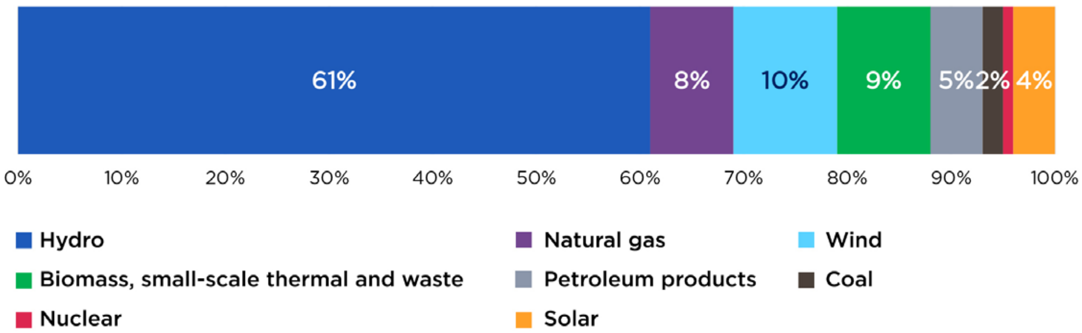
Thanks to the large-scale use of biomass, achieving climate goals in all scenarios was less dependent on the development of hydrogen and biomethane sources in replacement of emitting sources in hard-to-electrify industries.

The continued production and use of fossil fuels requires using CCUS technologies.

5.1. Power Generation

The power industry developed in Brazil on the back of the abundant water resources available and essentially relies on large hydropower plants whose reservoirs are managed over multi-year time spans and on long transmission lines that interconnect large subnational subsystems to create an interconnected generation and transmission system of continental proportions centrally coordinated by the National System Operator (ONS). This strong hydropower presence, which translates into a mostly renewable power mix, led the industry to put emissions curbing on the back burner. Hydropower has been losing share over time but still represented 61% of generation capacity in 2020.

CHART 9 INSTALLED CAPACITY BY SOURCE IN THE NATIONAL INTERCONNECTED SYSTEM - SIN (DEC 2020)



Source: ONS, 2022

In 2000, natural gas emerged as a complementary source and gained ground at a time when the expansion of hydropower generation was restricted and the management of reservoirs was constrained[14]. Since around 2011, the gathering pace of the expansion of wind and solar power has buttressed their role as a supplemental source that enhances system operation security.

That context gave birth to a debate around the role of natural gas focusing on its proper evaluation, on how to align the flexibility the power industry needs with the guarantees large-scale gas investments require. The requirement in the recently-enacted Eletrobras Capitalization Act for the system to purchase 8 gigawatts of gas-fired thermal power by 2032, which will entail the construction of new gas pipelines and transmission lines, has rekindled the debate on the economic attractiveness of market-coupling under these circumstances.

> The context gave birth to a debate around the role of natural gas focusing on its proper evaluation, on how to align the flexibility the power industry needs with the guarantees large-scale gas investments require.

Wind power plants have already surpassed natural gas in capacity: wind power accounted for 10% of installed capacity in 2020, while natural gas answered for 8%. Solar power has grown very significantly in recent years, especially in distributed generation, reaching 4% of capacity. In 2020, distributed generation surpassed centralized generation: 4.4 GW compared to 3.3 GW.

The Legal Framework for Distributed Generation (Law 14,300/2022) enacted in early 2022 mantained until 2045 the earlier exemption from the Distribution System Use Fee (TUSD) for solar power systems certified until January 6, 2023. That will support demand for new installations and will help Brazil maximize its solar generation potential. In the first eight months of 2022 alone, 3.7 GW in distributed solar generation were added to the system.

14. The introduction of less polluting thermal sources significantly contributed to make Brazil's power mix less emissions-intensive. In fact, the greater share of biomass, natural gas and nuclear power in the mix saved some 267 million tonnes of CO2-eq or 23% of what would have been emitted had Brazil's thermal power generation profile remained the same since 2000. See https://www.epe.gov.br/sites-pt/publicacoes-dados-abertos/publicacoes/PublicacoesArquivos/publicacao-660/EPEFactSheetEmissoesSetorEletrico.pdf

All scenarios projected show wind and solar sources as the main drivers of generation growth, with the consequent reduction in hydropower's share in the energy mix. Hydropower's share goes down to 55% in scenario BT, to 54% in scenario GT and to 30% in scenario AT. This reflects, on the one hand, the restrictions to the construction of new hydropower projects with dams, because of their environmental and social impact, and, on the other hand, the very competitiveness of other renewable sources. The share of renewable sources in Brazil's power generation mix will continue to grow, surpassing 90%. Starting from an already high 86% share of capacity in 2020, renewable sources reach 91% in 2050 in the scenario BT and 93% in scenario AT.

Wind power generation grows the most, from 9% in 2020 to 17%, 47% and 14% in 2050 in scenarios BT, AT and GT, respectively. Solar power also gains importance through photovoltaic plants and distributed generation. The latter grows in all scenarios, reaching 43 GW in potential capacity by 2050.

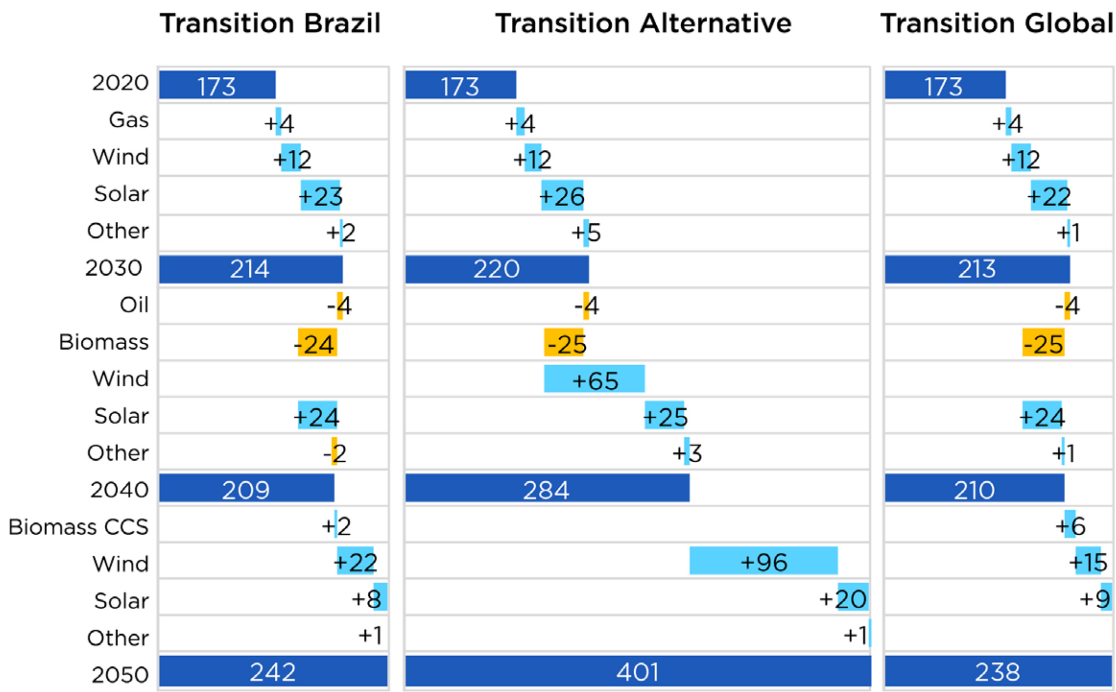
All scenarios projected show wind and solar sources as the main drivers of generation growth, with the consequent reduction in hydropower's share in the energy mix.

The most significant difference in scenarios BT and GT in relation to scenario AT is the penetration of biomass associated with carbon capture, as indicated in chart below showing the variation in installed capacity by source and by scenario. The greater need for negative emissions in scenario GT in relation to scenario BT further increases that penetration.

The technical and economic challenges involved caused CCS options for fossil sources (natural gas and coal) not to have passed the optimization test in any scenario. The model's optimization exercise indicates that CCS technologies are most suitable when associated with biopower generation because the high CO_2 concentration in its exhaust gases makes capture easier and also thanks to the resulting negative emissions (and only neutrality) over the life cycle[15].

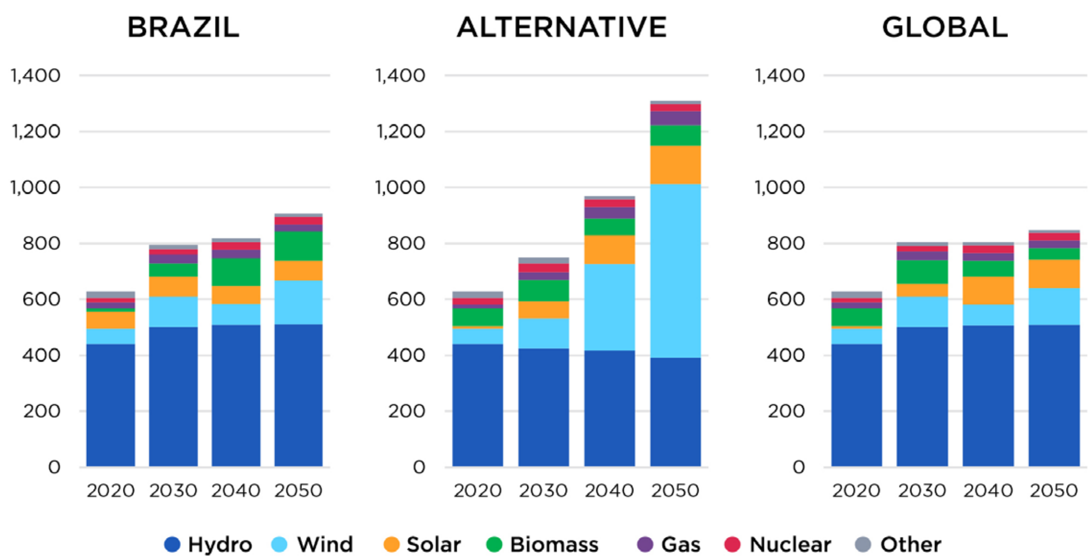
15. In some specific circumstances CCS investments may be required to make O&G projects viable after 2030.

CHART 10 VARIATION IN BRAZIL'S POWER GENERATION CAPACITY BY SOURCE AND SCENARIO



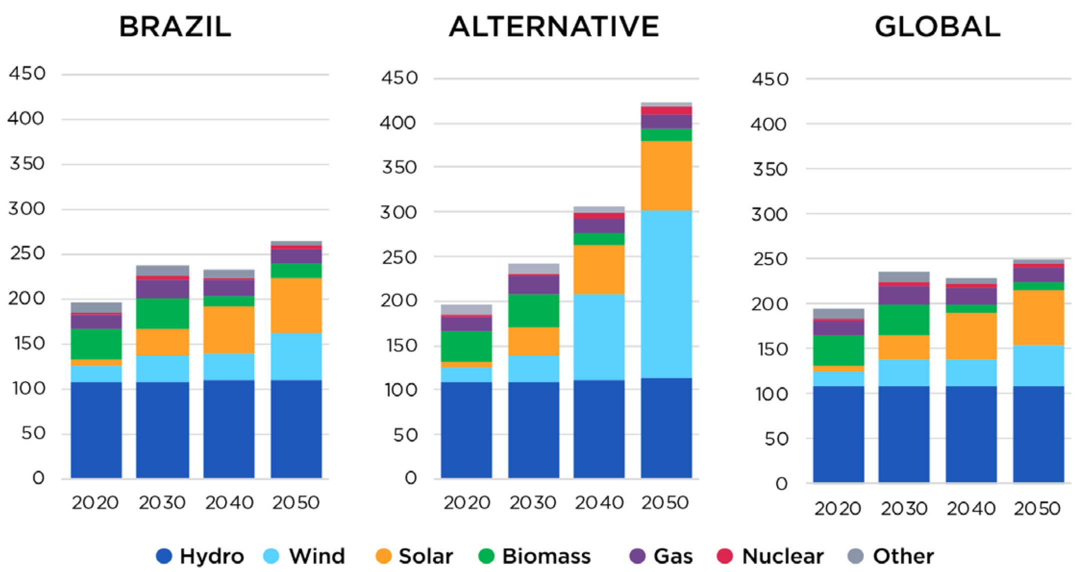
Demand for power is greater in scenario AT than in other scenarios, growing in average by 4% per annum in the former and by 2% in the latter between 2020 and 2040. Scenario AT further includes some restrictions to represent the paths the model did not deem optimal but that may occur in response to government policy intervention or to climate or technological uncertainties. Scenario AT projects 8 GW in nuclear power generation by 2050, while the others estimate 3.5 GW. Scenario AT does not include any CCS option and although its hydropower capacity is greater than in other scenarios (by 2.4 GW in 2050), average generation is lower, as shown in the chart below.

CHART 11 POWER GENERATION BY SOURCE AND SCENARIO (TWH/YEAR)



Generally speaking, the challenge of greater demand with less hydropower generation in scenario AT is met mostly through the expansion of wind and solar sources, especially the former (generation delta in 2050: 448 TWh for wind and 33 TWh for solar photovoltaic generation). The much higher growth in wind power, with no increase in dispatchable sources and with diminished ability to use hydropower reservoirs, is made possible through the use of storage systems. We estimated the introduction of 2 GW in installed capacity from electrochemical batteries.

CHART 12 BRAZIL'S POWER GENERATION CAPACITY BY SOURCE AND SCENARIO (IN GW)



The flip side to power generation growth is the ensuing need to expand transmission lines within the National Interconnected System (SIN) to support the increased flow of power. That expansion occurs both within subsystems and between them. We further assumed that new and more efficient transmission and distribution facilities will reduce transmission losses. The expansion in generation sources in scenario AT is accompanied by around 60% growth in power transmission. As the table below shows, that expansion is reduced to approximately 30% in the other two scenarios.

TABLE 5. EXPANSION OF BRAZIL'S IN ELECTRICITY TRANSMISSION CAPACITY

	BRAZIL	ALTERNATIVE	GLOBAL
2020	141	141	141
2050	185	221	181
Variation	+31%	+57%	+28%

The high potential for wind and solar plants may seemingly indicate that the power industry will face no hurdle to contribute with Brazil's energy transition process. However, some challenges are intrinsically associated with the industry's modernization agenda. Modernization is necessary to change how the system is operated and how power is marketed. Those changes will help rearrange the source mix and will foster the introduction of new technologies and capacity at no additional cost or even reducing cost for final consumers.

The flip side to power generation growth is the ensuing need to expand transmission lines within the National Interconnected System (SIN) to support the increased flow of power.

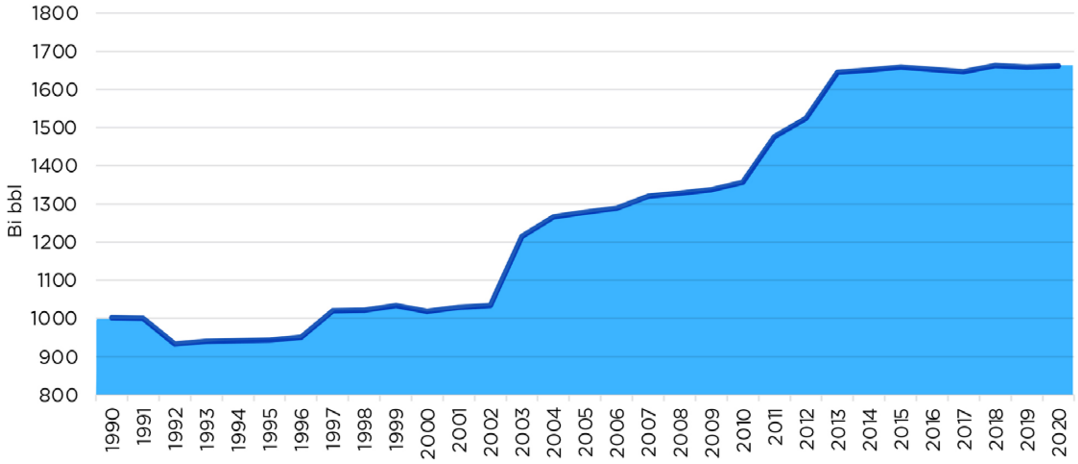
The modernization debate was sparked in 2017 through Public Comment Process no. 33 (CP 33). In 2019 the Ministry of Mines and Energy created an industry Modernization Committee working on 16 issues and whose partial reports are to be submitted until 2023. The first streamlined reserve power purchase tender and the first associated capacity reserve auction occurred in 2021 in anticipation of the debate on the separation between guaranteed capacity and power. Other noteworthy events were the initiation of hourly operations and the conversion of Provisional Measure 998 into Law no. 14,120 (March 1, 2021). Still in 2021, PLS 212 was introduced in the House of Representatives as bill PL 414/2021 including the recommendations of the Work Group and the contributions received through CP 33 and addressing issues such as market deregulation; improvements to the power market; improvements to the structure of power rates; and reduction in system fees.

5.2. Oil, Natural Gas and Petroleum Products

In the late 20th and early 21st centuries, the global energy market and academia had the recurring perception that the world was heading toward "peak oil", i.e., the moment when oil production would peak, and that the depletion of reserves would thereafter lead to a decline in the supply of oil and gas.

Some 20 years later, the oil industry faces very different challenges. First, new discoveries and production technologies (such as hydraulic fracturing) have significantly increased proven reserves. After remaining relatively stable throughout the 1990s, world reserves grew rapidly between 2002 and 2013. In 2020, they were 63% bigger than at the dawn of the century.

CHART 13 WORLD PROVEN RESERVES

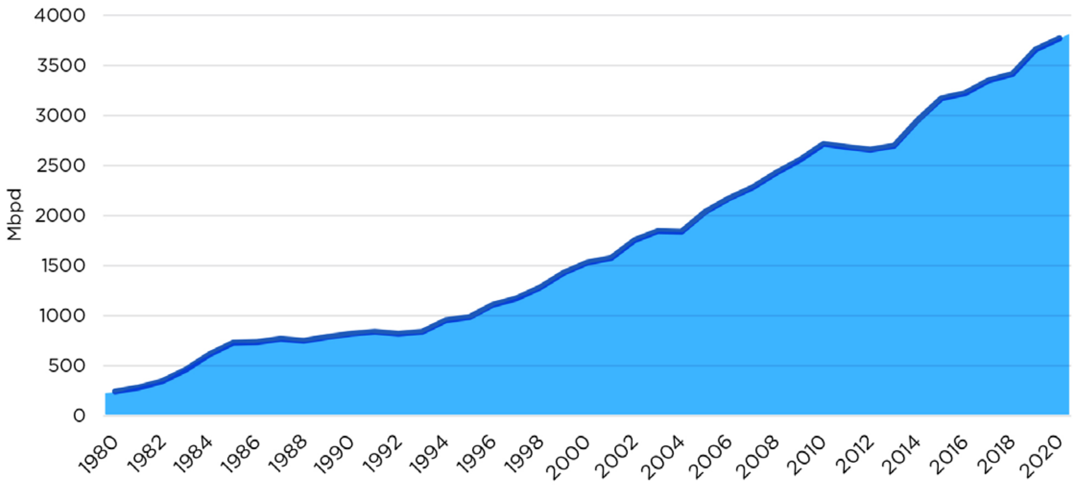


Source: U.S. Energy Information Administration

At the same time, the last few decades have also stressed the imperative of reducing GHG emissions and, to that end, to reduce the consumption of fossil fuels. The resultant of those two vectors is that instead of facing oil shortages, the oil and gas industry envisions the arrival of "peak demand", that is, the moment when oil demand - and not supply - peaks and then decreases.

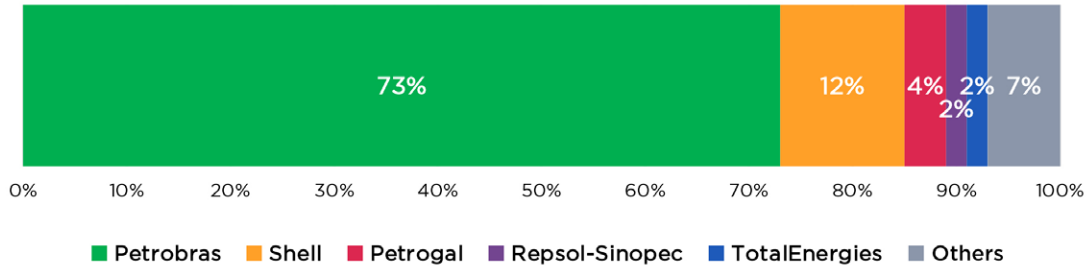
Brazil was one of the countries that contributed to the growth in world reserves and production. Domestic production more than doubled in absolute terms since the turn of the century. More players have joined the game, in special large international oil companies, which now represent more than a quarter of total. Among other effects, the increased presence of multinational companies ties the Brazilian oil industry more strongly to the perceptions and directions of the international industry and, in particular, to its energy transition strategies.

CHART 14 DOMESTIC OIL PRODUCTION



Source: ANP

CHART 15 OIL PRODUCTION BY COMPANY



Source: ANP

That circumstance represents a crucial dilemma for Brazil. On the one hand, the oil sector grows and internationalizes. On the other hand, it is the most heavily affected industry in any energy transition scenario focusing on reducing carbon emissions and/or on putting a lid on global temperature. The IDB estimated that if Paris Agreement's objectives are met at the international level, the ensuing drop in demand could reduce Brazil's oil production by almost half by 2035[16]. Other reports, however, indicate that Brazilian oil will have a significant global role to play in the future (IEA, 2022; EIA, 2021; OPEC, 2022), in particular thanks to its triple resilience (technical, economic and environmental) (Rystad Energy, 2022; Wood, 2018; Coppe-IBP, 2022).

