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**Energy Policy Implications of Carbon Pricing Scenarios for the Brazilian NDC
implementation**

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Abstract

This study assesses the expansion of the Brazilian energy system across three GHG emissions pathways simulating the achievement of the Brazilian Nationally Determined Contribution. In the Reference scenario, the NDC is achieved through command-and-control policies. We then compare this pathway to an Emissions Pricing Scenario (EPS), which simulates a carbon pricing scheme. The Sensitive Fuels Exemption Scenario (SFE) is similar to the latter, but gasoline, diesel and liquefied petroleum gas are exempted from pricing, **strengthening political buy-in to the mechanism.**

An integrated modelling approach combines bottom-up models representing energy demand and supply and a macroeconomic framework to ensure consistency across them. The adoption of carbon pricing schemes enables the use of a large potential of offsets (from the restoration of native vegetation) at a limited cost. This allows meeting NDC targets with bounded use of expensive mitigation actions comprised in command-and-control tools in the reference scenario. **This study shows** that a carbon pricing policy can increase the effectiveness of meeting climate commitments in Brazil, reducing GDP losses against business-as-usual trends. **However, the mechanism's scope and sectoral coverage are key to ensure that decarbonization is pursued in all economic sectors and in line with climate targets beyond the NDC horizon.**

Keywords: Brazil; emission scenarios; climate mitigation; carbon pricing; energy supply and demand; energy mix; energy modelling

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Highlights:

We explore three GHG emissions pathways of NDC for the Brazilian energy sector

We compare scenarios with command-and-control tools against carbon pricing schemes

An integrated modelling approach is applied, combining bottom-up and top-down models

Trading offsets from land use allows keeping mitigation costs low

A carbon pricing policy increases the effectiveness of short-term climate commitments

1 Introduction

The carbon intensity of the Brazilian energy mix is fairly low, thanks to an 83% share of renewables in power generation (64% from hydropower) and significant use of biofuels. Coal, the most carbon-intensive fossil fuel, accounts for barely 5% of the Total Primary Energy Supply (TPES), against 12% for natural gas and 34% for oil (EPE, 2020a). In contrast, high annual deforestation and degradation rates present the main challenge for Brazil to reduce its GHG emissions. Reducing land-use emissions is paramount if Brazil is to contribute to achieving global concentration levels consistent with limiting temperature increase to below 2° Celsius above pre-industrial levels, as preconised by the Paris Agreement (Postic et al., 2017). In fact, literature investigating mitigation options in Brazil often advocates that the most interesting opportunities lie in the land-use change and agricultural sectors (Chen et al., 2013; La Rovere et al., 2014).

In 2015, Brazil presented its Intended Nationally Determined Contribution to the UNFCCC Conference of the Parties (COP21) (iNDC, hereafter referred to as NDC, following its ratification in 2016). More recently, during the Climate Leader Summit organised by United States Presidency in 2021, the Brazilian government announced the country's commitment to reach climate neutrality in 2050, anticipating from 2060 as previously defined¹. The Brazilian NDC pledge consists of an economy-wide, absolute mitigation target. Brazilian GHG emissions were limited to 1.3 GtCO₂e in 2025 and 1.2 GtCO₂e in 2030, representing a reduction of 37% and 43% compared to 2005² (2.1

¹In its 2020 NDC ratification, Brazil had pledged to reach climate neutrality by 2060, and conditioned reaching this goal by 2050 on the proper functioning of carbon market mechanisms. The new 2050 target (announced in 2021) still needs to be formalized in an updated version of the NDC, and then be submitted to the UNFCCC.

²According to (Brazil, 2010).

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GtCO₂e) (Brazil, 2015). Table 1 lists the sectoral measures and targets included in the Brazilian NDC.

Table 1

In a global context, Bertam et al. (2021) argue that ambitious climate targets require decisive emission cuts at the international and national levels until 2030, with the most substantial contribution to decarbonisation coming from the power sector, requiring a shift of energy investments in solar and wind technologies in the coming decade.

In Brazil, as much as the NDC pledge defines the land-use sector as the primary contributor to emissions reductions in absolute terms, the required efforts do not seem to be on track. After a sharp decrease in annual deforestation rates from 2004 to 2012 (including an 80% decrease in the Amazon), the reversal of this trend has led to high deforestation rates again in 2019 and 2020. Reducing emissions from land-use change will require resuming command-and-control policies, as the bulk of them results from illegal activities (Bastidas and Mc Isaac, 2019; Grottera et al., 2017). In fact, recent projections to the Brazilian case alert that further efforts may be needed in most economic sectors to achieve the Brazilian NDC targets since the country has not been able to control its deforestation rates (Rochedo et al., 2018). Emissions from agriculture and energy have gained momentum and account for an increasing share of Brazil's emissions (Carvalho et al., 2020; Diniz Oliveira et al., 2019). Furthermore, NDC targets achievement is crucial to follow a GHG emissions pathway beyond 2030, aligning the

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country's most recent announcement with the general objective of the Paris Agreement (net-zero GHG emissions in 2050).

The main objective of this study is to assess the development of the Brazilian energy system (supply and demand) across three GHG emissions pathways of NDC targets achievement with and without emissions pricing schemes. The Reference scenario (REF) achieves NDC goals without carbon pricing, and its mitigation measures are induced mainly by command-and-control instruments. The Emissions Pricing Scenario (EPS) and Sensitive Fuel Exemption scenario (SFE) consider different carbon pricing schemes to induce the mitigation pathways.