The O&G industry historically is highly innovative and science- and technology-driven and quick to adapt to different market conditions and to turn challenges into opportunities. The advent of electricity in the 20th century, for example, displaced its then main product, lighting kerosene, but the O&G industry incorporated new processes and developed several fuels for transportation (automotive gasoline, diesel oil, bunker, aviation gasoline and kerosene), manufacturing (fuel oil, LPG and natural gas), petrochemical (naphtha, ethane, LPG, natural gas) and home (LPG, natural gas, heating oil) uses. The new energy transition brings huge challenges to the hydrocarbon (O&G) industry. It will need to reduce its carbon footprint and to progressively adapt its business portfolio. However, said challenges bring great opportunities for those players that best adapt to the context.

The oil that meets the remaining global demand must show double resilience: economic (low production cost) and environmental (low carbon intensity in the international market).

In Brazil, in particular, the wealth created by the O&G industry has contributed to fund the energy transition and the innovations needed to achieve carbon neutrality by 2050, including carbon removal through CCUS, greater energy efficiency (including the electrification and digitization of equipment, processes and production units) and the introduction of renewables into the O&G value chain (onshore and offshore wind, solar, wave power, biorefining, etc.), low-carbon hydrogen and forestry offsets (Machado, 2022). Reducing carbon emissions and "carbon removal" both are important elements in Brazil's mitigation strategy. Brazil's oil shows triple resilience (technical, economic and environmental). The world average carbon intensity of oil

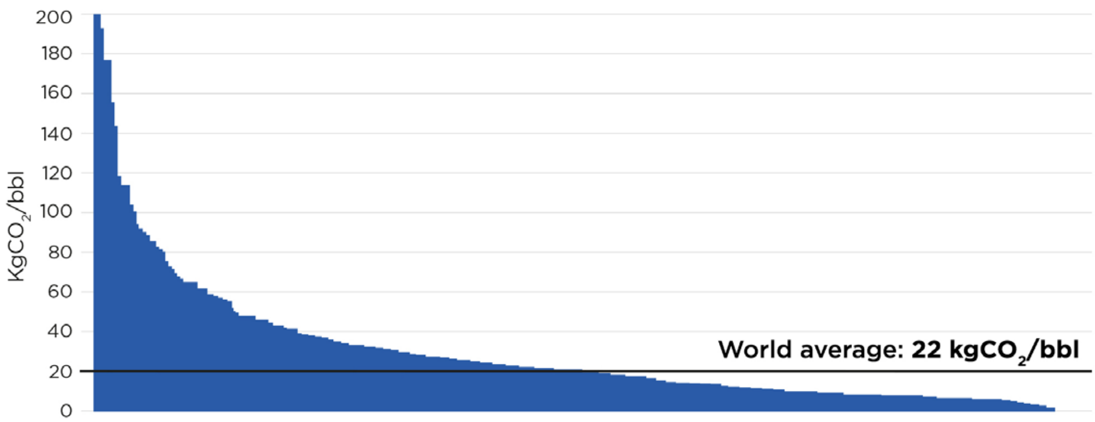
16. On energy transition implications and risks for extractive industries, see "Implications of Climate Targets on Oil Production and Fiscal Revenues in Latin America and the Caribbean" and "Marco Sectorial de Industrias Extractivas".

is 22 kilograms of CO_2 per barrel of oil equivalent produced ($KgCO_2/b$), with some oils showing carbon intensity between 50 kg CO_2eq/b and 200 kg CO_2eq/b. The average carbon intensity of Brazil's oil is about 15 kg CO_2eq/b, and oils from the pre-salt layer go below 10 kg CO_2eq/b (Rystad Energy, 2022; Petrobras, 2022[17]).

Oil will remain in use throughout the energy transition to meet national energy security needs. In the long run, global carbon neutrality scenarios project a residual demand for oil to serve hard-to-abate industries and for non-energy purposes (uses where petroleum products are not burned and therefore cause no direct emission). The International Energy Agency's most recent World Energy Outlook report (2022), for example, estimates oil demand at 23 million barrels per day in 2050. Brazilian oil helps mitigate global GHG emissions by displacing more carbon-intensive oils traded globally to meet the residual demand, and will probably be one of the last oils to leave the marketplace. In addition, refiners' preference for oils with similar physical and chemical characteristics to oil from the "pre-salt" layer (medium density and low sulfur content), whose refining process is less carbon-intensive, enhances the competitiveness of Brazilian oil. In other words, Brazil's O&G production emits relatively little GHG and by displacing more carbon-intensive O&G from the global market, Brazilian O&G helps mitigate GHG emissions. This will become more significant in coming years because of energy efficiency, the introduction of renewables and carbon removal (CCUS and forestry offset)[18].

Brazil's O&G production emits relatively little GHG and by displacing more carbon-intensive O&G from the global market, Brazilian O&G helps mitigate GHG emissions.

CHART 16 GLOBAL OIL CARBON INTENSITY (KGCO2 PER BARREL)



Source: Rystad (2022). Carbon Footprints of Crude Grades – Are they all alike?

17. Rystad Energy (2022). Carbon Footprints of Crude Grades–Are They All Alike? Free Global Emissions Series Report, May 2022. Petrobras (2022). Challenges and Opportunities for Petrobras' s Decarbonization. Presentation shown at 2022 OTC.

18. Machado, Giovani (2022). "Planejamento e o futuro do setor energético brasileiro aderente às preocupações da COP 26", chapter 12, pp: 92-98, in: CEBRI (2022). Energia em um mundo em transição: desafios, oportunidades e perspectivas.

Oil from Brazil's "pre-salt" layer is extremely cost-competitive. In its 2022-2026 Strategic Plan, Petrobras indicated average E&P costs (excluding vessel charter costs and the government's share of oil) of US$ 4.8/boe, potentially going as low as US$ 3.5/boe for "pre-salt" oil, which will represent 79% of the company's total production by late 2026.

The findings in our scenarios confirm this triple edge of Brazil's O&G industry. Oil is expected to lose ground (both in absolute and in relative terms) as a primary energy source in Brazil. The reduction in Brazil's oil consumption is expected to bring oil's share in the energy mix for the current 35% down to 15% in scenario BT and to 5% in scenario AT. But the opposite is projected for production. Domestic crude output will likely grow thanks to increased exports in all scenarios, except for the final years in scenario AT.

CHART 17 BRAZIL'S OIL CONSUMPTION

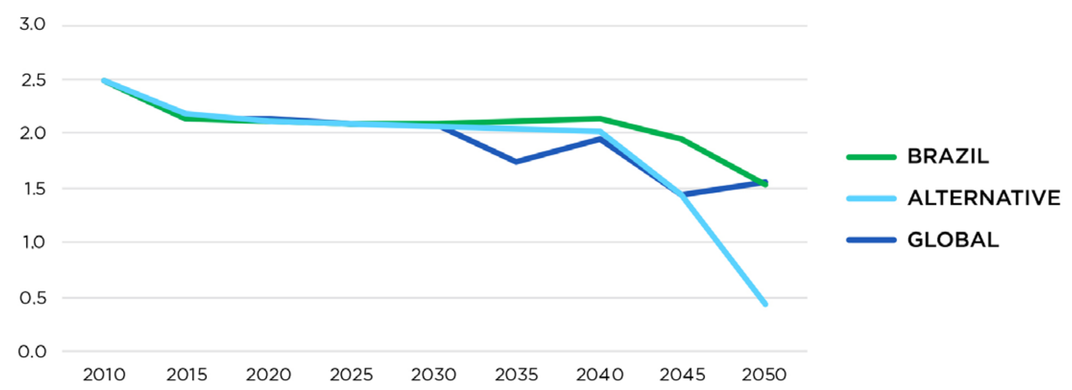


CHART 18 BRAZIL'S PRIMARY ENERGY USE

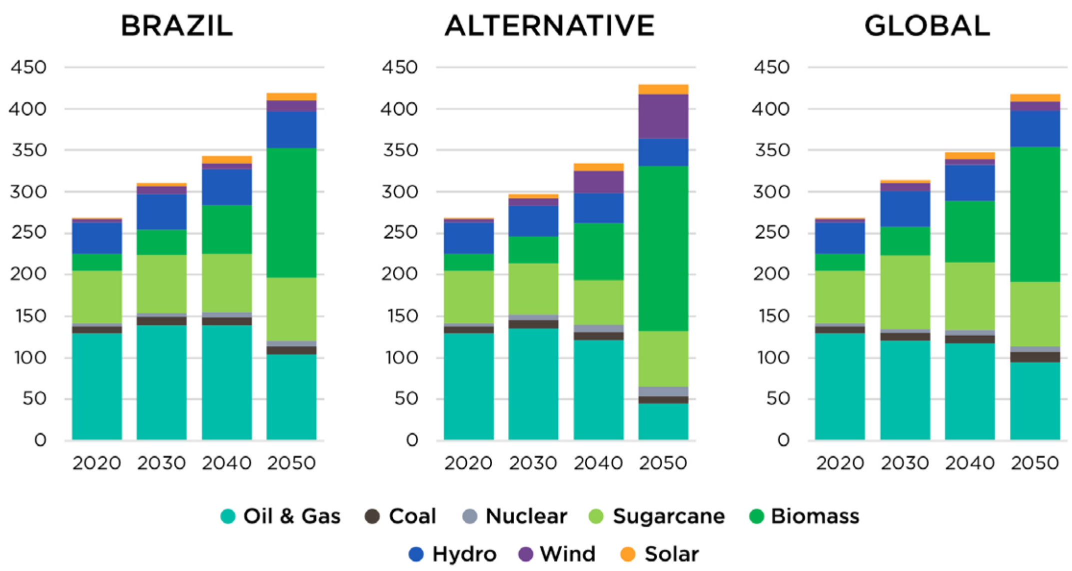
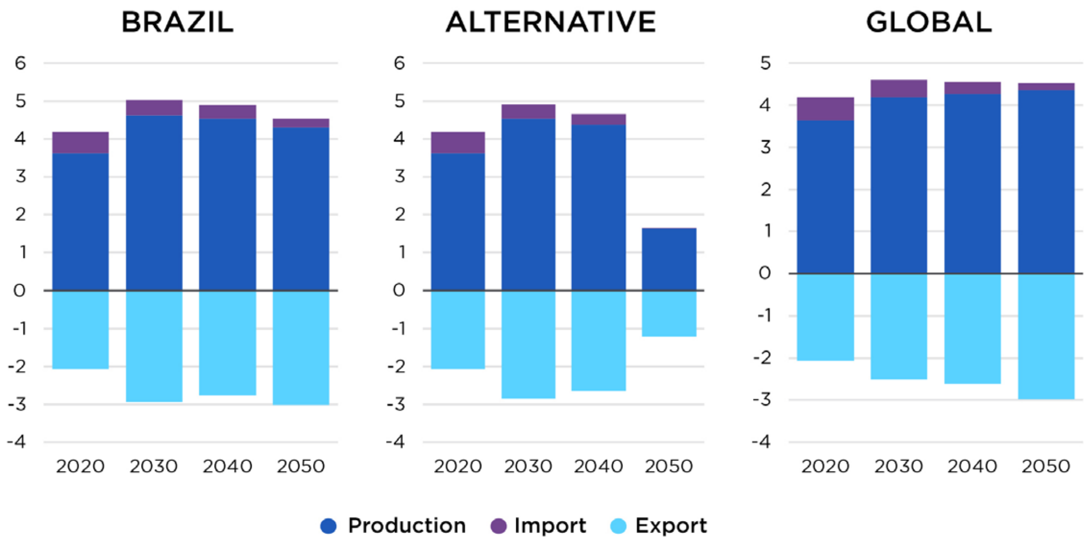


CHART 19 BRAZIL'S OIL PRODUCTION, EXPORT AND IMPORT



The maintenance of production supported by exports reflects the aforementioned triple resilience of oil: low carbon intensity in production and refining and low production cost. It is indeed important for Brazil that its oil reserves remain competitive[19].

The O&G industry will play a significant social and economic role in Brazil. The investment and innovation the industry will bring in the effort to drive its carbon intensity further down and to gradually change its business portfolio will help Brazil's energy transition and decarbonization process.

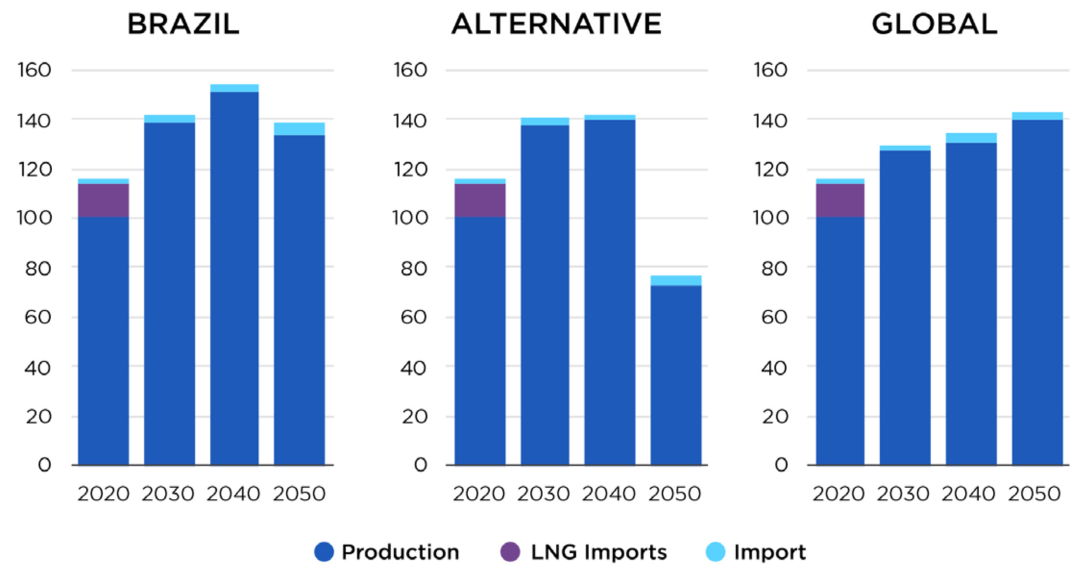
The wealth created by the O&G industry has contributed and will continue to contribute to fund the energy transition and the innovations needed to achieve carbon neutrality by 2050, including carbon removal through CCUS, greater energy efficiency (including the electrification and digitization of equipment, processes and production units) and the introduction of renewables into the O&G value chain (onshore and offshore wind, solar, wave power, biorefining, etc.), low-carbon hydrogen and forestry offsets.

Our analyses show that the increase in exports, together with the reduction in imports, will make domestic production more dependent on international oil demand, particularly Southeast Asia's.

Similarly to oil, natural gas production is expected to grow in the four scenarios (again, the exception is the last decade in scenario AT). But there are marked differences. First, imports will become marginal, concentrated on imports through pipelines (i.e., from Bolivia) and LNG imports will be negligible. Second, the increase in production will be absorbed by the domestic market without any dependence on the foreign market. In other words, domestic production will in all scenarios meet the growing domestic demand for natural gas (especially for industrial use).

19. The scientific literature also indicates that better-quality oil (less carbon-intensive) tends to remain on the market to serve hard-to-decarbonize industries. See Draeger et al, (2022) Stranded crude oil resources and just transition: Why do crude oil quality, climate ambitions and land-use emissions matter.

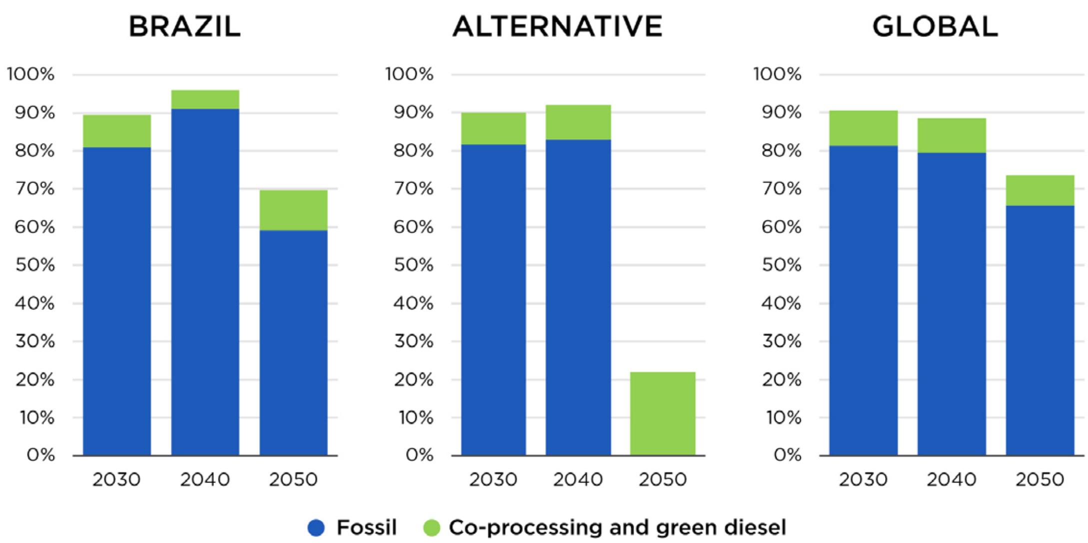
CHART 20 NATURAL GAS PRODUCTION AND IMPORT



Reduced domestic consumption of gasoline, diesel oil and other petroleum products will significantly affect refining assets for there will be less crude to process. Indeed, the refinery use factor (i.e., the percentage of primary refining capacity actually used) will fall in all 2050 carbon neutrality scenarios. Alternatively, refineries can be converted into biorefineries or energy complexes following an asset redesign logic aligned with the energy transition.

The refinery use factor will fall in all 2050 carbon neutrality scenarios.

CHART 21 REFINERY USE FACTOR



The oil refinery use factor will drop from 84% in 2020 to 70% in scenario BT and to 74% in scenario GT in 2050. In scenario AT the use factor plummets to 22% in 2050, fully dedicated to co-process oil and biomass streams, in reflection of the behavior of domestic consumption. Indeed, in all scenarios the introduction of vegetable oil, residual oil (UCOS) and pyrolysis oil co-processing in refineries equipped with HDT and FCC units will push up the use factor. Co-processing inputs are expected to have around 10% biomass content by 2050. Another trend noted is the increase in petrochemical yields in later years reflecting the behavior of the consumption of petroleum products (for non-fuel purposes) in a low-carbon economy.

5.3. Liquid Biofuels

Brazil boasts a number of attributes that give it a privileged position in the global bioenergy market. The country receives intense solar radiation year-round, has one of the largest fresh water reserves on the planet and extensive land available for energy agriculture. In many areas in the country multiple crops can be grown with no irrigation during the year, giving room to food production and to a thriving bioenergy chain.

Brazil has for decades employed public policies to boost the use of bioenergy as a tool to enhance energy security and to decarbonize the fuel mix. Four milestones stand out in the history of biofuels in Brazil: the 1975 National Alcohol Program (PROALCOOL), the implementation of flex-fuel technology in 2003, the 2005 National Program for Biodiesel Production and Use (PNPB) and the 2017 National Biofuels Policy (Renovabio). The latter involves a broader view of the key contribution all biofuels provide to meet Brazil's NDCs.

The success of said public policies has led the private sector to develop a significant biofuel production chain focusing on ethanol and biodiesel. Indeed, about 25% of the energy use of Brazil's transportation industry comes from renewable sources, in comparison to a global average of less than 5%.

Sugarcane is currently the main feedstock for ethanol production. In 2021, 581 million tonnes of sugarcane were processed to produce 29.9 billion liters of ethanol (MAPA, 2022). With 361 sugarcane processing plants in operation in December 2021, Brazil boasts an effective milling capacity of about 735 million tonnes (MAPA, 2022). The production of corn ethanol also has considerably grown. Twenty corn ethanol plants were in operation in 2021 with a total annual processing capacity of 15.3 million tonnes of corn and total ethanol production capacity of 4.2 billion liters per annum (EPE, 2022).

Biodiesel production reached 6.8 billion liters in 2021, corresponding to around 54% of installed capacity (12.3 billion liters) in the 53 authorized plants. Soy is the most important feedstock for biodiesel production, accounting for 72% of total feedstocks, followed by beef tallow and fatty materials (20% of total).

Thanks to that combination of natural resources, strategically-oriented public policies and private investments, Brazilian gasoline (with 27% of ethanol in its composition) is one of the least GHG-intensive in the world. In addition to anhydrous ethanol, Brazil also uses hydrated ethanol in flex-fuel vehicles. Because of the successful use of ethanol-gasoline blends, biofuels meet approximately 50% of the Otto cycle demand. Heavy vehicles currently use a blend of 10% biodiesel mixed with fossil diesel oil, to be increased to 20% by 2028 under current regulations.