We develop a framework to carry out a conceptual experiment regarding the Brazilian development strategy and its NDC targets. Through an integrated modelling approach that combines several bottom-up models representing the energy demand and supply in Brazil, and a macroeconomic framework to ensure consistency across them, we aim to investigate: (i) how do different carbon pricing schemes fit into climate mitigation strategies embedded in the Brazilian NDC, and what are the energy-related implications of such?; (ii) what are the main features of these mitigation pathways, and what insights do they provide to energy planning?

We assess these issues by examining the projected changes in the energy supply system, energy demand, associated GHG emissions and investment requirements in the aforementioned scenarios.

The remainder of this paper is structured as follows. The following section provides a brief literature review, focusing specifically on NDC implementation in developing countries, and convenes the most important contributions for climate policy in Brazil,

1 including exercises simulating carbon pricing mechanisms. Section 3 presents an
2 overview of the Brazilian energy system, including the main energy-demanding sectors,
3 and opportunities for decarbonisation. Section 4 describes the scenario storylines,
4 and opportunities for decarbonisation. Section 4 describes the scenario storylines,
5 methodological aspects of energy demand and supply models, and sectoral
6 assumptions. It also explores the integration between the energy and economic
7 frameworks and the main data sources. Section 5 presents and discusses the results
8 from the scenario comparative analysis. Finally, section 6 draws the main conclusions of
9 the study and provides insights on energy policy implications.
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22 **2 Overview of the Brazilian energy system**

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26 In Brazil, the energy transformation sector comprises the extraction of petroleum
27 and natural gas, petroleum refining, biofuel production, power generation and coke
28 production. Energy use strongly correlates with GDP, per capita income and
29 urbanisation levels, a pattern experienced worldwide (Cornillie and Fankhauser, 2004;
30 Ezcurra, 2007; Markandya et al., 2006; Mielnik, 2000; Nilsson, 1993; Ribas et al., 2017).
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40 In the past decade, the consumption of petroleum products, biofuels and electricity
41 increased steadily, namely to meet the demand of transportation and services sectors.
42 Primary energy continuously increased over the last years due to the exploitation of the
43 pre-salt layer petroleum. Renewable energy supply also increased, both regarding
44 biofuels for transportation and the expansion of intermittent power generation sources
45 such as wind and solar. Despite becoming one of the largest crude oil producers and
46 exporters globally, Brazil remains increasingly dependent on energy imports, namely
47 natural gas and oil products such as diesel, gasoline and naphtha (EPE, 2019a).
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In 2017, final energy consumption was distributed as follows: transportation (32.7%), industry (31.7%), buildings (14.8%), energy transformation (11.2%) and agriculture (4.1%), in addition to 5.5% from non-energy final consumption (EPE, 2019a).

In 2017, the Brazilian government launched the Brazilian Biofuels Program called RenovaBio³. It establishes GHG reduction mandates based on the overall carbon footprint of the road sector. Fuels distributors (obligated parties) are required to reduce their carbon footprint by 10% in 10 years. They will do so by buying decarbonisation credits from biofuels producers called Cbios (Carvalho et al., 2020), which correspond to 1t of avoided CO₂e. RenovaBio is, therefore, the first public policy in Brazil to put a price on carbon emissions⁴. The eligibility criteria of RenovaBio requires producers to demonstrate that the raw material is free of deforestation and in compliance with the Brazilian Forest Code, reducing the risk of land-use emissions⁵.

3 Literature review

Environmental economic theory tells that carbon pricing is the cost-efficient way to reach a given emissions target. Carbon prices create incentives for markets to use all levers available to reduce emissions, from the pursued activity, the chosen fuel, to the structure and energy intensity of a particular industry or the economy as a whole.

³Inspired by the Low Carbon Fuel Standard (2019) and the Renewable Fuels Standard (EPA, 2020).

⁴In its first year of implementation, the Program faced the COVID-19 crisis (which required revising the 2020 GHG emissions target) and a lawsuit from fuel distributors. Nevertheless, the program succeeded in engaging a large number of ethanol and biodiesel producers. As of November 2020, almost 14 million Cbios were emitted, of which 54% is already retired at an average price of 8 USD/Cbio (assuming an exchange rate of 5.5 BRL/USD).

⁵The Supplementary Material of this paper contains a section exploring the specificities of the Brazilian energy demand and supply, providing a brief overview and prospects of each sector and discusses its potential contribution to achieve NDC goals.

1 Equalising the marginal abatement costs across different ways of reducing emissions
2 ensures a necessary condition for an efficient transition to a low-carbon economy
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4 (Stiglitz et al., 2017), as opposed to command-and-control measures, which fail to do so.
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8 In practice, carbon pricing can take two forms: a carbon or GHG emissions tax –
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10 as a Pigouvian tax – or indirectly through an emission cap with trading of emissions
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12 allowances. In economic theory, these are the two sides of the same coin. With no
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14 market failure, implementing either a price or quantity-based carbon constraint leads to
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16 the same marginal abatement costs conditions and same total emission level: with the
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18 price-based instrument, all economic agents reduce their emissions until their marginal
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20 abatement cost equals the carbon tax. With a quantity-based tool, economic agents will
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22 trade emissions allowances until all marginal abatement costs equalise, regardless of
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24 the initial allocation for a given emission cap. In both cases, the same total minimum
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26 mitigation cost is reached. The difference lies in the distribution of this cost among
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28 economic agents. With full carbon taxes, economic agents pay for the remaining
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30 emissions beyond mitigation costs. In an Emissions Trading Scheme (ETS), the
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32 breakdown of costs depends, naturally, on the initial allocation of allowances (Lefèvre
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34 et al., 2018).
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45 Goulder and Schein (2013) show that, under aspired circumstances such as
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47 symmetric information (e.g., policymakers who know the private mitigation costs of the
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49 different economic agents) and the absence of transaction costs, a carbon tax, an ETS or
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51 a hybrid instrument with a similar design are equivalent instruments with no inherent
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53 difference in mitigation incentive and distributional impacts.
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3 Carbon pricing schemes have been increasingly adopted as an economic
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6 instrument to induce economic agents towards the required GHG emission reduction
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8 and particularly to achieve NDC targets (Stiglitz et al., 2017). A growing number of
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10 studies focus on analyses of NDCs in developing countries since they are envisaged to
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12 increasingly contribute to future emissions due to the yearning for economic
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14 development in these economies (Grottera et al., 2020). Scenarios of low-carbon
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16 development pathways with the application of different energy system models can
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18 support policymakers in the transition to a low-carbon society (Rogelj et al., 2016).
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25 In Dioha e Kumar (2020), scenarios simulations for Nigeria indicate that the
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27 implementation of a carbon tax level of US\$40–80/tCO₂ by 2020 and US\$50–100/tCO₂
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29 by 2030 promote a 77% energy system decarbonisation by 2050, delivering the most
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31 significant primary energy demand reduction and emission mitigation among other
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33 scenarios that do not consider carbon pricing policy. However, its modelling framework
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35 relies on a bottom-up energy system model that does not provide an economy-wide
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37 assessment of the carbon pricing implementation. The authors acknowledge that such
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39 a level of a carbon tax is not realistic, given its impacts on Nigerian economic
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41 development.
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49 Gupta et al. (2020) highlight that deep decarbonisation pathways are compatible
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51 with Indian economic growth despite the high investment costs required in renewables
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53 and energy efficiency enhancements. The results show that deviating from oil imports
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55 could result in foreign exchange savings of US\$1 trillion from 2012 to 2050. However,
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57 even relying on an integrated macroeconomic framework, the exercise proposed by the
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1 authors does not consider the implementation of carbon pricing policies to induce such
2 pathways, assuming that command-and-control policies would implement underlying
3 technological transformations of low-carbon scenarios.
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8 Le Treut et al. (2021) also consider an energy-macroeconomic modelling
9 framework to contrast an Argentinean NDC scenario with two ambitious
10 decarbonisation scenarios (DD), which differ in the transformation of power generation
11 (natural gas coupled with CCS versus nuclear and hydropower expansion). The results
12 lead to significant jobs and economic value displacements at the scale of the energy
13 sector in DD scenarios, even with limited macroeconomic implications in aggregate
14 terms. However, even considering capital cost requirements in DD energy system
15 transformation, the modelling framework does not include explicit carbon pricing
16 schemes to trigger the technological changes, implicitly assuming economically neutral
17 incentives.
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35 The significance of Brazil in Latin America's climate commitments is
36 incontestable since its decisions drive relevant changes in the regional energy mix
37 (Postic et al., 2017). While there is considerable debate about the best mechanism to
38 reduce emissions under a climate policy (da Silva Freitas et al., 2016), there are only a
39 few studies about carbon pricing schemes in the Brazilian case. A relevant portion of the
40 literature refers to the distributional impacts of carbon pricing in Brazil, even though
41 most studies do not focus on the energy system implications (Garaffa et al., 2021;
42 Grottera et al., 2017; La Rovere et al., 2018; Moz-Christofolletti and Pereda, 2021; Wills
43 et al., 2021).
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Regarding the Brazilian NDC specifically, Diniz Oliveira et al. (2019) investigate the environmental implications and associated costs for complying with EU and Brazilian NDCs targets from 2020 to 2030 with a global macroeconomic framework database. By contrasting different assumptions on ETS collaboration among regions to a BAU scenario, the authors discuss the emission allowances trade between Brazil and Europe considering carbon content from energy and industrial sectors. Linking the proposed Brazilian ETS to EU ETS implies more significant emissions reductions than the domestic ETS in 2020 and the opposite effect from 2025 to 2030. In this case, mitigation efforts are reallocated to Europe, which sells permits to Brazil. The mitigation costs reach US\$143/tCO₂ in 2030. The authors point that the inclusion of land-use change related emissions for the proposed Brazilian ETS would imply lower abatement efforts and costs and could stimulate Brazil to further abate and export permits to Europe.