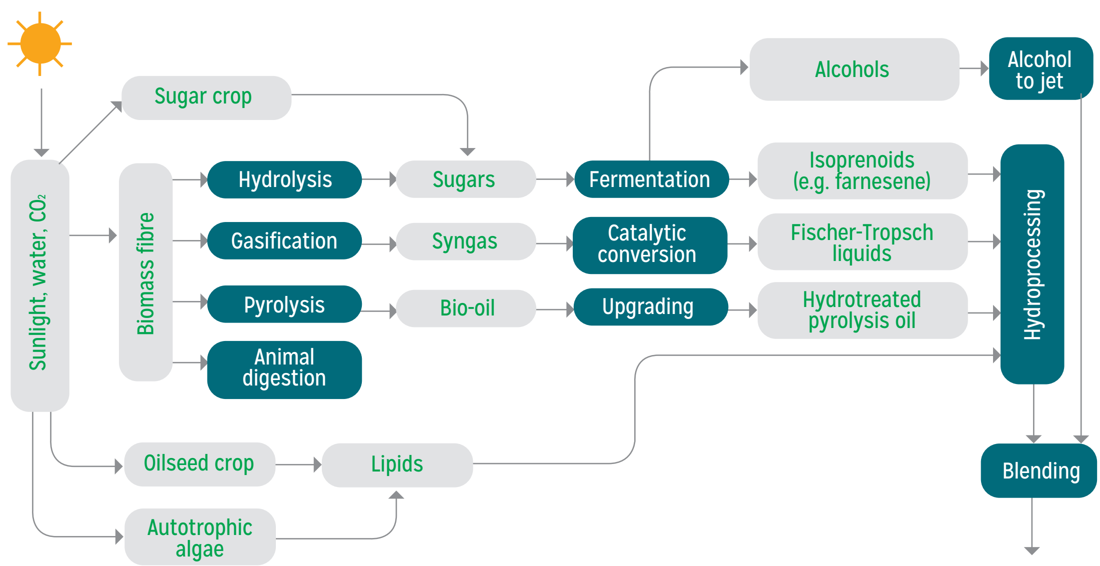
Thanks to that combination of natural resources, strategically-oriented public policies and private investments, Brazilian gasoline (with 27% of ethanol in its composition) is one of the least GHG-intensive in the world.

A major strategic advantage of liquid biofuels is that they can to a certain degree use the infrastructure in place for fossil fuels. The higher energy density of biofuels can contribute to decarbonize hard-to-electrify activities such as long-haul road freight transportation and industrial processes.

In addition to ethanol and biodiesel, new biofuels such as green diesel (or biofuel diesel), aviation biokerosene (or biojet), green gasoline and biofuels for maritime use are potential substitutes for their fossil counterparts in the pursuit of climate neutrality.

Advanced biofuels (premium products in relation to petroleum products but derived from biomass) such as green diesel and aviation biokerosene emerge as potential substitutes for traditional fossil fuels. These biofuels can be produced through various routes, as indicated in the figure below for biojet.

FIGURE 1 PRODUCTION ROUTES FOR AVIATION BIOKEROSENE OR BIOJET



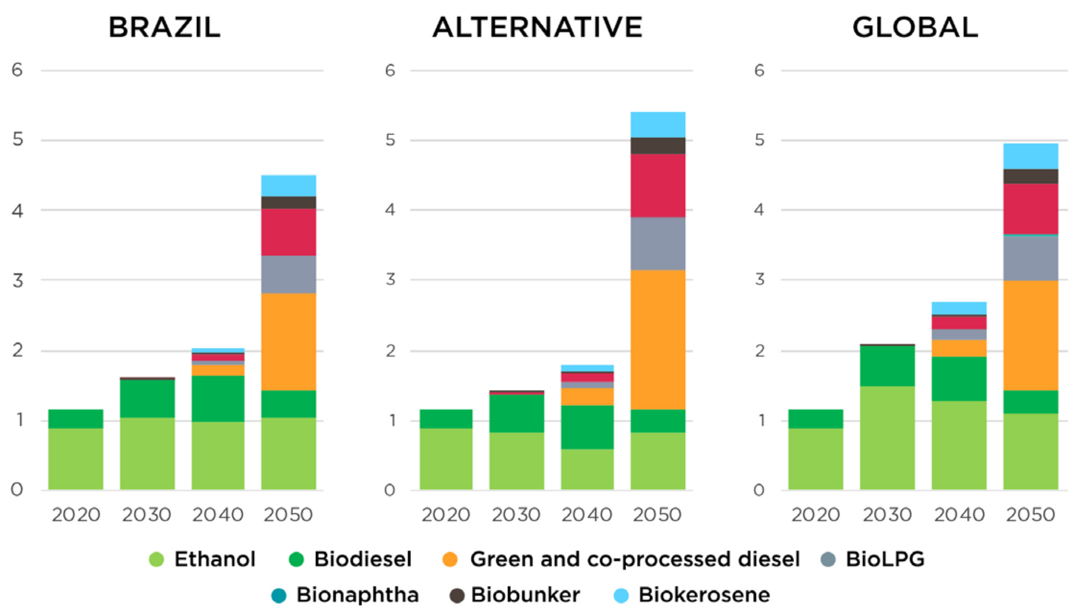
Source: Irena, 2021

The advanced fuel production route chosen in our scenarios was the thermochemical conversion of biomass via gasification and Fischer-Tropsch Synthesis (FT). That process yields high-quality biofuels and can also produce biojet, renewable diesel, biobunker for maritime transportation, gasoline, petrochemical naphtha and bioLPG. The fact that those fuels, just like ethanol and biodiesel, can use the existing fossil fuel transportation, distribution and supply infrastructure facilitates the prompt commercial use of that technology.

Although our optimization exercise gave priority to the gasification and Fischer-Tropsch route, this technology is not yet fully developed for biomass and requires additional R&D efforts to become ripe for industrial-scale use. The HEFA route, a hydrotreated vegetable oil process, has already proven itself in several green diesel (HVO) production projects and is now in use in early-stage biojet projects. Its main disadvantage is that it uses essentially the same feedstocks used to produce biodiesel.

The chart below shows biofuels production in our scenarios. Please note that the figures in the chart cannot be added one to the other because some of the biofuels shown are used to produce others. For example, biofuel naphtha is an input to prepare the biofuel kerosene blend[20].

CHART 22 BRAZIL'S BIOFUEL PRODUCTION (EJ)



Our model found the following on the decarbonization alternatives in the different scenarios:

a. Biofuels are key for Brazil's decarbonization to succeed;

b. Conventional biofuels (ethanol and biodiesel) grow in almost all scenarios. In parallel, advanced biofuels gain greater significance at the expense of conventional ones. Scenario AT shows a slight decline (2%) due to the greater fleet electrification and to the deeper advanced fuel penetration needed to achieve decarbonization targets;

c. Advanced biofuels grow significantly in the last decade to meet the demand for diesel, especially in scenarios BT, AT and GT.

20. The charts are in exajoule (EJ) because of the difference in the calorific value and density of different biofuels. For example, 1EJ corresponds to about 50 billion liters of hydrated ethanol and to around 28 billion liters of diesel oil.

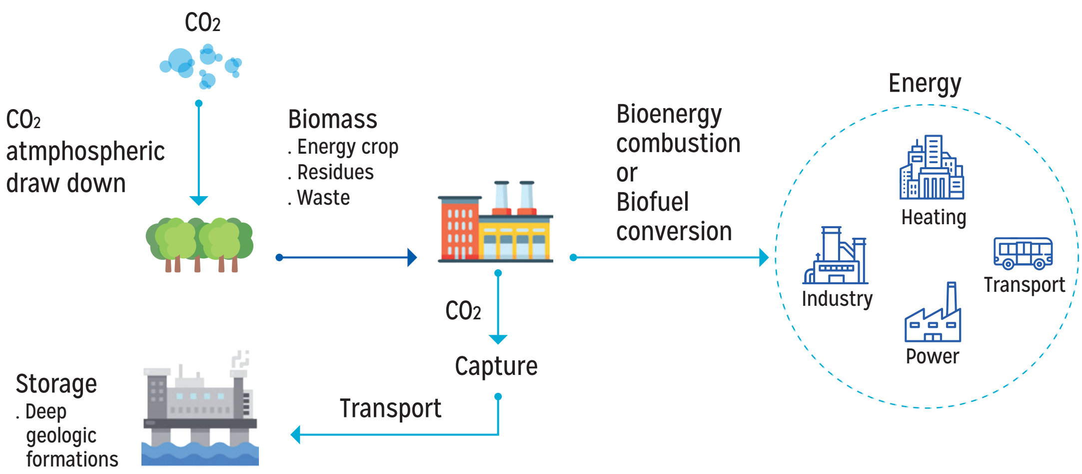
Our integrated model recommends the use of advanced biofuels for two major reasons: (i) decarbonization of hard-to-electrify transportation activities such as air, sea and road freight transportation; (ii) CO_2 capture and storage will reduce emissions from other industries.

In the challenging GHG reduction circumstances projected in our scenarios, achieving climate neutrality within the desired time horizon requires negative emissions to offset any GHG emissions that cannot be eliminated by 2050.

Biofuels are key for Brazil because existing technological arrangements for biofuel prod uction, such as eucalyptus or pine synthesis, provide negative emissions through the capture and storage of atmospheric CO_2 (designated BECCS - BioEnergy with Carbon Capture and Storage). During their development phase, eucalyptus and pine trees capture and store in the soil and in their cellular material large amounts of atmospheric CO_2.

In addition, the biofuel manufacturing process allows further CO_2 capture and storage. The CO_2 captured as pine and eucalyptus trees grow will not be fully returned to the atmosphere when the biofuel is used in engines so that the feedstock production life cycle and its subsequent conversion into biofuels causes the net removal of CO_2 from the atmosphere. The process is illustrated in the figure below.

FIGURE 2 BECCS SCHEMATIC PROCESS



Fonte: IRENA, 2020 baseado em Global CCS Institute, 2019

In relation to fossil fuels, the introduction of CCS will at best still produce slightly positive emissions due to the technical efficiency thresholds for carbon dioxide capture in industrial processes.

Their capacity to remove carbon will greatly enhance the importance of biofuels in Brazil's carbon neutrality strategy in comparison with the contribution ethanol and biodiesel today give in abating emissions in the transportation industry. The key importance of BECCS for Brazil's carbon neutrality is evidenced by the volume of carbon captured, reaching 274 and 369 million tonnes of CO_2 in 2050 in scenarios BT and GT, respectively.

That is a major challenge given that according to the GLOBAL CCS INSTITUTE (2021), all the CO_2 captured and carried in 27 facilities worldwide, from fossil or non-fossil sources (the vast majority from the former), amounted in September 2021 to less than 37 million tonnes per annum (Mtpa). Projects under development for implementation in the coming years are heavily focused on fossil fuels, except for three US plants designed to process ethanol production with a combined capacity under 1.5 Mtpa.

The huge technical and economic efforts BECCS feasibility requires are a major hurdle for the success of our neutrality scenarios.

A restriction on the introduction of carbon capture and storage arrangements was included in scenario AT to test the impact of BECCS unfeasibility. Regardless, cellulosic biofuels continue to play an important role in the decarbonization of transportation. Indeed, cellulosic biofuels are more heavily used to replace larger volumes of petroleum products in this scenario than in other ones because it has less room for abatement of emissions from fossil fuels.

Advanced biofuels may (especially in association with CCS) give Brazil a competitive edge in the next three decades thanks to Brazil's plentiful land, favorable agricultural and livestock productivity and experience in the field. Advanced biofuels may come to be a strategic investment in the transition to a low-carbon economy for several activities (e.g., for industrial use) not only as an energy source but also as input to make petrochemicals. Biofuels can be more widely used in the transportation industry to promote decarbonization with minimal change in the existing infrastructure and with lower impact on the consumption profile (e.g., in battery-powered electric vehicles).

Advanced biofuels may (especially in association with CCS) give Brazil a competitive edge in the next three decades thanks to Brazil's plentiful land, favorable agricultural and livestock productivity and experience in the field.

Agriculture and livestock can significantly contribute to the supply of advanced biofuels, in special by reducing the acreage of degraded pastures, which will ease the pressure the expansion of arable land for biofuel production puts on natural vegetation areas in scenarios BT, AT and GT. This is a least-cost optimal strategy found by the model.

The model also shows an increase in the participation of integrated crop-livestock (ICL) and agroforestry systems in 2050, expanding from 7.0 million hectares in scenario BAU up to 25 million hectares in scenario AT. This type of system is important because it allows growing different crops and raising different livestock in the same territory.

Finally, there may be a correlation between investments in the O&G chain and in biofuels, either in the logistics chain or in processing units. In short, the potential impacts on biofuel supply and costs caused by the conflicting and complementary risks and opportunities in both chains must be carefully reviewed.

5.4. Hydrogen and Biomethane

Hydrogen's versatility is a boon to the transition to a low-carbon economy. Its application as a direct source of low- or zero-carbon energy (depending on its production process, either through capture or from renewable sources) in hard-to-decarbonize industries or as vector for energy storage enables a greater input of intermittent renewables such as wind and solar power.

Hydrogen may come to be the link that allows the fast-paced reduction in renewable generation costs to also reach industries whose direct electrification is not as yet possible. It also allows connecting countries with high renewable energy generation potential, such as Brazil, with energy-hungry markets in other continents.

Some facts suggest that hydrogen may be on the cusp of a fast-paced race toward a hydrogen-based economy: i) the costs of renewables for low-carbon hydrogen production are falling; ii) several governments and major industrial players view the hydrogen economy favorably; iii) certain technological advances have enhanced hydrogen's competitiveness, opening the door for it to capture a significant percentage of the low-carbon energy mix in the future[21].

It is therefore unsurprising that hydrogen (H_2) has in recent years gained importance in the energy transition debate. H_2 can be produced from different energy sources such as electricity, natural gas, biomass (via electricity, gasification or reforming, depending on the biomass and on the conversion chain), etc. Hydrogen is considered a boon for the energy transition process because its use releases no CO_2 directly in the atmosphere.

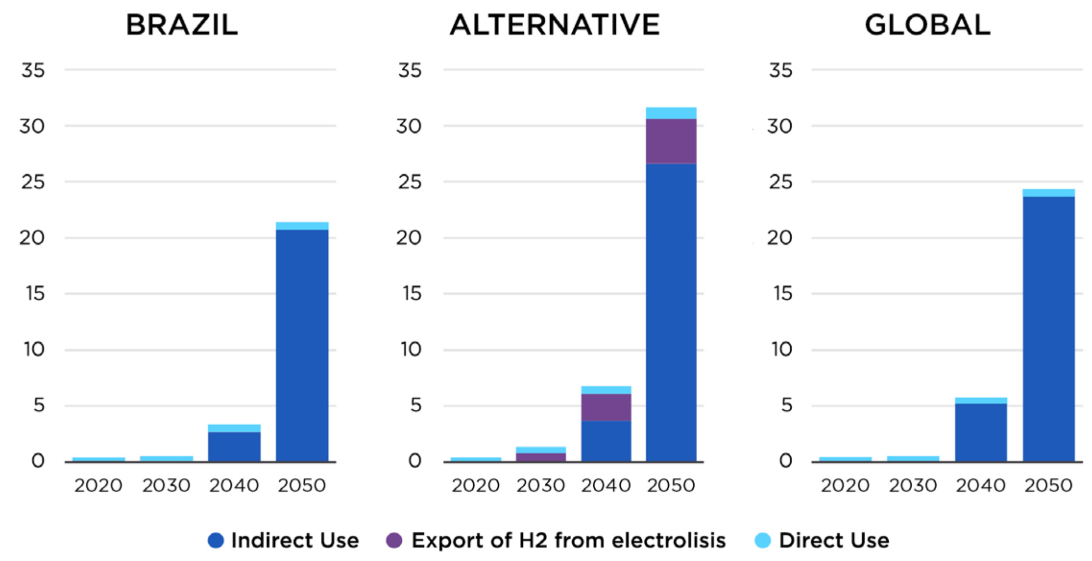
Brazil is one of the best-positioned countries to produce low-carbon hydrogen, including renewable from electrolysis.

Brazil is one of the best-positioned countries to produce low-carbon hydrogen, including renewable from electrolysis. With renewables representing 85% of its power sources, Brazil is the world's third largest producer of renewable power. Because of their ever-falling costs, wind and solar power answer for a significant portion of new capacity added to the system. Brazil's extensive transmission system, which covers most of the country, allows hydrogen producers to operate their electrolyzers more efficiently at greater use factors and to sell excess power to the grid.

We estimate that by 2050 Brazil may be producing very significant volumes, potentially ranging from 21 to 32 million tonnes. Most of that volume will be obtained indirectly, that is, when H_2 is used as an intermediate vector for other applications such as the production of syngas and in ethanol-powered batteries (often translated as cells).

21. Desafios e Oportunidades para o Brasil com o Hidrogênio Verde – E+ Transição Energética (emaisenergia.org)

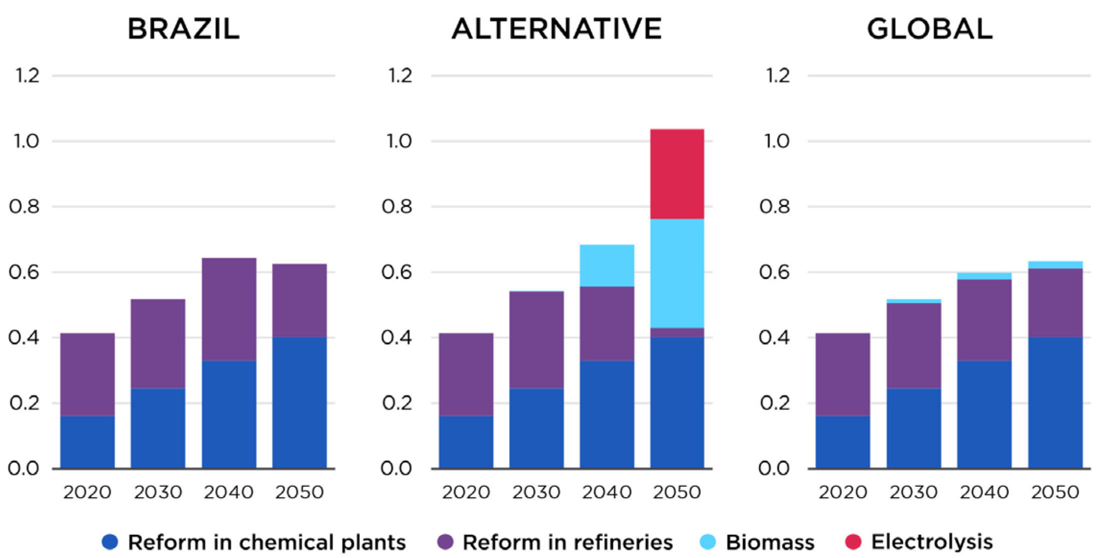
CHART 23 HYDROGEN PRODUCTION (IN MT)



We expect H_2 production to reach 21 and 25 million tonnes in 2050 in scenarios BT and GT, respectively. In scenario AT, H_2 production reaches 32 million tonnes in 2050, both for domestic use and for export, the latter obtained directly through electrolysis.

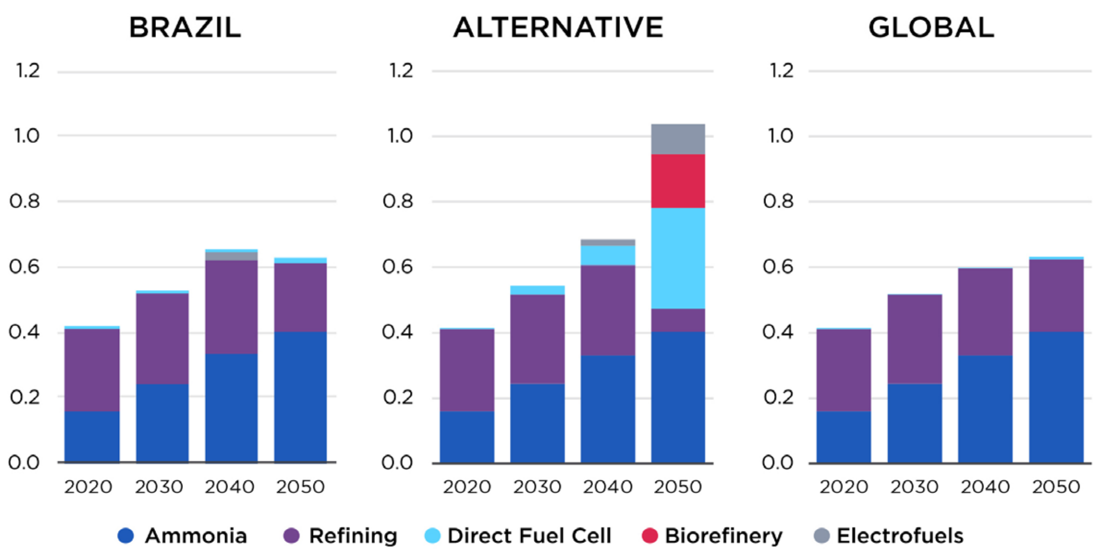
Direct H_2 production for domestic use, obtained mainly through natural gas reform, ranges from 0.6 to 1 million tonnes in all scenarios. Scenario AT includes H_2 production from biomass and through electrolysis in addition to natural gas reform. The chart below shows the direct H_2 production method for all scenarios.

CHART 24 DIRECT HYDROGEN PRODUCTION METHODS (IN MT)



The chart above shows the direct applications of hydrogen in each scenario. Applications in refineries (for fuel specification) and in the chemical industry (ammonia production) are the most significant. In scenario AT, H_2 is also used to produce advanced fuels and electrofuels and directly in fuel cells for the transportation industry.

CHART 25 DIRECT HYDROGEN USES (IN MT)



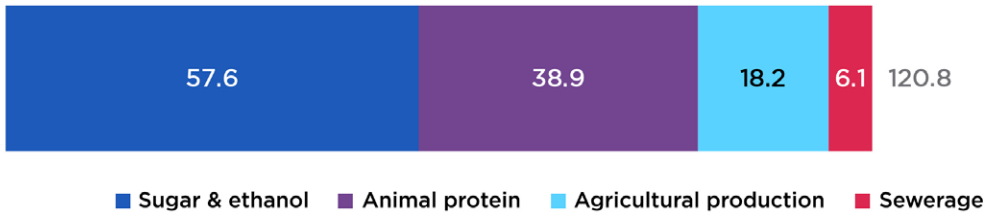
Biomethane is another gaseous fuel with an important role to play in energy transition scenarios. Both hydrogen and biomethane are expected to gradually displace fossil-origin natural gas.

Biomethane is the fuel created from biogas, a gaseous fuel derived from the decomposition of organic materials (of plant or animal origin). That gas mixture, composed mainly of methane, goes through a purification process that renders it interchangeable with natural gas for all applications. It can be transported through the pipeline network mixed with natural gas or via compression or liquefaction (Bio-LNG).

Brazil boasts high potential for biogas and, therefore, for biomethane. As reported by Abiogas and as shown in the chart below, Brazil's biogas potential could reach 120 million m^3/day. Fully processing that potential will yield some 73 M m^3/day in biomethane (assuming biogas to contain 60% methane in average).

Brazil boasts high potential for biogas and, therefore, for biomethane.

CHART 26 DAILY BIOGAS POTENTIAL (IN M³)



Source: ABiogás, 2021

Biogas is today mainly used for power generation. Biogas use to produce biomethane in substitution for gas remains incipient. In its "Technical Note 001/2021 – Overview of Biogas in Brazil 2020", and as shown in table 6 below, CIBiogás found that 19% of the biogas volume was used mainly to produce biomethane.

TABLE 6. USE OF BIOGAS FOR ENERGY PURPOSES IN 2020

MAIN ENERGY APPLICATION OF BIOGAS	NUMBER OF PLANTS		BIOGAS VOLUME (MM³/YEAR)	
Power	543	85%	1,328.3	73%
Thermal power	81	13%	148.6	8%
RNG/Biomethane	8	1%	334.7	19%
Mechanical energy	6	1%	7.5	0.4%
TOTAL	638	100%	1,829.1	100%

The regulation framework for biomethane has been evolving to encourage its use. In contrast with former statutes that addressed only fossil-origin natural gas, under the new Gas Act (Law no. 14,134/21) and its regulating decree (Decree 10,712/21), gases that are interchangeable with natural gas may be processed in the same way for all purposes, provided that they comply with the specifications required by the National Agency for Petroleum, Natural Gas and Biofuels (ANP).

In addition, Decree no. 11,003/22, published in March 2022, created the Federal Strategy to Foster the Sustainable Use of Biogas and Biomethane to encourage its use as a renewable energy source.

In order to include in the model a scenario where the efforts in favor of biomethane came to fruition, scenario AT assumed a production volume of no less than 10 million Nm^3/day from 2030 onward. However, the economic rationale of the model indicated a biomethane volume of 13.4 M m^3/day in 2040.

TABLE 7. BIOMETHANE PRODUCTION IN EACH SCENARIO

	BIOMETHANE			BIOMETHANE + CCS (M M³/DAY)		
	BRAZIL	ALTERNATIVE	GLOBAL	BRAZIL	ALTERNATIVE	GLOBAL
2025	-	-	-	-	-	-
2030	-	-	-	-	-	3.9
2035	0.1	6.5	-	0.6	-	11.3
2040	0.1	13.4	-	6.5	-	17.1
2045	0.1	17.6	-	15.2	-	18.2
2050	-	17.2	-	16.9	-	17.8

Biomethane can significantly contribute to achieve climate goals, with production growing to between 17 and 18 Mm^3/day in the three scenarios.

In scenarios BT and GT, the model associates biomethane production with CCS technology, generating negative CO_2 emissions. Scenario GT assumes biomethane will be used earlier than in scenario BT so that in the former production reaches the very challenging volume on 17 M m^3/day in 2040. Even in scenario AT, which by definition includes a restriction on CCS, production reaches 17 M m^3/day in 2050, between the volumes estimated for scenarios BT and GT.

Demand

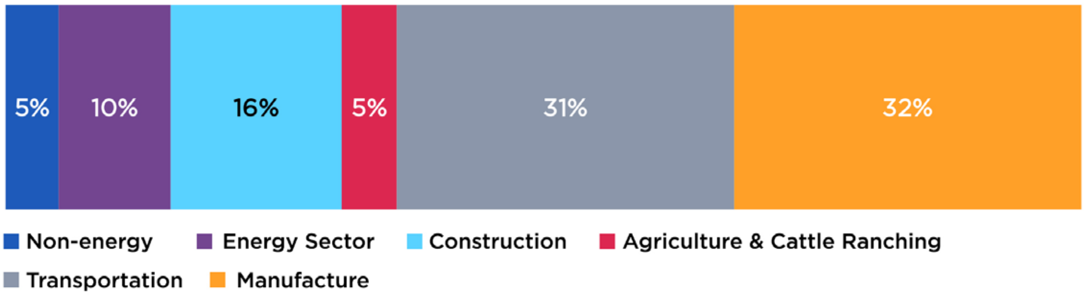
6

End use, the energy aggregate that more adequately reflects demand since it accounts for energy that reaches consumers directly, increases by 35 to 42% over the projection horizon depending on the scenario. In 2020, petroleum products accounted for almost 40% of final energy use, representing the main source for consumers to meet their energy needs.

However and as expected, in all climate neutrality scenarios petroleum products lose share by 2050, especially in scenario AT where the option for decarbonization via electrification pushes the share of petroleum products down to only 19% of end use in 2050. On the other hand, the widespread dissemination of biofuels in the transportation industry drives biomass products to gain significant share, to between 33 and 38%, thus taking the prominent position petroleum products now hold.

Emissions from energy use correspond to approximately 18% of Brazil's total emissions. Breaking down energy-related emissions by activity (see chart below) will show the contribution of each consumption group to the success of climate targets. The most energy-hungry activities, which therefore emit the most, are transportation, manufacture, and, to a lesser scale, construction, power and agriculture & livestock.

CHART 27 FINAL ENERGY USE BY ACTIVITY (2020)



Source: BEN - National Energy Balance

The decarbonization of those activities faces at least three major challenges: (1) the expected growth in demand for energy services in each of those activities, that is, everything remaining the same, emissions will likely increase and not decrease; (2) the technological solutions available to mitigate emissions for some applications need further development and scale; and (3) implementation costs remain high and funding and incentive mechanisms are incipient.

6.1. Transportation Industry

Brazil must dramatically reduce its consumption of fossil fuels to achieve its emission reduction targets[22]. That directly affects the transportation industry, which together with manufacture accounts for almost two thirds of Brazil's final energy consumption. Despite the wide use of biofuels in Brazil, fossil fuels such as diesel oil, gasoline, natural gas, fuel oil and aviation kerosene currently are predominant, representing three quarters of the total fuel volume used for transportation in 2020[23].

Two technological alternatives are available to decarbonize the industry: (i) fleet electrification through the replacement of vehicles now in circulation; and (ii) replacement of fossil fuels with biofuels. Those alternatives may complement each other not only in different market niches (luxury x economy) but also combine (flex hybrid vehicles, ethanol-based fuel cell vehicles, etc.).

Brazil boasts a consolidated decades-old biofuel industry combined with a nationwide supply network, public policies to stimulate biofuels and a significant fleet of flexfuel light vehicles. Those elements put the country in the peculiar position of having adopted decarbonization solutions that predate by many years electrification efforts that have been gaining traction elsewhere in the world[24]. However, if on the one hand Brazil's local solutions such as the widespread use of ethanol for flexfuel vehicles[25] already make its transportation industry "GHG light", on the other hand,

22. According to the Greenhouse Gas Emission and Removal Estimation System (SEEG), the greenhouse gas emissions from Brazil's transportation industry in 2020 totaled 185.5 million tonnes of CO2 eq., corresponding to 8.6% of Brazil's total emissions.

23. According to the National Energy Balance EPE (2022), fossil fuels accounted for 75% of the end consumption of the transportation industry in 2020.

24. According to the World Energy Outlook (IEA 2022), biofuels met less than 4% of world demand for the transportation industry in 2020 but that 25% of that industry's demand in Brazil.

25. According to the Summary National Energy Balance Report EPE (2022), ethanol supplied 43% of light vehicle energy demand.

the global automotive industry's movements and strategies increasingly point to the introduction of electrification in their major markets. This group of players with their own strategies and views on the process seem to create a conundrum for Brazil's transition. Brazil must find national solutions that can be included in the global automotive industry value chain such as, for example, the development of electric vehicles powered by ethanol-based fuel cells and the dissemination of hybrid flex technology to other markets (negotiations in that regard are now in progress between Brazil and India).

The significant complementarity of the alternatives mentioned above is examined in each scenario, taking into account public policy constraints and the peculiarities of the various transportation modes and activities.

Scenario AT found electrification to be the most suitable alternative for light vehicles such as motorcycles, automobiles and light commercial vehicles. Those vehicles usually travel shorter distances and operate for less time during the day, so that they are more easily adaptable to the battery charging routine, which is not to say that battery energy density should not be increased in the long run in order to extend range.

Scenario AT found electrification to be the most suitable alternative for light vehicles such as motorcycles, automobiles and light commercial vehicles.

The battery-based electrification of heavy vehicles, larger trucks in special, is more challenging because of the more complex battery charging logistics for freight vehicles traveling long distances. Higher technological readiness cellulosic biofuels produced from biomass, described in the energy supply section, are the most suitable alternative for those vehicles, mainly trucks and long-distance aircraft and maritime vessels. Indeed, that is the predominant decarbonization solution in scenarios GT and BT.

Scenario AT estimates that electric buses will serve around 40% of mass transit needs by 2050[26]. Short routes and predictable operation conditions make those heavy vehicles easier to electrify in this scenario. Still in scenario AT, fuel-cell vehicles, special heavy-duty ones, are expected to gain market share, serving 1/8 of road freight traffic by 2050.

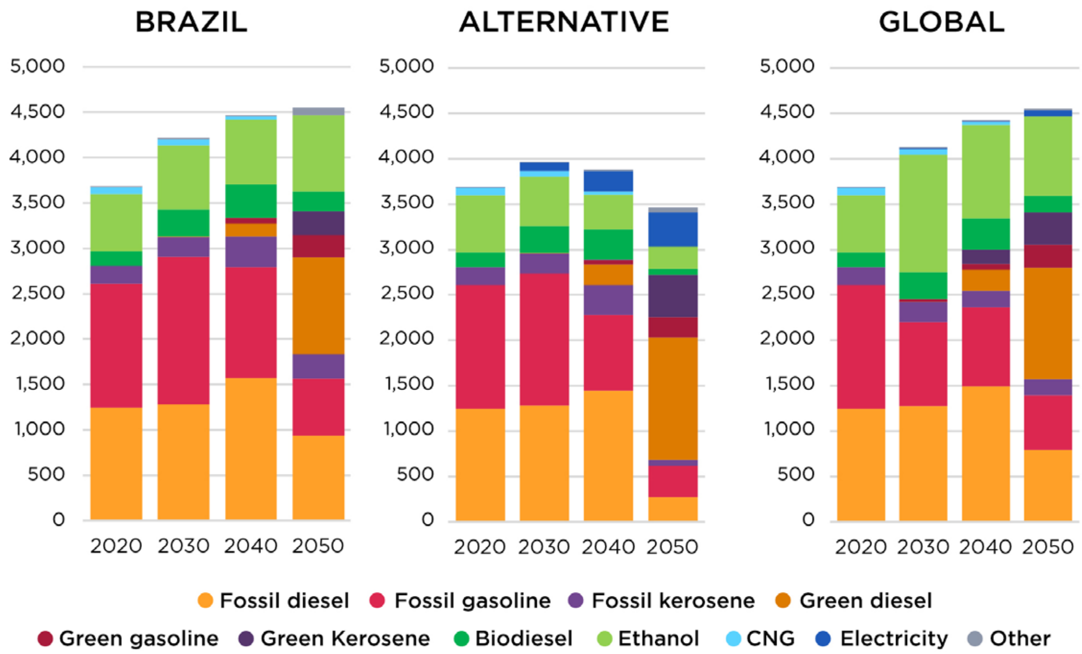
Scenarios BT and GT are essentially the same as far as the transportation industry is concerned, both including mainly biofuel-based decarbonization solutions.

Scenario AT addresses some electrification alternatives involving tax incentives for the purchase of vehicles, reduced licensing fees, increasingly stringent vehicle efficiency and emissions targets (as in the INOVAR AUTO Program (terminated) and in the ROTA 2030 Program (in progress) and the creation of preferential or restricted circulation areas (low and zero emission areas).

The chart below shows energy use in the transportation industry, which grows following a very similar pattern in scenarios BT and GT. Public policies that favor the electrification of passenger and freight transportation in scenario AT and the greater efficiency of electric engines causes total energy use in the transportation industry to fall by 22% and electricity to account for 11% of its energy demand by 2050.

26. Measured in passenger-kilometers carried (pkm).

CHART 28 ENERGY MIX OF THE TRANSPORTATION INDUSTRY (PJ)

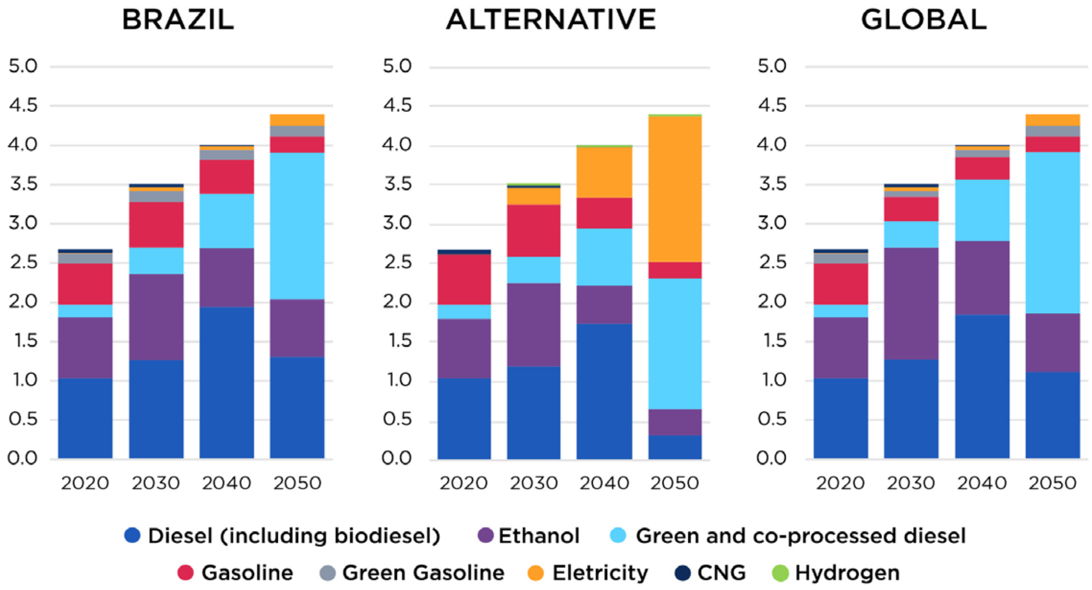


Given the importance of the road transportation mode in Brazil's mix, below we give details on road passenger and freight transportation. The fast-paced increase in the use of cellulosic biofuels for road passenger transportation shown in scenarios BT and GT makes way for reducing emissions despite the fleet relying in 2050 on essentially the same technology used today, with few battery-powered electric vehicles (BEV). The predominant decarbonization paths in those scenarios (BT and GT) are guided by the competitiveness of biofuels in Brazil and by the maturity of our biofuel industry, so that battery-based fleet electrification is not the least clostly option. The flexfuel technology will continue to dominate light vehicle sales throughout the projection horizon in those scenarios. Still in scenarios BT and GT, flexfuel automobiles are expected to be 70% supplied by biofuels in 2050. The chart below breaks down automobile sales by type of technology.

Scenario AT sees electric vehicles gaining greater share with the introduction of purely battery-based vehicles (BEV). Vehicles using that engine technology are projected to represent 40% of total automobile sales and 43% of energy demand in 2050. Electrification thus is not the sole decarbonization path in this scenario, which sees cellulosic biofuels significantly replacing fossil fuels for internal combustion vehicles and reaching 40% share of the energy mix[27]. Urban buses and light commercial vehicles and motorcycles will give the greater contribution to the electrification of passenger road transportation, the former two thanks to the predictability of their routes and to their operating regimes and the latter because of their short service life and their low replacement cost. The chart below shows the share of each fuel in passenger transportation.

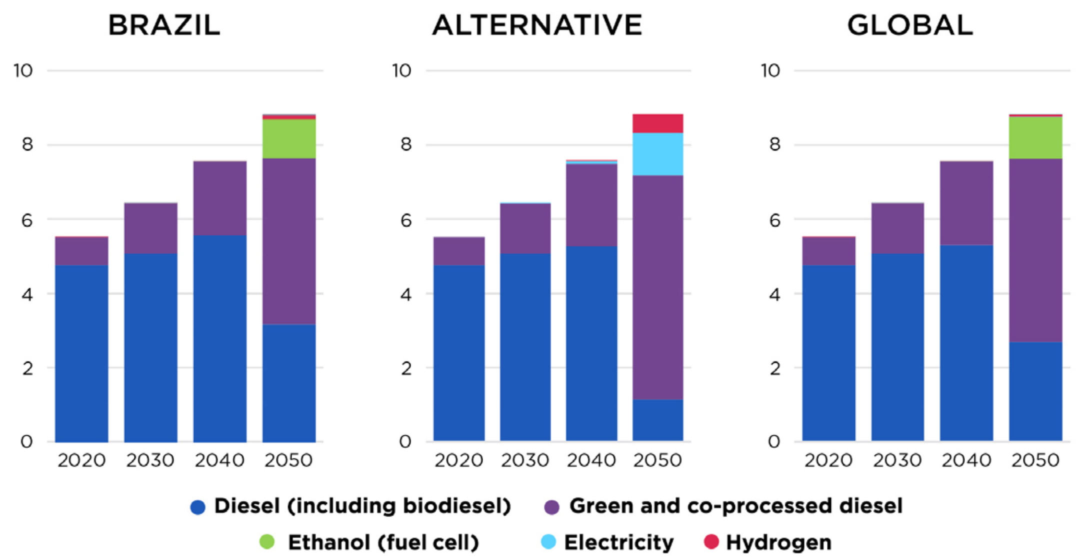
27. See ANFAEVA, O caminho da descarbonização do setor automotivo no Brasil, 2021. https://anfavea.com.br/docs/apresentacoes/APRESENTA%c3%87%c3%830-ANFAVEA-E-BCG.pdf

CHART 29 PASSENGER TRANSPORTATION BY TYPE OF FUEL (BN PKM)[28]



Energy use in road freight transportation is concentrated in high-capacity trucks driving long-haul. Energy density is particularly important when moving freight over long distances. The energy density of batteries is still significantly lower than that of liquid fuels, which makes heavy-duty transportation hard to electrify. The chart below shows that scenarios BT and GT use similar technological solutions. Sales of ethanol-based fuel cell trucks gather pace from 2040 on and as early as in 2050 this type of engine is projected to answer for 11% (BT) and 13% (GT) of energy demand, contributing along with green diesel to replace fossil diesel.

CHART 30 FREIGHT TRANSPORTATION BY TYPE OF FUEL (BN TKM)[29]



28. Billion passenger-kilometers carried. Unit used to measure passenger mobility demand/activity level.

29. Billion tonne-kilometers carried. Unit used to measure freight transportation demand/activity level.

In scenario AT, sales of electric light trucks rise throughout the projection horizon, gaining traction after 2035 and exceeding 80% of sales in 2050. For the reasons discussed above, sales of electric heavy vehicles do grow but less consistently, making room for the introduction of H_2 fuel cell vehicles during the 2040s. In scenario AT, by 2050 hydrogen is expected to account for 6% of all road freight transportation activity and electric vehicles are projected to represent 13% of the fleet.