Gurgel et al. (2019) compare NDC-complying scenarios for Brazil with different national ETS based on a global macroeconomic modelling framework that disaggregates the land-use sector into agriculture and secondary vegetation (non-agricultural use). The NDC scenarios differ on the sectoral coverage of the carbon market, excluding emission from deforestation (curbed by a specific tax), and are contrasted to a BAU scenario considering weak deforestation control. Results show that an economy-wide ETS could help avoid high compliance costs, considering the lower mitigation costs in land-use change and the agricultural sector - these sectors would sell emission allowances to those with higher mitigation costs. In particular, the agricultural sector can provide emission reduction at the cost of US\$2/tCO₂eq by 2030. However, these costs consistently rise to US\$354/tCO₂eq by 2050, illustrating its depletion in the long run. The

1 economy-wide ETS also leads to a lower carbon price in comparison to sectoral ETS
2 (US\$3/tCO₂e in 2030 and US\$103/tCO₂e in 2050).
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5 While both Diniz-Oliveira et al. (2019) and Gurgel et al. (2019) assess options for
6 achieving the Brazilian NDC through carbon pricing schemes, these studies are built on
7 a top-down vision of mitigation options within the standalone CGE model approach,
8 implying limited detailing of the energy system transformation. They also rely on global
9 databases, which may take no account of particular features of the Brazilian economy.
10 Multi-sectoral CGE models are powerful models since they are flexible in exploring how
11 alternative carbon pricing schemes (whether a carbon tax, an ETS or any combination of
12 the two) impact economic agents' decisions on production and consumption choices
13 (Timilsina, 2018). In CGE models, carbon pricing induces substitutions in production
14 inputs and consumption baskets as embedded in production and demand functions.
15 Nonetheless, as the sectoral disaggregation corresponds to the level of disaggregation
16 of micro-founded economic behaviours (e.g., each distinguished economic sector or
17 representative agent), it fails to capture specific mechanisms playing at a sub-sector
18 level (Lefèvre et al., 2018).
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43 This paper contributes to a growing body of literature examining low-carbon
44 development pathways with the application of energy system models to discuss sectoral
45 challenges in the search for safe, reliable, low-cost, clean and efficient energy supply
46 and use. More specifically, we intend to investigate the effectiveness of different carbon
47 pricing designs and their implications for transforming the energy sector in Brazil. An
48 integrated methodological framework, combining a hybrid CGE model (IMACLIM-BR)
49 and sectoral bottom-up models for energy use and production, is proposed to further
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1 assign the required technological transformation in the energy system to achieve NDC
2 targets. Furthermore, the sectoral mitigation portfolio is incorporated within a marginal
3 abatement cost curve (MACC), wherefrom the level of abatement and the carbon tax is
4 defined. Finally, the simulation of the carbon pricing scheme in IMACLIM-BR ensures
5 macroeconomic consistency to bottom-up models' estimation of GHG emission
6 pathways.
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17 **4 Methodology, scenario assumptions and data sources**

21 **4.1 Scenario methodology and overview**

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25 The definition of the scenarios' assumptions was undertaken through a
26 participatory process involving stakeholders from the Brazilian Forum on Climate
27 Change. This Scenario Building Team (SBT) comprises experts from the government,
28 private sector, academia and civil society, discussed and validated assumptions
29 concerning market trends, the performance of public policies and societal
30 transformation, critically appraised to outline possible development pathways for the
31 Brazilian economy. A more detailed description of such a process can be found in Goes
32 et al. (2020d) (with a particular focus on transportation mitigation measures). From this
33 process, the assumptions were then parameterised to quantify 24 mitigation options
34 required to achieve Brazilian NDC targets. Three scenarios were then developed:
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52 Reference Scenario (REF) – In this scenario, mitigation measures outlined by the
53 SBT are achieved through command-and-control measures implemented by the federal
54 government, with no carbon pricing scheme in force. Mitigation efforts are undertaken
55 in the land-use change and agriculture, industry, transportation and energy supply
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sectors. This scenario was created to serve as a basis for comparing its results with those obtained by the different carbon pricing packages. In this scenario, as well as in all carbon pricing scenarios, the government actively reduces emissions to meet NDC targets, and deforestation rates are set exogenously to reach 13,700 km²/year in 2025 and 12,600 km²/year in 2030 and are the same for all scenarios.

Emissions Pricing Scenario (EPS) – This is the basic emissions pricing scenario, in which NDC targets are met through the implementation of carbon pricing schemes (combining a cap-and-trade system in the industry with a carbon tax imposed on fossil fuels used in other sectors). The climate policy is fiscally neutral, using carbon revenues to reduce labour taxes. This aims to decrease potential negative impacts of carbon taxation by favouring employment creation, increasing the Brazilian tax system’s efficiency as a whole and thus enhancing national competitiveness, as advocated by Chen et al. (2013).

While emissions from deforestation are out of the scope of the carbon pricing mechanism, an underlying assumption of EPS is that the market structure created by the introduction of carbon pricing creates the necessary conditions for the transaction of offsets from the restoration of native vegetation, which are not available in REF. Offsets are credits related to emission reductions obtained by unregulated sectors, that is, in sectors not covered by the pricing mechanism⁶. The supply of such offsets is estimated at an average price of 6.3 US\$/tCO_{2e} and 8.4 US\$/tCO_{2e} for the 2021-25 and the 2026-

⁶ To prevent carbon prices from falling too low, undermining the incentive to decarbonise regulated sectors and sectoral technological innovation, and to minimize possible leakage effects, most jurisdictions introduce limits on the use of offsets by a regulated entity or in the aggregate total. This limit varies, but 20% is usually considered a reasonable level in market approaches (Margulis et al., 2019).

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30 periods, respectively. The abatement potential is estimated at 61 MtCO_{2e} and 122 MtCO_{2e} for the same periods (details in Margulis et al. (2019)).