CHART 31 LIGHT TRUCK SALES BY TYPE OF TECHNOLOGY

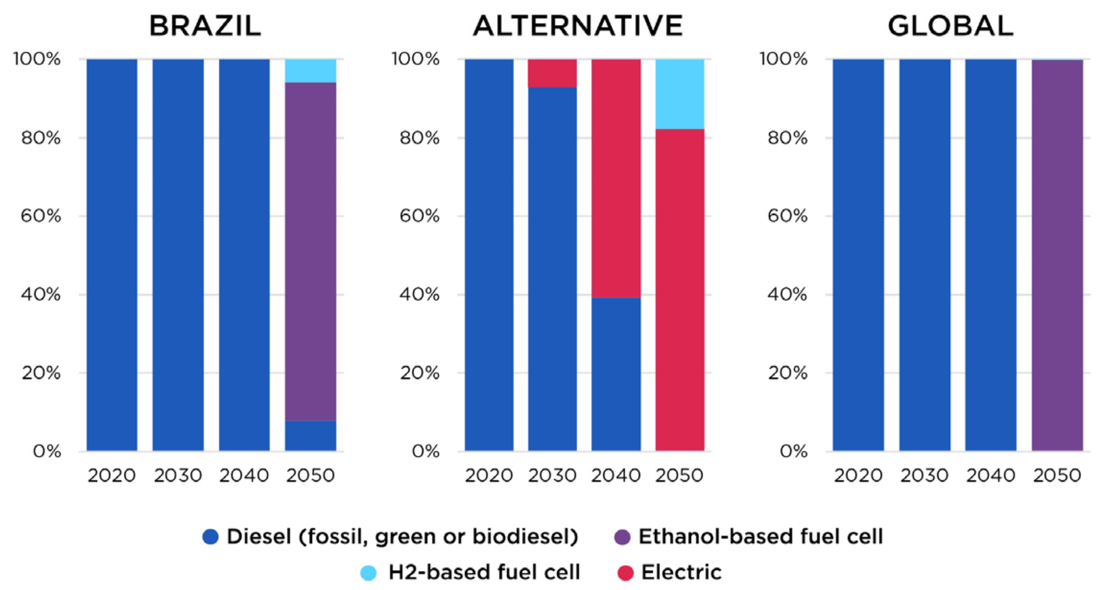
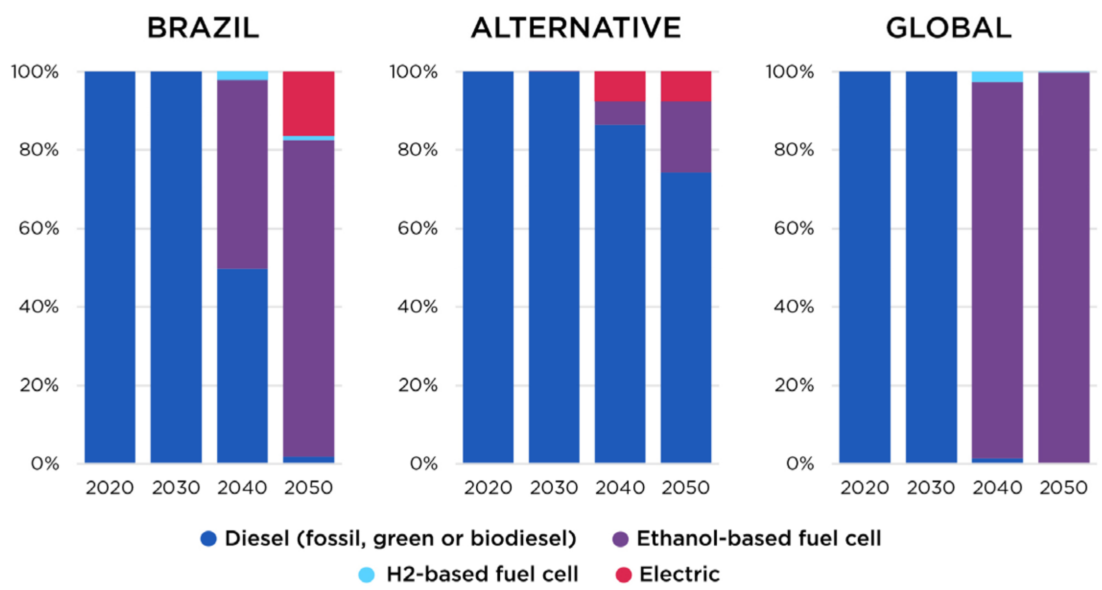


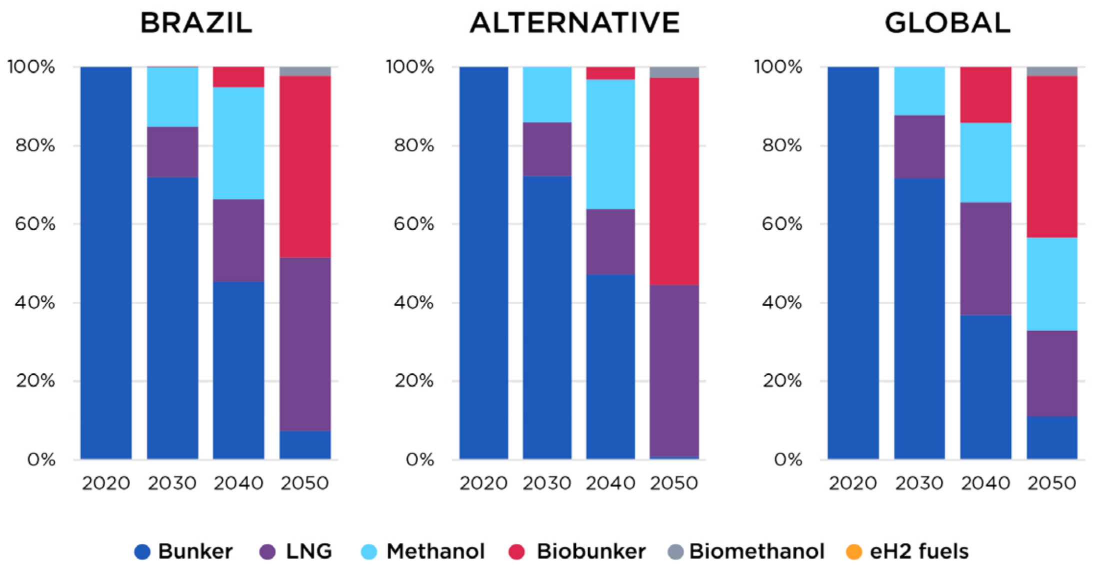
CHART 32 HEAVY TRUCK SALES BY TYPE OF TECHNOLOGY



A relatively diverse basket of technological solutions is already available to decarbonize road vehicles, which cause the largest share of the transportation industry's emissions. The same, however, is not true for aircraft and maritime vessels. Both require high energy density fuels to reduce the volume and mass of the fuel they carry. The selection of alternatives takes into account availability, energy density, certification standards, compatibility with the current fleet, storage infrastructure, technological maturity and safety for use. Aircraft electrification is not yet a viable alternative for long-haul commercial flights and hydrogen remains a distant promise. Drop-in fuels are the preferred alternative in all scenarios, with biokeresene representing 64% of aircraft fuel supply in scenario BT, 86% in scenario AT and 74% in scenario GT in 2050.

Based on the criteria mentioned above, our model found a slightly broader set of substitute fuels for waterway transportation activities. The chart below shows the importance of methanol and LNG as short and medium term alternatives and of biobunker as a longer term solution.

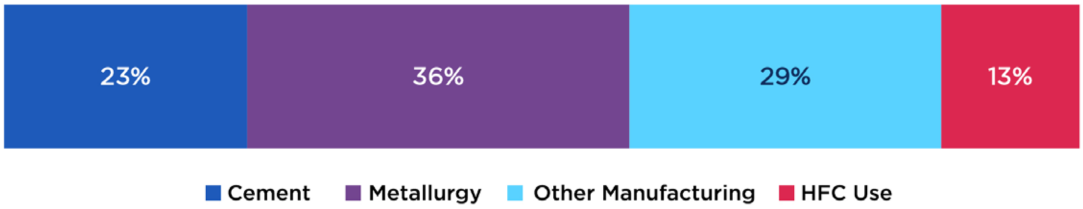
CHART 33 WATERWAY TRANSPORTATION BY TYPE OF FUEL



6.2. Manufacturing

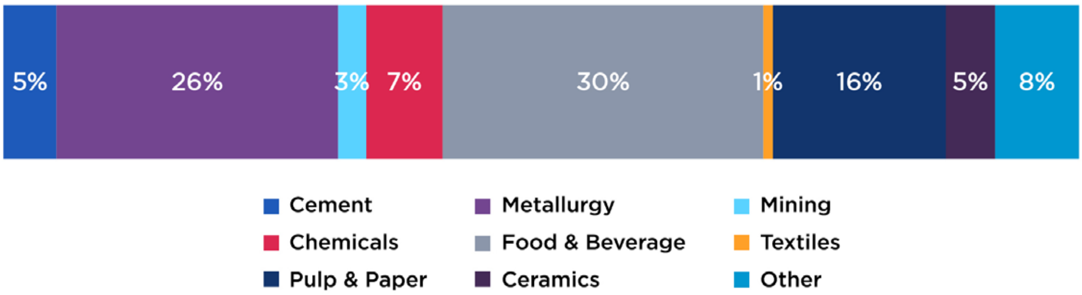
Manufacturing adds to Brazil's total emissions both by burning fossil fuels and through industrial production processes. In relation to the latter, the industries that emit the most are metallurgy and cement manufacturing. Those industries not only are the biggest emitters but also face the hardest technological hurdles to decarbonize because emissions are intrinsic to their manufacturing processes. The Food and Beverage industry is noteworthy because it emits little GHG despite being a heavy energy user relying on fossil sources for more than 80% of its energy.

CHART 34	GHG EMISSIONS BY INDUSTRY (2020)



Source: Greenhouse Gas Emission and Removal Estimation System (SEEG)

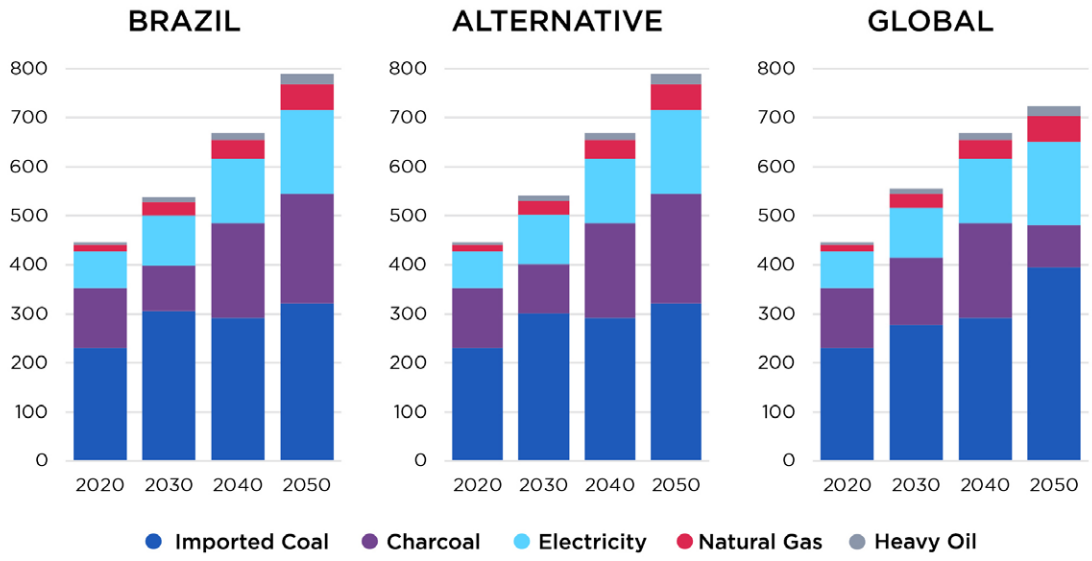
CHART 35	FINAL ENERGY USE BY INDUSTRY (2020)



Source: EPE National Energy Balance (2022)

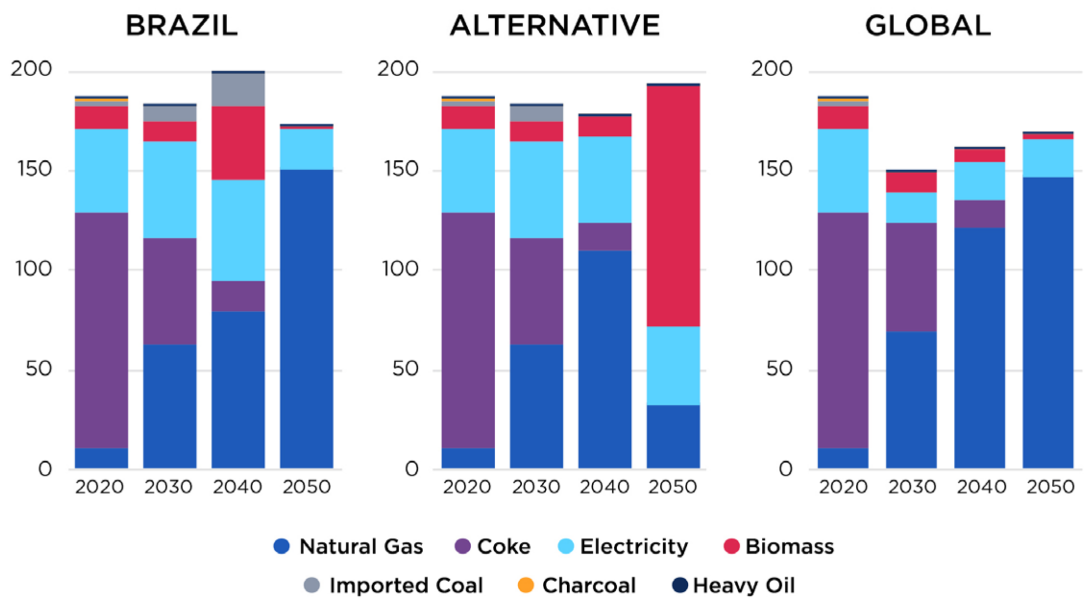
Scenarios BT and AT project that during the 2040s charcoal will replace mineral coal as energy source for steelmaking, which is the main activity in the metallurgical industry. End use in both scenarios in 2050 is 6% higher than in scenario BAU in 2050. The increase is due mainly to the lower calorific value of charcoal, which degrades the efficiency of the process. The end use shows efficiency gains in scenario GT due mainly to greater industry electrification. Steel can be produced through two main processes: (i) integrated blast furnaces (BOF) or electric arc furnaces (EAF). Integrated plants make steel from iron ore and need coal as reducer and EAF plants use scrap or sponge iron as their main feedstock. The use of electric arc furnaces (EAF) favors recycling and, combined with the supply of renewable power, can potentially mitigate the industry's emissions. The option for that industrial process obviously requires plentiful scrap, which is more readily available in more mature economies. Direct reduction using H_2 (DRI-H_2) is a promising option that deserves careful analysis in future studies.

CHART 36 END USE OF ENERGY IN THE STEEL INDUSTRY



The decarbonization of the cement industry is one of the biggest challenges in the transition to a low-carbon manufacturing sector because emissions are intrinsic to its production process. Barring the emergence of new technological production routes, the best solution currently available to reduce process emissions (when feasible) is carbon capture (CCS). The substitution for cleaner energy sources can also contribute to mitigate emissions. As the chart below shows, our model projects that petroleum coke, which today accounts for around 70% of the industry's energy supply, will be fully replaced by other energy sources: natural gas and in scenarios BT and GT and also biomass in scenario AT, given its on CCS restriction.

CHART 37 END USE OF ENERGY IN THE CEMENT INDUSTRY



Petrochemicals are one of the few applications for fossil fuels, particularly oil and natural gas, that offer the oil and gas industry some resilience amid the energy transition. That said, plastic waste pollution already imposes certain constraints on that industry's growth. Disposable plastics are increasingly prevalent around the world. They pose a threat to natural ecosystems and are a vector for climate change. The current situation is deemed a global crisis requiring systemic change in the way plastics are produced, consumed and disposed of in the economy.

Petrochemicals are one of the few applications for fossil fuels, particularly oil and natural gas, that offer the oil and gas industry some resilience amid the energy transition.

All transition scenarios see a lower demand for energy in 2050 if that trend continues. Scenario AT shows noticeable greater participation of ethanol (ethylene and butadiene production routes) and electricity and smaller participation of natural gas. In that circumstance, the increased production of bio-ethene requires routes that can produce propene and Benzene Toluene and Xylene (BTX), for example, via petrochemical bio-naphtha (originated from biomass to liquids processes described in the supply section, for use in conventional steam crackers) and bio-GLP (idem, but in this case using PDH-type processes). Routes to produce petrochemicals from renewable feedstocks are already available in Brazil. Braskem's Triunfo/RS plant includes a unit that makes green ethylene from ethanol.

6.3. Construction Industry

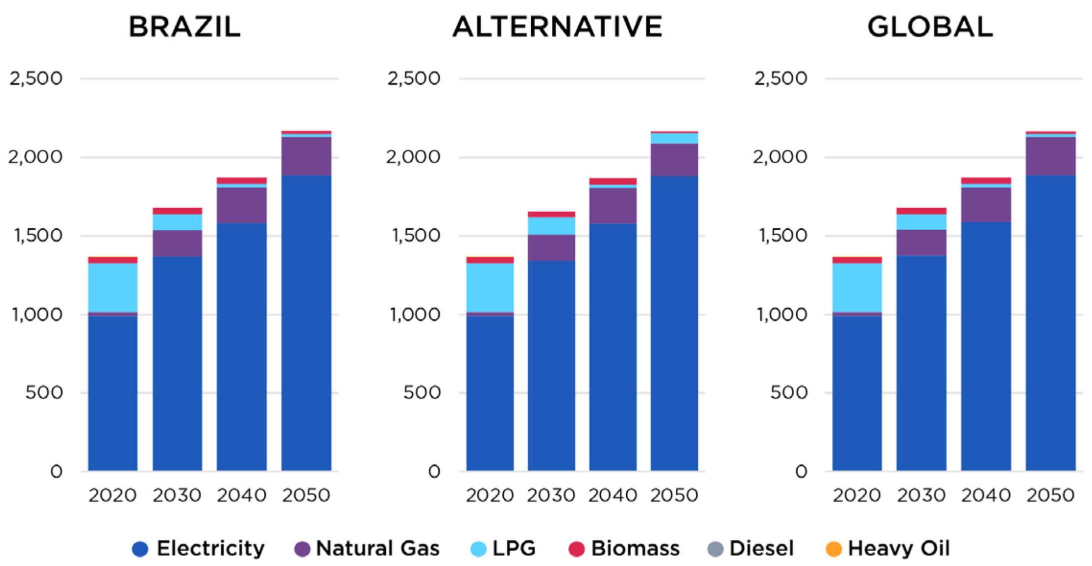
The main sources of end use energy for the Residential sector were electricity (47%), firewood (27%) and liquefied petroleum gas (24%). The residential sector represents about 70% of total demand of the aggregate designated "construction".

The growing ownership and use of equipment, magnified by income growth and by the electrification and digital transformation of buildings, and the rapid expansion in the total built area in emerging countries such as Brazil indicate that energy demand in those countries will increase. Electricity, which already is one of the main sources of energy for end use in the residential sector, will gain ground in all scenarios. The increased purchasing power of an expanding middle class is a significant driver of growth in energy demand. The challenge of energy transition will be to reconcile this demand growth trend with sustainability.

Our projections found no significant variation between scenarios for the residential and services sector, whose energy use is expected to grow by approximately 60%. In parallel to the increased importance of electricity as energy source, reflecting the greater use of equipment, liquefied petroleum gas (LPG) will be widely replaced by natural gas for cooking and heating applications. Demand for natural gas will grow almost tenfold between 2020 and 2050 in the construction industry.

Our model projects no increase in the use of firewood, which will occur only in response to social problems that for economic reasons restrict access to modern fuels. Our results are based on the premise that this current problem will be solved in scenarios that also involve ambitions to decarbonize the economy.

CHART 38 END USE OF ENERGY IN THE CONSTRUCTION INDUSTRY (PJ)



In relation to electricity consumption, distributed generation (GD) using solar panels stands out. DG installed capacity will have reached the maximum potential (43.2 GW) for all scenarios by 2050 and five years earlier in scenario AT.

Public Policy Recommendations

7

Our decarbonization scenarios indicate the importance of using new policies, new tools and energy vectors to accelerate the reduction in emissions in a robust path toward carbon neutrality.

The trends outlined in our decarbonization scenarios suggest the creation of public policies: (i) to eliminate deforestation and to enhance nature-based carbon removal solutions; (ii) to develop advanced biofuels (cellulosic, HVO, etc.), with special focus on BECCS; (iii) to modernize the power industry and to foster the increase in generation using renewable sources; (iv) to promote the electrification of the transportation industry using Brazilian solutions that can be included in the global automotive industry value chain (flex hybrid vehicles, ethanol-based fuel cell vehicles, entry-level or economic internal combustion vehicles that use e-fuels for lower income markets, for example); (v) to extend the competitiveness of oil and natural gas resources through the maintenance of their triple resilience (technical, economic and environmental). The implementation of those five policies requires the consolidation of medium and long-term indicative and integrated energy planning tools to identify opportunities that take advantage of Brazil's competitive edge and their articulation in national plans and roadmaps that promote open and competitive market designs (without technological locks) and coordinated actions to open paths (flexible or not) and to monitor the achievement of objectives.

The key actions to take by 2030 are those associated with land use. They require relatively little investment and will hugely impact Brazil's emissions, with significant repercussions on post-2030 mitigation efforts. Changes in the energy sector may be implemented gradually, with greater impact in the long term, after 2030. But they also merit attention and policies (some already exist) to encourage their implementation, especially policies associated with R&D and with the institutional framework[30]. The actions recommended below should be implemented until 2030 for our energy transition scenarios to succeed.