Sensitive Fuels Exemption Scenario (SFE) – This scenario reduces the scope of the carbon pricing scheme by exempting gasoline, diesel and liquefied petroleum gas (LPG) from carbon taxes. The high political cost of charging these fuels could jeopardise carbon pricing viability, as experienced in recent events such as the yellow vests in France and the truckers’ strike in Brazil in 2018, both related to rising fuel prices. The exemption could therefore allow buying political support for the regulatory instrument. This scenario seeks to identify the required efforts of other emitting sectors and the system’s efficiency as a whole when a sensitive fuel exemption scheme is applied. As in EPS, economic sectors can buy carbon offsets from native vegetation restoration.

Table 2

The GHG emission scenarios are then confronted with the expected abatement potential of the mitigation measures relative to a business-as-usual scenario (BAU), a construct used to determine the necessary increase in ambition and mitigation actions to achieve the Brazilian NDC targets in 2025 and 2030.⁷ Mitigation measures are implemented in ascending order according to their cost until the required abatement to achieve NDC targets is reached. Table 3 presents the abatement potential (MtCO_{2e}) and

⁷The BAU assumptions and methodology are detailed in the Supplementary Material.

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cost (USD/tCO₂e - avoided) in the 2021-25 (a) and 2026-30 (b) periods, for the 24 mitigation measures.

Table 3

The mitigation cost assessment approach is proposed by Gouvello et al. (2010) to calculate the total cost of a given mitigation action and its abatement potential⁸. Measures are ranked by ascending abatement cost, which may vary largely between the two periods due to increasing abatement potential over time and variations in costs assumptions (e. g., decreasing costs for electric vehicles and renewable electricity).

As explained, in the emissions pricing scenarios, carbon offsets from the restoration of native forests are transacted, sparing the implementation of costly mitigation measures (those below the dashed line in Table 3 are not implemented in the EPS and SFE scenarios). The following sections describe the methodology of energy demand and supply estimates.

4.2 Energy demand projection methodology and assumptions

The estimates for energy demand in this study are undertaken through sectoral bottom-up models combining the approaches described. The models share the same nature, in the sense that they require similar inputs, such as demographic (population) and macroeconomic (GDP, sectoral GDP) data, as well as activity levels and energy

⁸The cost assessment methodology and parameters are described in the Supplementary Material.

1 intensity, to provide comparable outputs (e. g., final energy demand and GHG
2 emissions). However, they may differ broadly in terms of sectoral specification, level of
3 detail and data availability.
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8 This section provides a brief description of the main features and assumptions of
9 the energy demand models, which are detailed for transportation and industry, the two
10 sectors for which mitigation measures are simulated in NDC scenarios. We also describe
11 how the demand from the buildings and commercial sector is computed - even though
12 there are no mitigation efforts in these sectors. In section 4.3, we then describe the
13 methodology for estimating the energy supply required to meet the demand. While we
14 put particular emphasis on the sectoral assumptions considered in the scenarios, the full
15 description of the models and the data used to calibrate the scenarios and conduct the
16 cost assessment can be found in the Supplementary Material.
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36 **4.2.1 Transport**

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38 The ‘Transport-Energy-Emissions Multi-Tier Analysis’ (TEMA) model calculates
39 the energy use scenarios in the Brazilian transport sector. The model was developed by
40 Gonçalves et al. (2019) and applied in a variety of studies (Goes et al., 2020a, 2020b ;
41 Gonçalves et al., 2020). Energy-climate scenarios are designed by simulating the
42 application of climate policies, market trends and user behaviour that best represent
43 the transformations of society over the years. In this process, macroeconomic inputs
44 from Table 2 are used as proxy variables to project transport activity and the consequent
45 use of energy and carbon emissions. GDP is the variable that determines freight
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1 transport activity (t-km), whereas GDP per capita is used to predict passenger transport
2 activity (pass-km).
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5 TEMA considers 31 technologies from road transport, combining vehicle
6 categories (e.g., cars, buses, trucks) and power trains (e.g., internal combustion engines,
7 ICE, battery-powered electric vehicles, etc.). The rail, air, water, and pipeline transport
8 modes are not specified at the technology level but account for the activity, structure
9 and intensity levels, as well as fuel use.
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11
12 The narratives common to all scenarios cover general transformations in human
13 settlement, land development, spatial organisation and some aspects of the auto
14 industry. Brazilian society experiences new configurations of mobility in the initial years
15 after the COVID-19 pandemic. Teleactivities gain importance, but the effect on transport
16 activity is minor, as only telework and teleservices significantly reduce travel. Along the
17 period, the densification process in large cities stabilises as they become more compact.
18 Land-use planning considers the decentralisation of activities, creating important trip-
19 attracting zones in different neighbourhoods. However, public transportation still faces
20 predatory competition from individual motorised transport and car ownership rates
21 increase by 2030 (Gonçalves et al., 2020).
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46 Transformations that vary across scenarios include infrastructure, consumption
47 patterns, trade, fuel generation and carbon content (Table 4). They are summarised in
48 mitigation measures, selected through the analysis of national commitments, current
49 policies, international trends, and market awareness. The measures implemented in
50 each scenario are defined after conducting the marginal abatement cost curves (MACC)
51 analysis, as explained in section 4.1.
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Part of the mitigation measures related to infrastructure is selected from the National Logistics Plan and the Ten-Year Energy Expansion Plan, which project the expansion of railways and waterways (EPE, 2020; EPL, 2018). The expansion of subway systems, logistics optimisation and the increased active transportation are also considered, selected from Gonçalves et al. (2019b) and Goes et al. (2020c).