30. See CNPE Resolution no. 2/2021, the RenovaBio Policy, the New Gas Market Policy, the Brazilian Nuclear Policy, the Zero Methane Program, the "Abastece Brasil" Program, the Fuel of the Future Program, the National Hydrogen Program - PNH2, the Route 2030 Program, the Sanitation Legal Framework, the Micro and Mini Distributed Generation Framework - MMGD, the offshore wind regulation process, etc.

1. **Build an energy policy agenda and design markets that can open flexible decarbonization paths** to address the technological and market uncertainties identified taking advantage of the synergies provided by Brazil's diverse energy resources, in line with an economy-wide approach to Brazil's NDC goals;

2. **Minimize regrets through open, diverse and competitive market approaches** and through the combination of and competition between different technological solutions (technological neutrality);

3. **Harmonize sustainable development, energy transition and energy security objectives** taking advantage of Brazil's resource potential and market and innovation opportunities;

4. **Take advantage of Brazil's existing competitive edges to build and fund the competitive edges of tomorrow, upgrading assets and focusing expertise** on the energy transition of the O&G, biofuels, renewables and nuclear industries (co-firing with renewables, new decarbonized energy sources, synergies with renewables projects, new uses for infrastructure and assets, funding new businesses, etc.);

5. **Meet Brazil's current objectives/targets in line with (net) climate neutrality commitments**, such as eliminating illegal deforestation by 2028, recovering degraded areas, reducing fugitive methane emissions, decarbonizing fuels and others;

6. **Ensure that the transition of the Brazilian energy sector is fair, inclusive and cost-effective** and does not involve offsetting GHG emissions associated with land use, forestry and extensive livestock in any way that will cause higher costs for Brazil's society and economy;

7. **Improve or establish institutional, legal and regulatory frameworks conducive to the development and use of technologies and business models focused on reducing emissions and on removing carbon from greenhouse gas emissions**. In particular, it is critical to establish or improve frameworks for CCS (key to BECCS and to define the role of O&G in energy transition), renewables for power generation, advanced biofuels, new energy sources (low-carbon hydrogen, synthetic fuels, etc.), energy storage and carbon pricing, as well as for the adoption of new end-use technologies (including the electrification of transportation, new industrial applications, etc.);

8. **Map, supplement and disseminate information on the technical, economic and market potential of the alternatives identified in the different scenarios**, especially CCS, renewables for electricity generation, advanced biofuels and hydrogen;

9. **Further study the climate resilience of the energy solutions found in the project**, especially hydro, wind and solar power and biofuels (energy agriculture).

Appendix
Methodology

Critical Uncertainties

The road to build long-term scenarios for Brazil's Energy Transition began with the identification of the critical uncertainties that guide this process. When preparing scenarios, "critical uncertainties" mean information, questions, issues or arguments that assist the specification of the dynamics of all other variables that influence the outcome of a scenario. Building scenarios based on their critical uncertainties makes the exercise less complex and shifts focus to their practical use so as to get answers and insights.

The first step to identify the critical uncertainties in the PTE occurred through seminars and interviews, followed by an information prioritization phase carried out through an ideation exercise. Those interactions were used to capture the perceptions doubts, certainties, desires and concerns of stakeholders focusing mainly on the energy transition. Forty-two industry representatives from businesses, associations, universities and regulatory agencies were interviewed. Their perceptions were reviewed, consolidated and categorized to guide the issues the scenarios were to address[31].

31. The full list of these topics can be found in "Tendências e Incertezas da transição energética no caso brasileiro" at: https://www.cebri.org/br/doc/228/tendencias-e-incertezas-da-transicao-energetica-no-caso-brasileiro

Identification of uncertainties

Questionnaires put to experts present at events held during the 1st phase of the project (Divergence Phase) raised a number of uncertainties

Meetings with business in the 2nd phase of the project (Convergence Phase) raised another uncertainty

The validation process in the 2nd phase with CEBRI, EPE and IDB experts raised 3 new uncertainties

The next step involved identifying the variables that synthesized all those issues and defining the filters to trim the number of variables as much as possible. Targeted research was used to help categorize the information gathered based on their impact and uncertainty levels. Low-uncertainty issues/variables were designated "trends" and high-impact and high-uncertainty ones were deemed candidates to become "critical uncertainties". The latter included, among others:

- Public policies;
- Changes in the geography of global value chains;
- Price of oil;
- Price of natural gas;
- Oil and Gas taxation in Brazil;
- Carbon pricing policies in Brazil;
- Electrification of the light vehicle fleet;
- Ethanol-based fuel cell;
- Production of low-carbon hydrogen in Brazil;
- Investments to expand the gas pipeline network;
- Stakeholder behavior;
- Income growth in Brazil;
- The role of natural gas in Brazil's transition;
- Changes in the Brazilian power industry;
- Emissions for non-energy use.

The 3rd step used a "cross-impact matrix" to reduce the number of variables selected for treatment. The method prioritizes those variables that better affect and explain the others. The matrix is organized to describe the level of impact that each variable placed in the row has on the variable placed in the column. The rows that scored the highest were those whose variables have the greatest influence on the others. Six variables stood out in this exercise: i) Public policies; (ii) Price of oil; (iii) Price of natural gas; iv) Oil and gas taxation in Brazil; v) Carbon pricing policies in Brazil; and vi) Consumer behavior.

Variables "Price of Oil" and "Price of natural Gas" were ultimately excluded because they were deemed to be scenario outputs and not necessarily inputs to build scenarios. Variables "Oil and gas taxation in Brazil" and "Carbon pricing policies in Brazil" were also excluded because they are contingent on variable "Public policies"[32].

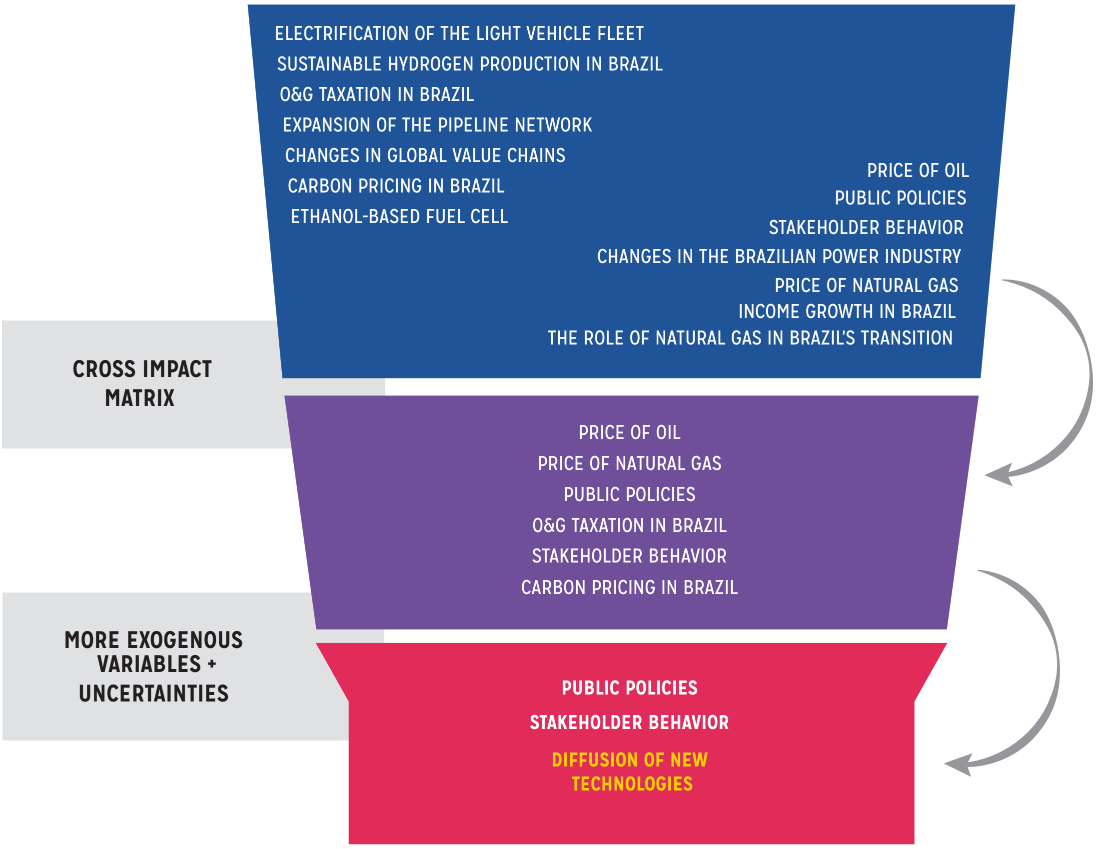
The CEBRI, EPE and IDB teams then agreed to include a technological aspect to the transition so that the three critical uncertainties selected were:

- Public policies;
- Stakeholder behavior;
- Technological diffusion.

The logic of our scenarios was based on those three variables.

32. The fact that those variables were not used as critical uncertainties does not mean that they will be ignored in the scenario preparation process. The point is that their dynamics will be guided by the critical uncertainties selected.

Uncertainty priority



Starting Point

Let us now focus on the starting point for the variables that guided the paths created for each scenario. The question to ask is: how did we get here? What are the current characteristics of the energy transition process, of energy markets, and of the forces that shaped it?

The main drivers are the United Nations Conference of the Parties (COP) and the growth of renewable energy.

How did we get here?
What are the current characteristics of the energy transition process, of energy markets, and of the forces that shaped it?

The United Nations Conference

In 1992, Rio de Janeiro hosted the United Nations Conference on Environment and Development. Twenty years after the first Stockholm Conference, which marked the beginning of international discussions on the environment, the so-called "Earth Summit" gathered the record-breaking total of almost 180 nations to jointly review the world's major environmental problems and to discuss solutions to combine social and economic development with environmental preservation.

The Climate Convention, also known as UNFCCC (United Nations Framework Convention on Climate Change), was signed during the meeting. This Convention consolidates the commitments of all signatory nations and, although it does not establish mandatory compliance with each nation's voluntary goals, the fact that it is an international agreement turned it into a decisive element in foreign policy agendas.

The first COP (Conference of the Parties) took place three years after the Earth Summit, when the UNFCCC already was in force. The Conference of the Parties emerged as an annual state meeting to define global rules to implement actions to combat the climate crisis. The table below (Figure 1) describes major COP milestones in recent years.

FIGURE 3 KEY MILESTONES OF THE UNITED NATIONS CONFERENCE

1992	1995	1997	2015	2021
Earth Summit	**COP 1 - Berlin**	**COP3 - Kyoto**	**COP21 - Paris**	**COP26 - Glasgow**
The Climate Convention, also called the United Nations Framework Convention on Climate Change (UNFCCC), was signed in the meeting and entered into force in 1994.	First meeting of the UN Conference of the Parties established the legal grounds for the Climate Convention.	Early-development countries agreed to shoulder a larger share of costs in combating the climate crisis. The protocol was not approved by the US, the largest emitter at the time.	The Paris Agreement established the commitment to stabilize global warming "well below 2°C" and that all nations should adopt NDCs (Nationally-Determined Contribution).	The Glasgow Climate Pact was signed to limit global warming to 1.5°C and to reduce subsidies for coal and fossil fuels.

The agreement subjacent to the commitments now in place was established in the COP21, in 2015. The so-called "Paris Agreement" proposes to reform of the world economy to reduce greenhouse gas (GHG) emissions and includes provisions to encourage developed countries to give financial and technological support to enable less developed countries to take further action.

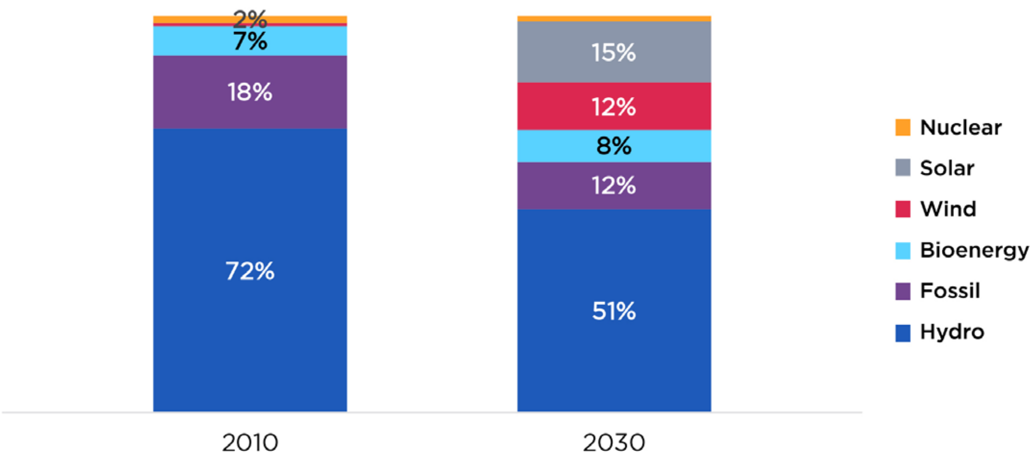
As signatory to that Agreement, Brazil committed to reduce its GHG emissions by up to 37% by 2025 (compared to 2005 levels) and by up to 43% by 2030. Brazil also committed to bringing forward the elimination of illegal deforestation from 2030 to 2028.

Renewable Energy Growth

The International Energy Agency (IEA) projects that renewable energies will gradually and continually grow from their current 80% share of Brazil's power generation mix to reach 86% by 2030.

However, although Brazilian built its power generation infrastructure on the back of its water resources, the IEA does not see renewable energy growing through hydropower (on the contrary, hydropower's share is expected to decrease) but through wind and solar power and bioenergy, which together will represent 35% of Brazil's installed generation capacity in 2030, showing almost four-fold growth in relation to their 2010 share.

CHART 39 BRAZIL'S POWER GENERATION CAPACITY (GW)

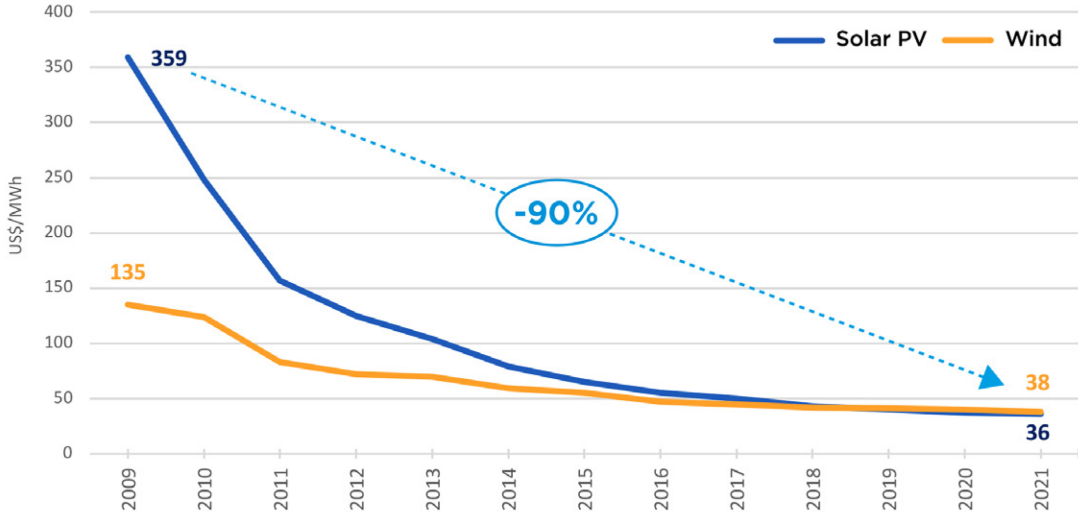


Source: IEA, WEO 2020

That increase results from the combination of the huge reduction in cost for those sources in the last decade with Brazil's high potential for wind generation (thanks to strong, constant and single-direction winds in most of the country), for solar generation (Brazil's annual average irradiation exceeds that of most European countries) and for bioenergy generation (Brazil's bioenergy industry is well-developed).

Although Brazilian built its power generation infrastructure on the back of its water resources, the IEA does not see renewable energy growing through hydropower but through wind and solar power and bioenergy.

CHART 40 REDUCTION IN THE COST OF RENEWABLE ENERGY



Source: Lazard Levelized Cost of Energy, 2021

Economic Assumptions

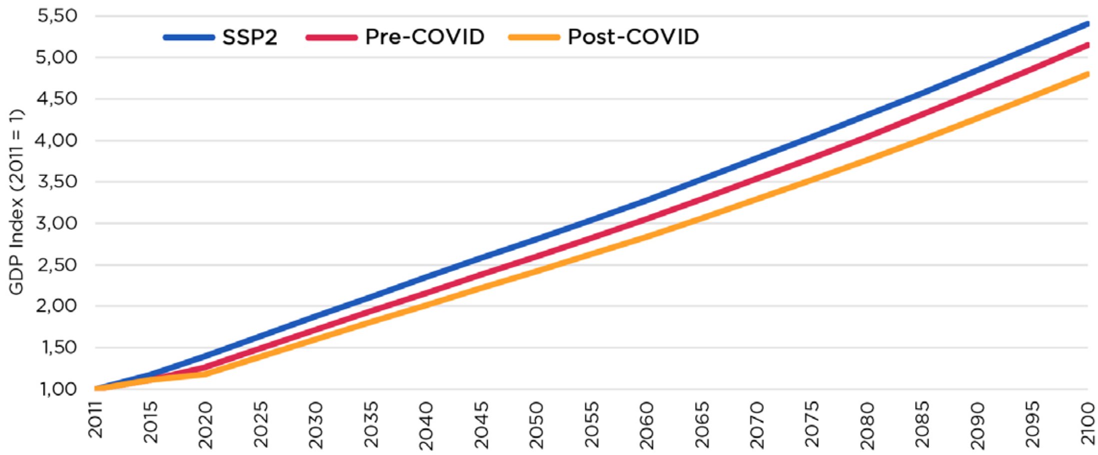
The macroeconomic assumptions embedded in our economic model are based on Shared Socioeconomic Pathways (SSPs)[33] . SSPs qualitatively and quantitatively describe different evolution pathways for society, the economy and ecosystems until the end of the century (Riahi et al., 2017).

The first step in preparing the macroeconomic assumptions in our work involved updating the SSP2 (Middle of the Road) scenario, where the world's social, economic and technological trends do not change significantly and adhere to historical patterns. SSP2 economic projections were developed by the OECD (Organisation for Economic Co-operation and Development) Environment Directorate, OECD Economics Department, Wittgenstein Centre for Demography and Global Human Capital and Potsdam Institute for Climate Impact Research (Riahi et al., 2017; KC, and Lutz, 2017; Dellink et al. 2017).

The SSP2 update used historical data from the World Energy Outlook (IEA, 2019), represented by the blue line shown in the chart below, and 2020-2100 global GDP projections based on the SSP2 scenario. Long-term regional Gross Domestic Product (GDP) estimates were adjusted based on the most recent IMF/WEO (2020) projections to incorporate the impacts of the COVID-19 pandemic on economic activity in 2020 (yellow line). The impacts of the pandemic on global economic activity were taken into account so that the economic recovery tracked the post-2020 SSP2 annual economic growth rate.

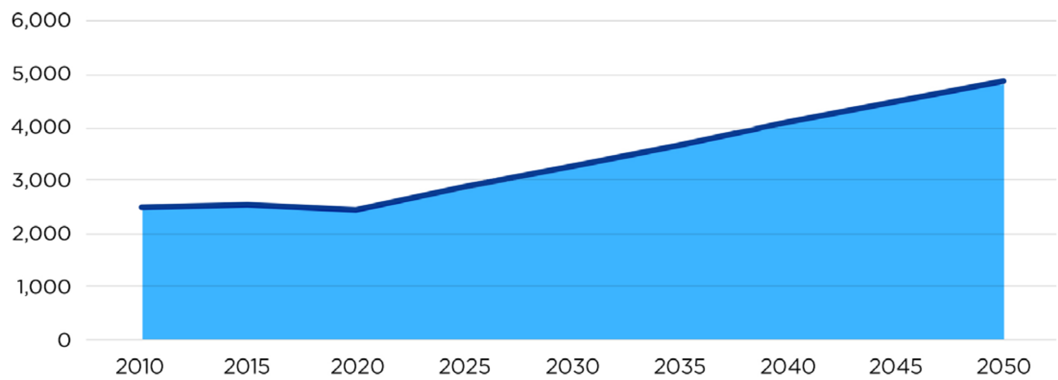
33. SSPs represent 5 possible socioeconomic paths for the global future, with differences in population growth, economic development, cooperation between countries, changes in inequality levels, among others.

CHART 41 GLOBAL GDP BETWEEN 2020 AND 2100 BASED ON THE SSP2 SCENARIO



Despite including no post-crisis (COVID-19) recovery, the SPP2 growth projection for the Brazilian economy (blue line) exceeded the Focus projection. However, the SSP2 scenario expects economic growth to lose steam from 2031 onward in line with the projected population slowdown (+0.3% p.a. between 2020 and 2050 in SSP2). The Actual/SSP2 scenario to be used in our model thus reflects the update in historical 2011-2019 GDP growth rates and the impacts of COVID-19 on economic activity in Brazil in 2020.