Biofuel-related measures are the increased use of ethanol, biodiesel and biokerosene, in line with sectoral studies from Brazil and Europe, such as EPE (2020), Dafnomilis et al. (2017) and Kousoulidou and Lonza (2016). Measures related to electromobility comprise incentives to battery-powered electric and plug-in hybrid electric trucks, buses, and cars. They were selected based on the Global EV Outlook (IEA, 2018) and Goes et al. (2020c).

Table 4

4.2.2 Industry

The industrial model details the Brazilian industrial sector disaggregated into eleven segments: (i) Iron and Steel, (ii) Cement, (ii) Chemical industry; (iv) Non-ferrous metals; (v) Pulp and Paper, (vi) Food and Beverage, (vii) Textile, (viii) Mining and pelleting, (ix) Ceramic, (xi) Other Industries. It considers the activity, structure and intensity levels, as well as fuel use, to derive energy demand and GHG emissions.

The estimation of GHG emissions comprises: (i) emissions from energy consumption and (ii) emissions from industrial process and product use (IPPU) from

1 metals, chemical products and cement and other mineral products. The utilisation of
2 hydrofluorocarbons (HFCs) for refrigeration and air conditioning and SF₆ in electricity
3 transmission and distribution equipment are also emitting processes.
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8 The estimated growth of industrial segments varies according to macroeconomic
9 trends, including demand from importing countries and international competition
10 (Table 2). They are defined by the SBT, mainly based on long-term national prospects
11 such as EPE (2015). Mitigation options in the industrial sector include (i) energy
12 efficiency; (ii) increased use of renewable fuels (or natural gas replacing more carbon-
13 intense fuels); (iii) research and deployment of low-carbon process routes (Fischedick et
14 al., 2014; IEA, 2020).
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27 Energy efficiency in the iron and steel sector focuses on reducing consumption
28 in the main processes of steel production: sintering, coke making, iron making,
29 steelmaking, casting refining and other general measures (Carvalho et al., 2015; EPE,
30 2018a; Guedes and De Aragão Neto, 2017; Hasanbeigi et al., 2013; Worrell and Price,
31 2010). Replacing coking coal with charcoal from planted forests can also significantly
32 reduce GHG emissions in the Brazilian iron and steel industry(Pinto et al., 2018).
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44 Mitigation in the cement sector includes reducing consumption in raw material
45 preparation, clinker production and cement grinding (Kajaste and Hurme, 2016; Li et al.,
46 2017). There is also potential for mitigating emissions in cement production by reducing
47 the amount of clinker in its composition (Miller et al., 2018).
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54 General energy efficiency in all industrial sectors includes process optimisation,
55 heat and steam recovery, more efficient equipment, process control and
56 integration(EPE, 2018a; Guedes and De Aragão Neto, 2017; Guedes, 2017a; Henriques
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et al., 2010; Pinto et al., 2018). Table 5 describes the energy intensity in the base year (2015) for industrial sectors and the measures implemented in each scenario. The improvements are described (as reduced GJ/t of product for iron and steel and percentage gains (%) for other sectors).

Table 5

4.2.3 Energy demand of buildings, agriculture and other sectors

The energy demand of other sectors is estimated considering historical trends and different drivers. In the residential sector, energy demand responds to demographic growth and per capita income, while in services and agriculture to sectoral GDP growth. No mitigation measures were assumed, as no major technological changes are expected. As a result, differences in energy demand pathways reflect only minor changes in per capita income and GDP shares across scenarios. In all scenarios, firewood for cooking is gradually replaced (LPG) in the residential sector, and there is an increase in the share of electricity compared to firewood and LPG in the services sector. In agriculture, the share of electricity increases slightly while diesel oil and fuelwood remain nearly stable.

4.3 Energy supply methodology and assumptions

4.3.1 Power sector and oil refining

The MATRIZ model (CEPEL, 2018) represents the Brazilian energy system and details the electricity and refining sectors. MATRIZ is a linear programming bottom-up

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model for medium to long-term energy system planning, similar to MESSAGE and TIMES (IEA-ETSAP, 2020; IIASA, 2020). Considering exogenous inputs of final energy demand (i.e., the resulting aggregation of all energy demand models) and availability of resources, its objective function minimises the present value of the total cost of investment and system operation for capacity expansion and energy supply on the assessed horizon.

Energy chains are represented by linking primary, secondary, final, and useful energy levels. A mix of different technologies represents energy conversions and resource extractions. Four operating subsystems are considered in order to account for the electricity sector's complexity. Each analysis period is detailed into four seasons, each containing two energy demand levels: peak and non-peak. Such a level of specification is essential for energy security, as it ensures the system meets seasonal and horo-seasonal demands, as well as periods of critical hydrology. MATRIZ also computes GHG emissions endogenously. A penalty is simulated in the objective function specifically for fossil-fuel technologies to represent the carbon pricing.

The main mitigation measures considered are renewable energy for power generation and fugitive emissions control technologies (flaring and venting activities on platforms and fuel distribution). In the electricity sector, wind, photovoltaic, CSP, hydroelectric, nuclear, and bioelectricity technologies are included. However, mitigation only occurs from 2023 on since, up to this year, the sectoral expansion is already defined through the past energy auctions outcomes. For photovoltaic, CSP, and wind power, a linear decrease of 10% in costs is assumed until 2030. For fuel supply, ethanol, biodiesel, biokerosene, and natural gas are taken into account. Given the cost-minimising nature

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of the MATRIZ model, we highlight that natural gas can be considered a mitigation measure if it displaces energy sources with higher carbon content, such as coal and diesel oil. Table 6 summarises the main scenario assumptions for the projections).