CHART 42 BRAZIL'S GDP BETWEEN 2020 AND 2050 BASED ON THE SSP2 SCENARIO (IN US$ BILLION AT 2010 PRICES)



Source: Project team based on Febraban data (2020)

The economic scenarios were used as basis to project industry demand for energy and for food, necessary for the BLUES – Brazil Land-Use and Energy Systems technological model (Rochedo et al., 2018; Koberle, 2018). In a nutshell, BLUES is an optimization model geared to meet Brazil's demand for energy services and for food (for domestic use and export) at the lowest possible cost. The model minimizes the total cost of energy and land use systems, including the power generation, agriculture and livestock, manufacture, transportation and construction industries, subject to constraints that represent real-world constraints for the full range of pertinent variables, including land use.

TABLE 8. ECONOMIC AND DEMOGRAPHIC ASSUMPTIONS

	POPULATION (MILLION INHABITANTS)	**GDP** (in 2010 US$ bn/year)
2010	282.4	2,486.1
2015	304.0	2,530.1
2020	324.7	2,455.5
2025	343.0	2,886.0
2030	358.2	3,294.3
2035	371.5	3,686.3
2040	382.6	4,089.7
2045	391.1	4,496.1
2050	396.7	4,896.8

Integrated Assessment Models

The methodology uses models developed over the last twenty years by a multidisciplinary team with experience in engineering, economics and public policy at the Coppe/UFRJ Cenergia laboratory. Those models, designated Integrated Assessment Models (IAMs), create representations of energy, land use and water resource systems and of their environmental impacts that are used to build medium- to long-term scenarios based on social, economic, technological, public policy and environmental assumptions. IAMs are often used by international research groups and by the Intergovernmental Panel on Climate Change (IPCC) to define transition scenarios for a low-carbon world considering the interactions between different economic sectors, greenhouse gas (GHG) emissions and their consequences on the global climate.

We used the three IAMs developed by Cenergia/COPPE and described below to build our long-term scenarios.

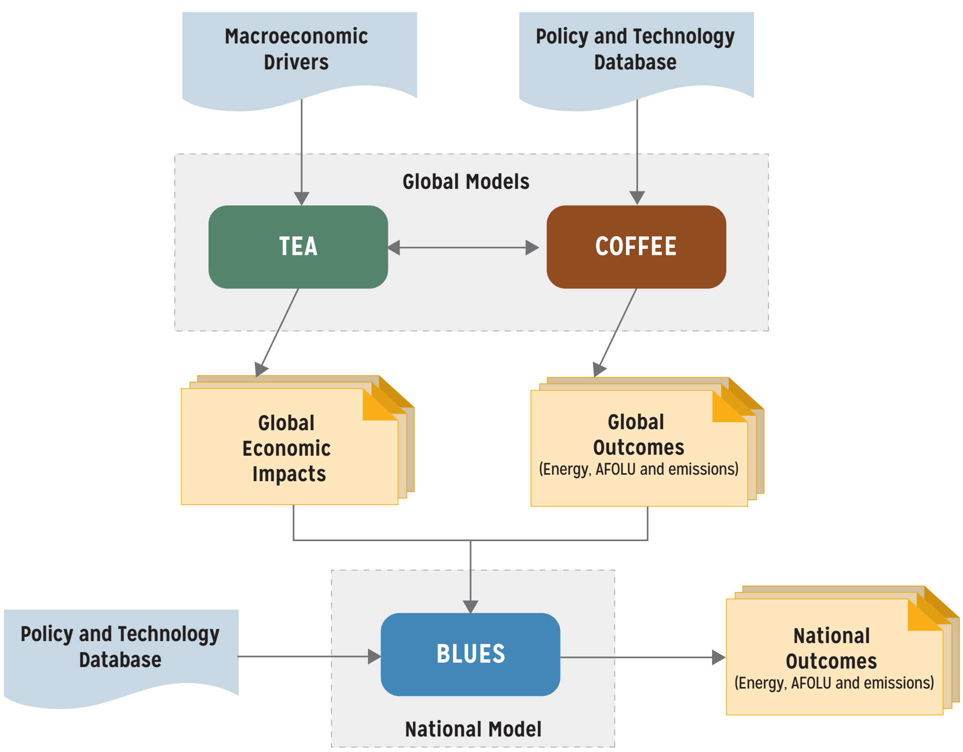
- **COFFEE** (*Computable Framework For Energy and the Environment*): bottom-up optimization model with extensive technological details on global energy and land use systems, used to assess global and regional mitigation strategies and technological development. It divides the world into 18 regions.

- **BLUES** (*Brazilian Land-Use and Energy System*): national bottom-up optimization model with a more fine-grained description of conventional and mitigation technologies and of the investments and operation and maintenance costs for the energy, land use and water use sectors across five Brazilian regions, better described below.

- **TEA** (*Total-Economy Assessment*): Computable General Equilibrium (CGE) global model that simulates the operation of the economy through simultaneous analysis of existing interactions between regions and economic sectors and agents. The model uses the same 18 world regions as the COFFEE model and employs a more detailed representation of the agricultural and energy sectors, in addition to international trade.

Those models interact to build scenarios and to capture strategies for achieving decarbonization and other environmental goals. The use of different models allows us to capture elements that are better analyzed according to the type of methodology (general computable or technological equilibrium) and to the level of detail (national or global). Model integration occurs through a process of continuous improvement and exchange of information illustrated below.

FIGURE 4 INTERACTION BETWEEN INTEGRATED ASSESSMENT MODELS



The flow of information and data begins with the definition of macroeconomic scenarios and their main drivers, such as population and GDP growth rates. Using the macroeconomic drivers as a starting point, the general equilibrium economic model (TEA) and the global (COFFEE) and national (BLUES) technological models exchange information and interact.

The COFFEE and BLUES models provide information on the evolution and penetration of different technologies and changes in land use, as well as on the behavior of sectoral energy intensity, represented by the relationship between sector energy use and activity levels over the projection horizon. Because they involve a high level of technological detail, those models provide a fine-grained representation of policy effects (e.g. climate policies), of learning curves and of the interaction between different industries within the energy and land use sectors.

On the economic analysis side, the general equilibrium model (TEA) mimics the behavior of the end demand for goods and services for each sector in each world region – which is then fed into the COFFEE model[34]. The latter will subsequently provide demand data (input for the BLUES model) and Brazil's 2050 aggregate emissions limits for different climate governance scenarios. Demand affects the behavior of energy and land use systems, changing the optimal decision for those models, which triggers an iteration process that ends when projections for the pertinent sectors converge. The final output will be the economic impacts on the level of activity (GDP), on investment and on the productivity of capital and labor.

The BLUES model proved to be the most suitable for the Energy Transition Scenarios because it works at greater technological detail and, being a national-scale model, provides results for Brazil's five regions.

The TEA-COFFEE integrated models will thus provide the boundary variables for domestic demand and international trade within the energy and agricultural systems for each world low-carbon transition scenario. The boundary variables will be used as input data for the national energy and land use model (BLUES) to assess specific impacts on the power (power mix and electrification of transportation), O&G (production, refining), biofuels and agriculture and livestock (commodities, food) industries. The flow of information between the models makes it impossible to completely separate one from the other. The model is chosen based on how well its characteristics and specificities suit the type of analysis required and the model selected is used independently. The BLUES model proved to be the most suitable for the Energy Transition Scenarios because it works at greater technological detail and, being a national-scale model, provides results for Brazil's five regions.

34. Energy sector demand in the COFFEE and BLUES models is deemed demand for energy services and the model is free to choose the portfolio of end energy sources that can meet that demand through different energy end-use technologies (vehicles, thermal power plants, industrial boilers, residential water heaters, etc.). Demand in the land use model is deemed to be demand for agricultural products based on the domestic and foreign markets provided by the TEA model.

The BLUES Model

The MESSAGE model was originally developed by Austria's International Institute for Applied System Analysis (IIASA) to optimize an energy system's demand and supply (Gritsevskyi & Nakicenov, 2000; IAEA, 2007). It is currently used by several research groups around the world and has been for decades applied to energy sectors, both for energy and for mass balances purposes (Clarke et al., 2014; Riahi et al., 2014; Lucena et al., 2015).

The mathematical principle behind MESSAGE is the optimization of an objective function subject to a set of restrictions that define the feasible region containing the possible solutions for the problem (IAEA, 2007). The value of the objective function helps choose the best solution according to a specific criterion, usually cost minimization. In a more general classification, MESSAGE is a mixed integer programming model (allowing some variables to be defined as integers) used for energy system optimization.

The model was designed to create and review alternative energy supply strategies in line with restrictions such as limits on investment, fuel availability and price, environmental regulation and market penetration rates for new technologies, among others. Environmental aspects can be factored in by accounting and, if necessary, limiting pollutant emissions from various technologies at different levels along the energy chain. That helps assess the impact of environmental regulations on the development of the energy system.

In this work we used the BLUES (Brazilian Land-Use and Energy System) model, which is a minimal cost optimization model for Brazil was built on the MESSAGE model generation platform (Model for Energy Supply Strategy Alternatives and their General Environmental Impacts). The costs and performance characteristics (efficiencies, capacity factors, environmental indicators, etc.) of each technological alternative are very important inputs for the model. Those values can change over the model's time horizon, making it very sensitive to the former. For example, the model can represent the reduction in the cost of a certain technology and the improvements to its efficiency over time. Each primary energy source can be divided into a number of classes taking into account production costs, the source quality and the location of reserves. Those primary energy sources then are directly or indirectly transformed into secondary and end-energy sources and ultimately into energy services used to meet demand. Energy demands can be divided regionally and, in certain circumstances, the model can represent a power system load curve. The total cost of the energy system includes investment costs, operating costs and additional costs such as "penalties" for certain alternatives or environmental and social costs.

The costs and performance characteristics of each technological alternative are very important inputs for the model.

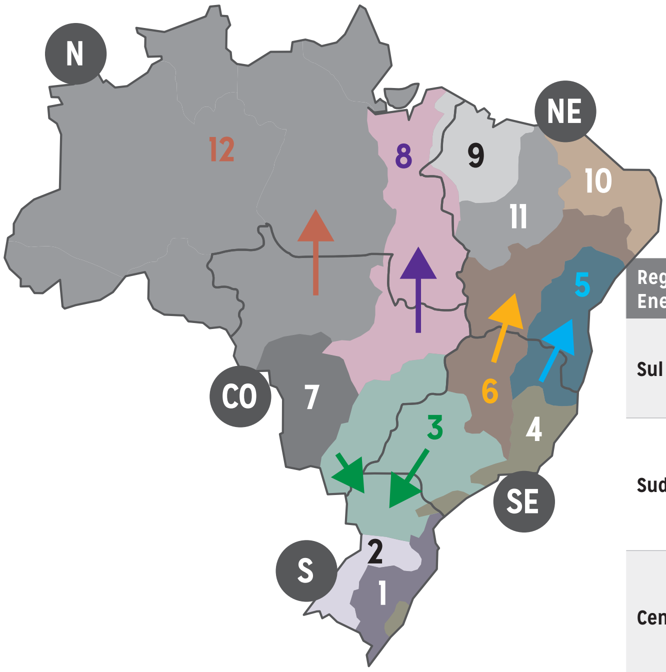
The model minimizes the total cost of the energy system, encompassing the power generation, agriculture, manufacture, transportation and construction industries, subject to constraints that represent real-world constraints for the full range of pertinent variables and including land use, according to the methodology proposed in Koberle (2018).

BLUES operates with six regions, one representing nationwide processes in which five sub-regions are nested following Brazil's geopolitical divide. BLUES optimizes the perfect-foresight energy system in relation to future technical and economic (policy) conditions between 2010 and 2050 at 5-year intervals, minimizing total system cost. Each representative year is divided into 12 representative days (one for each month) encompassing 24 representative hours. In other words, there are twelve 24-hour load curves totaling 288 time-slices in the year. Power generation must balance supply for each time-slice. The energy system is represented in detail in the manufacture, transportation and energy use sectors, with more than 1500 technologies customized for each of the six native regions.

Vásquez-Arroyo (2018) incorporated into the BLUES model a module to account for, restrict and price the use of water resources by the energy system. Vásquez-Arroyo (2018) proposed the harmonization shown in Figure 30 to address differences in the regional divide for the energy sector (based on political macro-regions) and for the water resources sector (based on hydrographic macro-regions). Orosco (2020) developed a model with a BLUES interface for integrated analysis of water resources. With said modules, the BLUES model can run integrated assessments of food, energy and water security.

FIGURE 5 SCHEMATIC REPRESENTATION OF THE BLUES MODEL

FIGURE 6 HYDROGRAPHIC AND ENERGY REGIONS USED IN THE BLUES MODEL



Região Energética	Região Hidrográfica (Sistema Hidrográfico)	Bacia (Unidade Hidrográfica)
Sul	Atlântico Sul	Bacia 1_S
	Uruguai	Bacia 2_S
	Paraná	Bacia 3_S
Sudeste	Paraná	Bacia 3_SE
	Atlântico Sudeste	Bacia 4_SE
	Atlântico Leste	Bacia 5_SE
	São Francisco	Bacia 6_SE
Centro-Oeste	Paraná	Bacia 3_CO
	Paraguai	Bacia 7_CO
	Tocantins	Bacia 8_CO
	Amazônica	Bacia 12_CO
Nordeste	Atlântico Leste	Bacia 5_NE
	São Francisco	Bacia 6_NE
	Nordeste Ocidental	Bacia 9_NE
	Nordeste Oriental	Bacia 10_NE
	Parnaíba	Bacia 11_NE
Norte	Amazônica	Bacia 12_N
	Tocantins	Bacia 8_N

Power Industry

The BLUES model works at a high level of detail along the power generation chain, from the detailed availability of national (and imported) energy resources, through power generation technologies, to the different end-use technologies. At the final end, the level of detail allows the review of energy efficiency options, electrification of industrial processes and electromobility. Table 4 lists the power generation technologies available in the BLUES model, their costs and technical parameters. The five regions in the BLUES model suffice for the analysis of power flows between Brazil's actual regions and of the use of local energy potential.

The model also provides a representation of the demand load curve, as well as the seasonal and daily profiles of renewable energy resources, especially hydro, wind and solar power. One can then review the energy balance at the hourly level, maintaining the equilibrium between supply and demand and the variability of variable renewable sources. That equilibrium is further guaranteed by intermittent source integration constraints and requirements.

TABLE 9. ECONOMIC PARAMETERS FOR POWER GENERATION TECHNOLOGIES

COSTS (US$ 2010/KW)	2020	2030	2040	2050
Onshore Wind	1,236	980	874	752
Offshore Wind	6,560	5,467	4,783	4,100
Photovoltaic	941	888	738	512
Concentrated Solar Power - 7.5h storage	5,298	4,434	4,080	3,912
Concentrated Solar Power - Parabolic Cylinder - 12h storage	6,055	5,036	4,620	4,422
Concentrated Solar Power - Solar Tower - 12h storage	9,614	7,996	7,335	7,021
Concentrated Solar Power with Jurema biomass	5,856	4,496	3,919	3,708
Open Cycle Gas	800	720	600	600
Combined Cycle Gas	1,190	1,000	1,000	1,000
Flexible Combined Cycle Gas	1,500	1,300	1,200	1,200
Flexible Combined Cycle Gas CCS	3,091	2,790	2,520	2,400
Domestic Coal	3,000	2,700	2,250	2,250
Imported Coal	2,500	2,250	1,875	1,875
Imported Coal CCS	4,275	4,275	3,563	3,563
Imported Coal - Combined Cycle Gasification	2,600	2,600	2,600	2,600
Coal Gasification Combined Cycle with CCS	3,500	3,500	3,500	3,500
Existing Biomass	4,665	4,665	4,665	4,665
New Biomass	5,300	5,300	5,300	5,300
Existing Nuclear	4,000	4,000	4,000	4,000
New Nuclear	4,000	4,000	4,000	4,000
Small-Scale Hydropower	2,936	2,936	2,936	2,936
Medium-Scale Hydropower	2,513	2,513	2,513	2,513
Large-Scale Hydropower	2,091	2,091	2,091	2,091
Reversible Hydropower	2,650	2,650	2,650	2,650
Rankine Oil	1,400	1,400	1,400	1,400
Generator Oil	900	900	900	900
Generator Gas	900	900	900	900
Generator Biodiesel	1,200	1,200	1,200	1,200
Generator Ethanol	1,500	1,500	1,500	1,500

O&G and Biofuels Industry

The BLUES model starts from the resource potential of different types of oil and natural gas, including assessments of resource availability at different production costs. The methodology to review O&G upstream transition considers three possible phases of crude oil development and production: primary, secondary and tertiary (or improved) recovery. During primary recovery, the reservoir's natural pressure is raised by gravity and by artificial elevation techniques (such as pumps) that bring oil to the surface. Secondary recovery techniques extend the production life of a field by injecting water or gas to replace the oil and take it to a production well. Finally, Enhanced Oil Recovery (EOR) involves techniques to increase how much crude oil can be taken from an oil field, which extends its production life but at higher production costs (Rochedo, 2016). The model will represent the impacts of decarbonization scenarios as variations in crude oil production and export volumes is response to that range of possibilities.

BLUES also provides a detailed representation of biofuel options, from conventional (e.g. ethanol and biodiesel) to advanced biofuel options. The latter category includes technological options for energy sources akin to conventional fossil fuels (e.g. diesel, kerosene, bunker) that can be used directly (drop-in) and do not contribute with direct CO_2 emissions.

Advanced biofuels may give Brazil a competitive edge in energy transition in the next three decades thanks to Brazil's plentiful land, favorable agricultural and livestock productivity and experience in the field. Advanced biofuels may come to be a strategic investment in the transition to a low-carbon economy for several activities (e.g., for industrial use) not only as an energy source but also as input to produce petrochemicals. Biofuels can be more widely used in the transportation industry to promote decarbonization with minimal change in the existing infrastructure and with lower impact on the consumption profile (e.g., in battery-powered electric vehicles).

Some routes to produce advanced petrochemicals using biofuel and biomass may help achieve more ambitious economy decarbonization targets through Carbon Capture and Storage (CCS) methods. CCS coupled to the biomass conversion chain can achieve negative emissions.

Some routes to produce advanced petrochemicals using biofuel and biomass may help achieve more ambitious economy decarbonization targets through Carbon Capture and Storage (CCS) methods.

Finally, there may be a correlation between investments in the O&G chain and in biofuels, either in the logistics chain or in processing units. In short, the conflicting and complementary risks and opportunities in both chains must be carefully reviewed.

TABLE 10. ECONOMIC PARAMETERS FOR BIOFUEL TECHNOLOGIES

INVESTMENT COSTS (US$ 2010/KW)	2020	2030	2040	2050
Advanced Biokerosene	8,016	8,016	8,016	8,016
Advanced Biokerosene with CCS	8,120	8,120	8,120	8,120
Advanced biodiesel (large-scale plant)	5,350	5,350	5,350	5,350
Advanced biodiesel with CCS (large-scale plant)	5,420	5,420	5,420	5,420
Advanced biodiesel	7,758	7,758	7,758	7,758
Advanced biodiesel with CCS	7,859	7,859	7,859	7,859

Transportation Industry

The BLUES model divides the transportation industry into the passenger and freight activities.

TABLE 11. ECONOMIC PARAMETERS FOR CARS

COST (US$2010/VEHICLE)	2020	2030	2040	2050
Gasoline	18,000	18,000	18,000	18,000
Gasoline + Efficient	22,715	21,272	19,828	18,384
Flex	18,000	18,000	18,000	18,000
Flex + Efficient	22,715	21,272	19,828	18,384
CNG	20,000	20,000	20,000	20,000
CNG + Efficient	26,000	26,000	26,000	26,000
Gasoline hybrid	30,000	27,991	23,411	19,287
Hybrid + Efficient	50,992	50,992	50,992	50,992
Flex Hybrid	44,441	44,441	44,441	44,441
Battery-Powered Electric	37,297	33,116	26,176	21,425
Hydrogen Fuel Cell	52,995	36,707	30,327	24,703
Ethanol-Based Fuel Cell	51,409	38,483	31,773	25,980

TABLE 12. PARÂMETROS ECONÔMICOS PARA MOTOS

COST (US$2010/VEHICLE)	2020	2030	2040	2050
Gasoline	7,000	7,000	7,000	7,000
Gasoline + Efficient	10,000	10,000	10,000	10,000
Flex	10,000	10,000	10,000	10,000
Electricity	8,000	7,000	7,000	7,000

TABLE 13. PARÂMETROS ECONÔMICOS PARA ÔNIBUS

COST (US$2010/VEHICLE)	2020	2030	2040	2050
Diesel	80,000	80,000	80,000	80,000
Diesel + Efficient	107,000	107,000	107,000	107,000
Etanol	107,000	107,000	107,000	107,000
Electric	226,990	181,642	134,640	111,577
Hydrogen Fuel Cell	227,937	175,323	134,080	111,227
Ethanol-Based Fuel Cell	227,937	179,673	137,129	113,599
Mini Diesel	70,000	70,000	70,000	70,000
Mini Diesel + Efficient	72,000	72,000	72,000	72,000
Mini Ethanol	73,000	73,000	73,000	73,000

TABLE 14. PARÂMETROS ECONÔMICOS VEÍCULOS COMERCIAIS LEVES (CARGA)

COST (US$2010/VEHICLE)	2020	2030	2040	2050
Diesel	30,000	30,000	30,000	30,000
Diesel + Efficient	34,000	34,000	34,000	34,000
Battery-Powered electric	48,394	42,203	31,751	28,165
Hydrogen Fuel Cell	51,650	36,180	31,291	26,984
Ethanol-Based Fuel Cell	50,736	36,593	31,721	27,441

TABLE 15. PARÂMETROS ECONÔMICOS PARA CAMINHÕES SEMILEVES

COST (US$2010/VEHICLE)	2020	2030	2040	2050
Diesel	35,000	35,000	35,000	35,000
Diesel + Efficient	41,000	41,000	41,000	41,000
Battery-Powered electric	56,460	49,237	37,043	32,859
Hydrogen Fuel Cell	60,259	42,210	36,506	31,482
Ethanol-Based Fuel Cell	59,192	42,691	37,007	32,015

TABLE 16. PARÂMETROS ECONÔMICOS PARA CAMINHÕES LEVES

COST (US$2010/VEHICLE)	2020	2030	2040	2050
Diesel	40,000	40,000	40,000	40,000
Diesel + Efficient	46,000	46,000	46,000	46,000
Battery-Powered electric	64,525	56,271	42,335	37,554
Hydrogen Fuel Cell	68,867	48,240	41,721	35,979
Ethanol-Based Fuel Cell	68,867	52,576	45,240	38,841

TABLE 17. PARÂMETROS ECONÔMICOS PARA CAMINHÕES MÉDIOS

COST (US$2010/VEHICLE)	2020	2030	2040	2050
Diesel	55,000	55,000	55,000	55,000
Diesel + Efficient	61,000	61,000	61,000	61,000
Battery-Powered electric	103,681	92,328	71,662	63,603
Hydrogen Fuel Cell	107,574	80,578	70,117	60,897
Ethanol-Based Fuel Cell	107,574	86,141	74,661	64,565

TABLE 18. PARÂMETROS ECONÔMICOS PARA CAMINHÕES SEMIPESADOS

COST (US$2010/VEHICLE)	2020	2030	2040	2050
Diesel	100,000	100,000	100,000	100,000
Diesel + Efficient	108,000	108,000	108,000	108,000
Battery-Powered electric	148,579	131,850	101,764	90,414
Hydrogen Fuel Cell	137,206	109,647	95,248	83,221
Ethanol-Based Fuel Cell	133,419	112,149	97,521	85,032

TABLE 19. PARÂMETROS ECONÔMICOS PARA CAMINHÕES PESADOS

COST (US$2010/VEHICLE)	2020	2030	2040	2050
Diesel	140,000	140,000	140,000	140,000
Diesel + Efficient	152,000	152,000	152,000	152,000
Battery-Powered electric	208,011	184,590	142,470	126,580
Hydrogen Fuel Cell	192,088	153,505	133,347	116,509
Ethanol-Based Fuel Cell	186,786	157,009	136,530	119,046

Agriculture and Livestock Industry

Brazil's agriculture and livestock industry is of great global significance both for its food and for bioenergy commodities production capability. The BLUES model can use its ability to operate at fine-grained technological detail and at the level of Brazil's geographical regions to detect how each long-term scenario influences the country's agriculture and livestock industry. The model represents 21 agricultural products (Table 15) produced to meet the international demand for food and bioenergy commodities informed by the TEA-COFFEE models. BLUES will estimate the volume of agricultural and livestock inputs required to produce traditional and advanced biofuels in satisfaction of Brazil's energy mix and of global climate goals.

FIGURE 7 AGRICULTURAL, LIVESTOCK AND ENERGY PRODUCTS

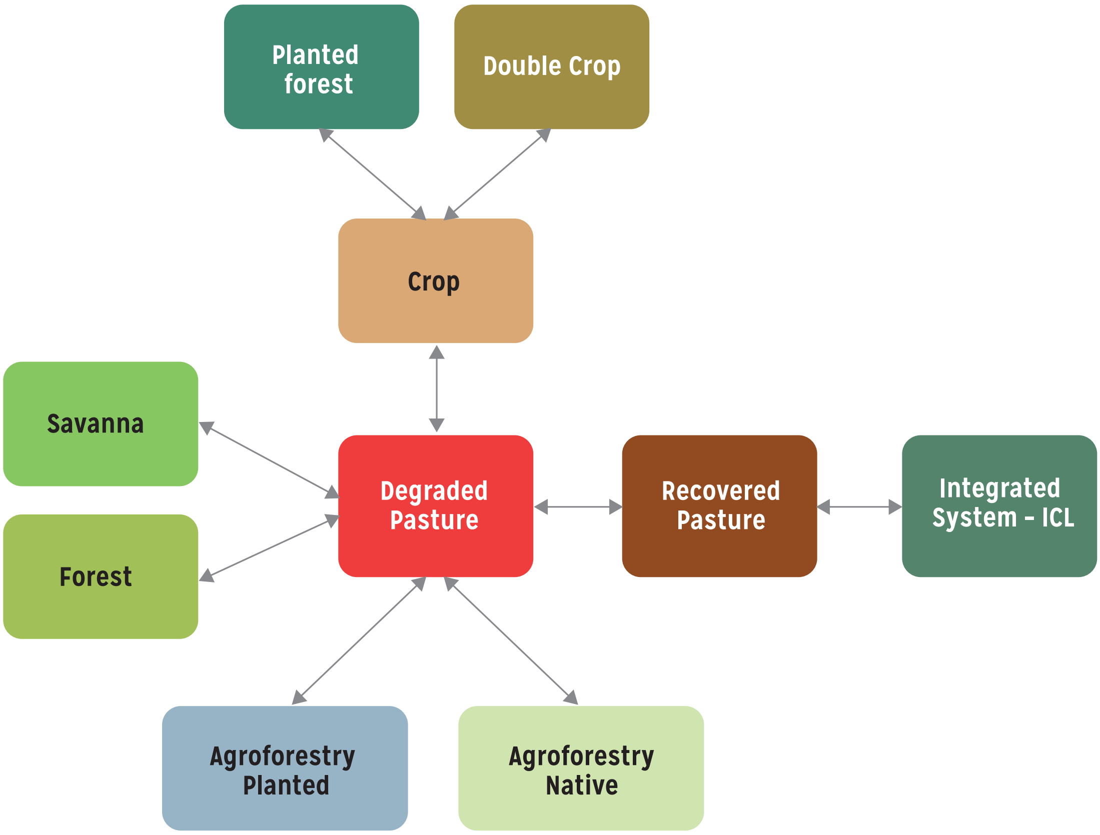
	AGRICULTURE	
Cotton	Sugarcane	Vegetables
Rice	Grains	Fruit
Coffee	Beans	Grasses
Planted Forest	Corn	Roots
Wheat	Nuts	Soya
	Oilseeds	
	LIVESTOCK	
Beef	Dairy Cattle	Laying Hen
Chicken Meat	Pork	

The model uses three types of single-crop agricultural production method (Historical Standard, High Productivity and Organic) and one double-crop (harvest and off-season) developed in regionalized fashion and respecting the edaphoclimatic conditions, cultivation aptitudes and specificities of each region in Brazil to find suitable technical and economic parameters for agricultural production. The model further considers two types of cattle ranching, extensive on degraded pastures and extensive on recovered pasture, and integrated agriculture and livestock systems within the same region.

That level of detail in the agriculture and livestock industry is of paramount importance for the model to find how land use should change.

That level of detail in the agriculture and livestock industry is of paramount importance for the model to find how land use should change (Figure B4), such as turning degraded pastures into forests or opening up new areas for bioenergy crops. The model will factor in the emissions, inputs and costs for each type of land use transition to indicate the cost-optimal mitigation measures that help achieve long-term climate goals.

FIGURE 8 LAND USE TRANSITIONS MODELED IN BLUES



Glossary

BECCS	Refers to bioenergy associated with carbon capture, transportation and storage systems or BECCS (BioEnergy with Carbon Capture and Storage). The difference between CCS and BECCS lies in the fuel burned. BECCS requires renewable fuel such as biomass (waste, pine, eucalyptus, sugarcane bagasse). The CO2 (carbon dioxide) absorbed in the biomass growth cycle is captured when converting biomass into bioenergy so that the CO2 absorbed by plants will not return to the atmosphere. The system is capable of "removing CO2 from the atmosphere" (net negative emissions) because it includes a phase to capture the CO2 absorbed during plant growth. Some examples of BECCS include the capture of carbon emitted during the fermentation stage of sugarcane for ethanol production, during the combustion of biomass for power generation and during the production of advanced biofuels. BECCS technology remains under development, with few projects in operation around the world.
Biodiesel	Biodiesel is a type of diesel oil derived from plants or animals and consisting of long-chain fatty acid esters. It is usually made by chemically reacting lipids such as animal fat (tallow), soybean oil or some other vegetable oil with an alcohol, producing a methyl, ethyl or propyl ester.
CCS	Carbon capture and storage (CCS) is the process of capturing and storing carbon dioxide (CO2) to prevent its release into the atmosphere. It can be used in thermal power plants to generate electricity, for example, so as to reduce emissions. CCS involves not only capturing the gas but also transporting and storing or using it.
CSP	Concentrated Solar Power (CSP) encompasses technologies to generate power and/or heat through the conversion of concentrated solar power. Lenses or mirrors are used to concentrate solar power for a variety of industrial applications such as water desalination, enhanced oil recovery, food processing, chemicals production and ore processing.
1st Generation Ethanol	Ethanol is produced through the fermentation of sugars (mainly glucose) using yeast strains. The main raw materials for first generation ethanol are sugarcane and corn.
2nd Generation Ethanol	Second generation ethanol, unlike first generation ethanol, is produced from sugars extracted from biomass cellulose, such as sugarcane straw and bagasse.

Ethanol BECCS	During the fermentation of ethanol, sugars from conventional biofuel feedstocks are fermented into ethanol and CO2. Two-thirds of the carbon contained in sugars end up in ethanol; the remaining third forms nearly pure CO2. The CO2 stream can then be separated through gas-liquid separation, while the ethanol/water mixture usually is separated through distillation.
Biokerosene (HEFA)	Vegetable oils, animal fat and other fatty acids can be converted into biojet fuels in three ways: hydroprocessing, known as hydrotreated renewable jet (HRJ), or Hydrotreated fatty acids and esters (HEFA); Catalytic hydrothermolysis and fast pyrolysis, known as Hydrotreated Depolymerized Cellulosic Jet (HDCJ). HEFA processes use triglyceride-based feedstocks and free fatty acids (FFAs) are produced through glyceride cleavage by propane and by thermal hydrolysis, respectively. The bio-oil used in the HDCJ pathway is obtained through biomass feedstock pyrolysis. So far, only the HEFA pathway has been approved for blending and ASTM-specified.
Biokerosene (BTL)	The Biomass-to-Liquid (BTL) route comprising biochemical and thermochemical technologies is considered one of the main green alternatives to produce bio-based chemicals, fuels and energy. Among those products, one of the liquid fuels that has been receiving a lot of attention is a substitute for conventional aviation fuel, called renewable aviation fuel or just biojet.
Biofuel diesel (BTL)	The term Biomass-to-Liquid (BTL) is applied to synthetic fuels made from biomass via some thermochemical route. The aim is to produce fuel components akin to those of current fossil fuel (gasoline) and diesel fuels and that can be used in existing fuel distribution systems and standard engines.
Diesel biofuel (BTL) CCS	FT fuel plants offer a unique opportunity for carbon capture and storage (CCS). Syngas is removed from CO2 during gas cleaning to increase the partial pressure of the reactants in the FT section. The resulting near-pure CO2 stream from the Selexol process unit can be easily captured for carbon storage, if desired.
PV	Photovoltaic (PV) solar power uses the photovoltaic effect to directly convert solar energy into electricity. PV systems can operate on a fixed base or on mobile axes, in the latter case to better capture solar energy during the year. Alternatively, floating modules may be installed on water bodies.
DG	Distributed Generation (DG) is the term used to designate power generation at or near the consumer's location, where the consumer can generate their own electricity from renewable sources or through cogeneration.

References

ANGELKORTE, G. B. Modelagem do Setor Agropecuário Dentro de Modelo de Análise Integrada Brasileiro – Rio de Janeiro: UFRJ/COPPE, 2019. XIV, 123p.: il.; 29,7 cm.

CLARKE, L., JIANG, K., AKIMOTO, K, 2014. Assessing Transformation Pathways. In: IPCC Fifth Assessment Report, Cambridge University Press, Cambridge, United Kingdom.

CLARKE, Cenergia/COPPE, IBP. O setor de O&G brasileiro em um contexto de emissões líquidas nulas (net zero emissions). 2022. Disponível em: https://www.ibp.org.br/personalizado/uploads/2022/08/relatorio-ibp-cenergia-coppe.pdf.

DE OLIVEIRA, C. C. N., ANGELKORTE, G., ROCHEDO, P. R. R., et al. "The role of biomaterials for the energy transition from the lens of a national integrated assessment model", Climatic Change, v. 167, n. 3–4, p. 57, 28 ago. 2021. DOI: 10.1007/s10584-021-03201-1. Disponível em: https://link.springer.com/10.1007/s10584-021-03201-1 .

EIA, International Energy Outlook, 2021. Disponível em: https://www.eia.gov/outlooks/ieo/

GRITEVSKYI, A., NAKICENOVI, N., 2000, "Modeling uncertainty of induced technological change", Energy Policy, 28, pp. 907-921.

IAEA, 2007. International Atomic Energy Agency, MESSAGE – User Manual, Vienna, Austria.

IEA. Net Zero by 2050 - A Roadmap for the Global Energy. 2021. International Energy Agency.

IEA. World Energy Outlook 2022. Disponível em: https://www.iea.org/reports/world-energy-outlook-2022.

KÖBERLE, A. Implementation of Land Use in an Energy System Model to Study the Long-Term Impacts of Bioenergy in Brazil and its Sensitivity to the Choice of Agricultural Greenhouse Gas Emission Factors. Universidade Federal do Rio de Janeiro, 2018. 135 f. Disponível em: http://www.ppe.ufrj.br/images/publicações/doutorado/aKoberle.pdf.

KÖBERLE, A. C., GARAFFA, R., CUNHA, B. S., ROCHEDO, P., LUCENA, A. F., SZKLO, A., SCHAEFFER, R., 2018, "Are conventional energy megaprojects competitive? Suboptimal decisions related to cost overruns in Brazil", Energy policy, v. 122, pp. 689–700.

LUCENA, A., CLARKE, L., SCHAEFFER, R., SZKLO, A., ROCHEDO, P., NOGUEIRA, L., DAEBZER, K., GURGEL, A., KITOUS, A., KOBER, T, 2015, “Climate policy scenarios in Brazil: A multi-model comparison for energy”, Energy Economics, 56, pp. 564-574.

MCTI, 2017. Modelagem integrada e impactos econômicos de opções setoriais de baixo carbono. Brasília, Ministério da Ciência, Tecnologia, Inovações e Comunicações, ONU Meio Ambiente. Disponível em: https://www.mctic.gov.br/mctic/opencms/ciencia/SEPED/clima/opcoes_mitigacao/Opcoes_de_Mitigacao_de_Emissoes_de_Gases_de_Efeito_Estufa_GEE_em_SetoresChave_do_Brasil.html.

MÜLLER-CASSERES, E., CARVALHO, F., NOGUEIRA, T., *et al.* “Production of alternative marine fuels in Brazil: An integrated assessment perspective”, Energy, v. 219, p. 119444, mar. 2021. DOI: 10.1016/j.energy.2020.119444. Disponível em: https://doi.org/10.1016/j.energy.2020.119444.

OPEC. World Oil Outlook 2045. Organização dos Países Exportadores de Petróleo, 2022. Disponível em: https://www.opec.org/opec_web/en/publications/340.htm

MCTIC. Acordo de Paris. Brasília, Ministério da Ciência, Tecnologia, Inovações e Comunicações, 2015. Disponível em: https://www.gov.br/mcti/pt-br/acompanhe-o-mcti/sirene/publicacoes/acordo-de-paris-e-ndc/arquivos/pdf/acordo_paris.pdf.

OROSCO, R. T., 2020. Proposta de introdução do nexo da água com energia e uso do solo dentro de um modelo de avaliação integrada brasileiro (Dissertação de mestrado). Universidade Federal do Rio de Janeiro, Rio de Janeiro, RJ.

RIAHI, K., VAN VUUREN, D.P., KRIEGLER, E., EDMONDS, J., O’NEILL, B.C., FUJIMORI, S., et al. The Shared Socioeconomic Pathways and their energy, land use, and greenhouse gas emissions implications: An overview. Glob Environ Chang 2017; 42:153–68. https://doi.org/10.1016/j.gloenvcha.2016.05.009.

ROCHEDO, P. “Development of a global integrated energy model to evaluate the Brazilian role in climate change mitigation scenarios”, v. 53, n. 9, p. 1689–1699, 2016.

Rystad Energy. Carbon Footprints of Crude Grades–Are They All Alike? Free Global Emissions Series Report, Maio 2022.

VÁSQUEZ-ARROYO, E. M, 2018. Incorporação Do Nexo Energia-Água Em Um Modelo De Otimização Da Expansão Do Sistema Energético Brasileiro. 2018. 232. Universidade Federal do Rio de Janeiro.

Board

International Advisory Board

Albert Fishlow
Alfredo Valladão
André Corrêa do Lago
Antonio Patriota
Felix Peña
Flávio Damico
Hussein Kalout
Ivan Sandrea
Jackson Schneider
Joaquim Levy
Leslie Bethell
Marcos Caramuru
Marcos Jank
Monica de Bolle
Paolo Bruni
Sebastião Salgado

Senior Fellows

Adriano Proença
Ana Célia Castro
Ana Paula Tostes
André Soares
Benoni Belli
Carlos Milani
Carlos Pereira
Daniela Lerda
Denise Nogueira Gregory
Diego Bonomo
Evangelina Seiler
Fabrizio Sardelli Panzini
Francisco Gaetani
Igor Rocha
José Mário Antunes
Larissa Wachholz
Leandro Rothmuller
Leonardo Burlamaqui
Lia Valls Pereira
Lourival Sant'anna
Mário Ripper
Matias Spektor
Miguel Correa do Lago
Monica Herz
Patrícia Campos Mello
Paulo Sergio Melo de Carvalho
Pedro da Motta Veiga
Philip Yang
Ricardo Ramos
Ricardo Sennes
Rafaela Guedes
Rogério Studart
Ronaldo Carmona
Sandra Rios
Sergio Gusmão Suchodolski
Tatiana Rosito
Vera Thorstensen
Victor do Prado

Members

Aegea
Air Products
Altera
Arara.io
BAMIN
Banco Bocom BBM
BASF
BAT Brasil
Bayer
BMA Advogados
BRF
Bristow
Brookfield Brasil
CCCC/Concremat
Consulado Geral dos Países Baixos no Rio de Janeiro
Consulado Geral da Irlanda em São Paulo
Consulado Geral do México no Rio de Janeiro
Consulado Geral da Noruega no Rio de Janeiro
Desenvolve SP
Dynamo
EDF Norte Fluminense
EDP
Eletrobras
Embaixada da Austrália
Embaixada da China no Brasil
Embraer
ENEVA
ENGIE Brasil
Equinor
ExxonMobil
Furnas
Galp
Grupo Lorentzen
Grupo Ultra
Haitong
Huawei
IBÁ
IBRAM
Icatu Seguros
Instituto Clima e Sociedade
Itaú Unibanco
Klabin
Light
Machado Meyer
Mattos Filho Advogados
Museu do Amanhã
Microsoft
Neoenergia
Paper Excellence
PATRI
Petrobras
Pinheiro Neto Advogados
Promon Engenharia
Prumo Logística
Repsol Sinopec
Sanofi
Santander
Shell
Siemens
Siemens Energy
SPIC Brasil
State Grid
Suzano
Total E&P do Brasil
Unilever
Vale
Veirano Advogados
Vinci Partners

CEBRI Team

Direction

CEO
Julia Dias Leite

Director of External Relations
Carla Duarte

Director of Projects
Luciana Gama Muniz

Academic Director
Feliciano Guimarães

Administrative Financial Director
Ana Paula Marotte

Executive Secretary
Julia Cordeiro

Projects

Projects Manager
Léa Reichert

Project Coordinators
Bárbara Brant
Davi Bonela
Thais Jesinski Batista

Project Assistant
Larissa Vejarano

Intern
Daniel Fontes

External Affairs

Deputy Director of External Affairs
Fernanda Araripe

Institutional Relations Coordinator
Fernando Mattos

Special Projects Coordinator
Caio Vidal

Institutional Relations Assistant
Beatriz Pfeifer

Communications and Events

Events Manager
Nana Villa Verde

Events Analyst
Adriano Andrade

Events Assistant
Isabella Ávila

Communications Assistant
Daniele Thomaselli

IT Analyst
Eduardo Pich

Administrative and Financial

Administrative-Financial Manager
Fernanda Sancier

Financial Analyst
Gustavo Leal

Development:

CEBRI
BRAZILIAN CENTER FOR INTERNATIONAL RELATIONS

epe
Empresa de Pesquisa Energética

cenergia

IDB

Sponsorship:

engie equinor NEOENERGIA SIEMENS energy

Support:

BMA ADVOGADOS