Table 6

4.3.2 Biofuels and biomass

Finally, the Brazilian Land Use Model (BLUM) is applied to estimate the ethanol and biodiesel production levels. BLUM is a single country, partial, multi-sectoral and multiregional equilibrium model, which has been applied in a variety of studies investigating the climate impacts of land use policies in Brazil (Harfuch et al., 2017; Moreira, 2016; Moreira et al., 2020). It represents the Brazilian agricultural sector through two modules: supply-demand and land use. The model includes 14 products, among them soybean and sugarcane. In terms of land use, these commodities are broadly classified between agricultural land and pasture, while commercial forests are considered exogenous projections. These activities account for approximately 95% of the total Brazilian agricultural area.

BLUM uses a simple equation to estimate the production level of biodiesel, adopting the official mandate stipulated by the Brazilian government for the assessed year for the diesel consumption estimated by the TEMA model. BLUM uses the total energy demand for the vehicle fuels (estimated by the TEMA model) to estimate ethanol production levels as a starting point. It then combines equations and databases

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representing: (i) the total fleet (e. g., number of flex-fuel vehicles); (ii) user behaviour (in particular, the decision to consume either hydrous ethanol or gasoline according to relative prices); (iii) the level of biofuels supply according to the prices received by producers (linked to the land market).

4.4 Integrated modelling framework

The final step of the GHG emissions pathway simulations is to ensure consistency across the energy and economic systems, namely energy demand, supply and mitigation investment requirements induced in NDC scenarios. The IMACLIM-BR model is used for this purpose.

IMACLIM-BR is a hybrid multi-sectoral computable general equilibrium model (CGE) that reconciles an open economy with the energy system. Its calibration to the base year of 2015 relies on harmonising data from the Brazilian national accounting system, market prices statistics, and the national energy balance (Le Treut, 2020)⁹. The model depicts the economic growth with dynamic simulations resulting from assumptions of labour endowment and productivity¹⁰.

The coupling between IMACLIM-BR and bottom-up models consists of exchanging key outputs of one model as exogenous parameters for another. The bottom-up models provide consistent national energy balances and the investment requirements of each

⁹ IMACLIM-BR first developments are described in Grottera (2018), Lefèvre (2018) and Wills (2013), where more details on data requirements and the hybridization procedure can be founded. The calibration of the first version relied on 2005 and counts on a series of applications (Grottera et al., 2020; La Rovere et al., 2018, 2013; Lefèvre et al., 2018).

¹⁰The full set of IMACLIM-BR 2015 equations can be found at Le Treut, (2020). For the sake of transparency, a platform in open-access has been released to support the development of national IMACLIM versions (Le Treut et al., 2019). The hybrid IOT built to 2015 calibration can be founded at Grottera et al., (2021). Wills et al. (2021) is another example of IMACLIM-BR 2015 application.

1 scenario. Together with the carbon pricing policy implementation (when applicable),
2 these energy and investment scenarios are used in IMACLIM-BR to constrain the
3 economy-wide projection to 2030 and generate a response from the rest of the
4 economy.
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10 First, the energy balances are converted into an input-output format compatible
11 with IMACLIM-BR, detailing the energy consumptions per energy type in volume (ktoe)
12 across the economy. On the one hand, imports and exports are directly used in absolute
13 terms (ktoe) to be set as exogenous parameters in the IMACLIM-BR model. On the other
14 hand, energy intensities (absolute terms divided by sectoral production from BU
15 models) are exogenously informed into IMACLIM-BR for the economic sectors. The
16 energy consumption, in absolute terms, is then resulting from the sectoral activities that
17 are endogenously determined by the model.
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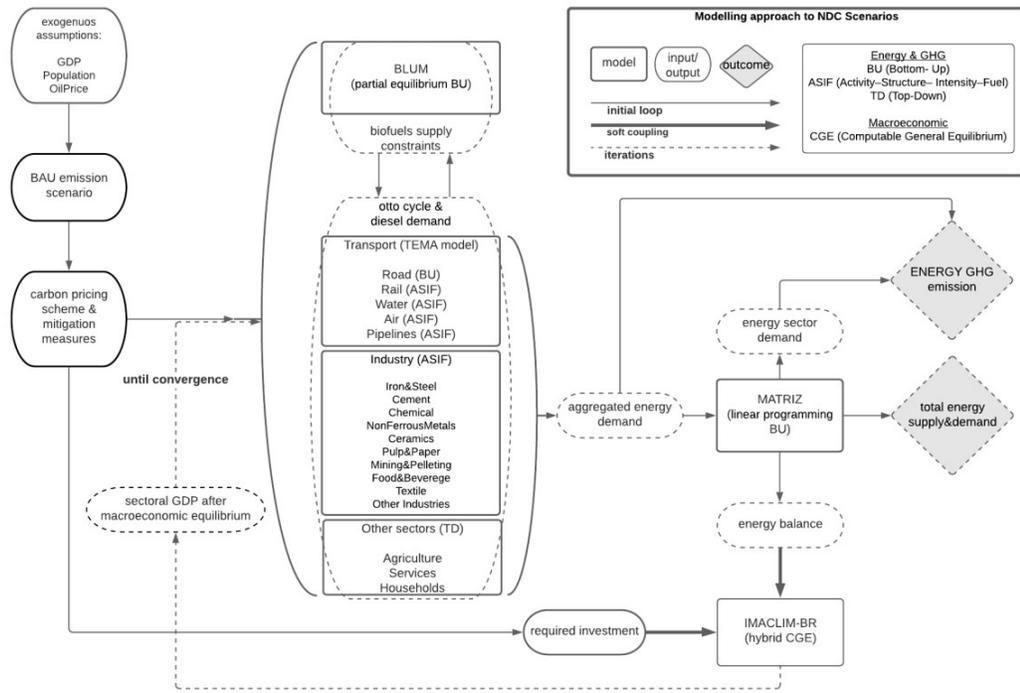
31 Second, the sectoral models also provide the capital requirements (considering
32 the investment in the sectors that adopted mitigation measures), which are summed up
33 to the capital consumption of the BAU scenario. The new level of capital consumption
34 allows estimating the capital cost of each NDC scenario (absolute terms of sectoral
35 capital consumption divided by sectoral production from BU models). The capital cost is
36 then set as an exogenous parameter in IMACLIM. As for the energy, the capital
37 consumption results from the sectoral activities that are endogenously determined by
38 the model.
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53 After macroeconomic equilibrium, the IMACLIM-BR model provides the yearly
54 sectoral economic activity (endogenous sectoral production), feeding the bottom-up
55 models once again. This is the key output that ensures consistency across the energy
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and economic system, e. g., the endogenous sectoral production is the convergence criteria between IMACLIM-BR and bottom-up models. The GHG emission pathway is then estimated from the second loop of bottom-up runs.

As explained in section 4. 1, BAU is initially simulated, tracing the current trend in growth, population, GHG emissions and mitigation policies. The REF scenario is then implemented to represent the achievement of NDC goals in 2025 and 2030 as a result of regulatory enforcement and command-and-control implementation of mitigation measures. While the BAU is the scenario upon which the modelling shock is assimilated, the REF scenario is the baseline to compare the simulation outcomes of the carbon pricing scenarios (EPS and SFE). Figure 1 illustrates the integrated modelling framework developed for this study.

Figure 1 - Integrated modelling framework



Source: the authors

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4 In the REF, EPS and SFE scenarios, the iterations among bottom-up models are
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6 carried out until the economy-wide achievement of NDC. The simulations of EPS and SFE
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8 differ regarding the scope of the carbon pricing scheme, which induces the investment
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10 requirements in mitigation and, consequently, the mitigation measures implemented.
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14 The bottom-up modelling process starts from the energy demand models
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16 (industry, transport and others). The BLUM model plays a role in translating bioenergy
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18 supply constraints from the land-use sector and fuels relative prices to the consumers.
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20 After reconciling this iteration, the aggregated energy demand feeds the MATRIZ model,
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22 which optimises the energy system and provides the energy supply profile. Thus, the
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24 national energy balances are set to load IMACLIM-BR.
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31 Linking energy models through IMACLIM-BR endogenous sectoral production
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33 allows capturing more detailed feedbacks between the energy and economic systems.
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36 Compared to the standalone CGE approach, it ensures the richness of both approaches,
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38 simulating endogenous energy system transformations triggered by carbon pricing. On
39
40 the other hand, sectoral models do not provide economy-wide impacts, so the
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42 integration embraces both features, providing better insights for the macroeconomic
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44 and sectoral effects in the long term.
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49 50 51 **5 Results and discussion**

52 53 54 **5.1 Sectoral results**

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This section presents the results for the two main energy-demanding sectors (transport and industry) and energy supply. Additional results such as energy use by source can be found in the Supplementary Material.

5.1.1 Transport

Table 7 summarises the main results of energy demand and GHG emissions across the scenarios up to 2030.

Table 7

The REF scenario presents the lowest GHG volume emitted in 2030 (144 Mt CO₂e), 29% lower than 2015 levels. This result stems from the intense use of biofuels, either by increasing the mandated blend (biodiesel and biokerosene) or by the preference for hydrated ethanol in flex-fuelled vehicles. As a result, this scenario represents the largest share of renewable energy in the transportation sector, reaching 40% in 2030, against 21% in 2015. The greater participation of buses and active transport and a higher share of plug-in electric and hybrid cars reduce the energy consumption of light passenger vehicles, also contributing to mitigation.

Lower shares of renewable energy are observed in the SFE scenario, with volumes of biodiesel and hydrous ethanol consumption 29% lower than in the REF scenario, in 2030. This reflects the deliberate choice of exempting both gasoline and diesel from taxation, reducing the attractiveness of hydrous ethanol in flex-fuel vehicles (only 47%

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3 of the market share in 2030 in SFE), and hampering the economic viability of increasing
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5 the mandated biodiesel blend (10% blend in SFE vs 20% in REF and EPS).

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8 Only the REF scenario considers biokerosene, although limited to the minimum
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10 requirements of the initial phases of the Carbon Offsetting and Reduction Scheme for
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12 International Aviation (CORSIA) since production costs do not reach competitive prices
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14 in the short and medium-term. Even though biokerosene does not have a significant
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16 mitigation potential in the 2030 time frame, it can play a crucial role in post-2030
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18 scenarios.
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22 The shift from internal combustion engine (ICE) to hybrid and electric light vehicles
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24 still presents low economic viability in the 2030 horizon (Table 3). This is due to the lower
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26 VKT¹¹ usually performed by users in Brazil, which reduces the savings on maintenance
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28 and operating costs compared to acquisition costs. In the REF scenario, 2.5 million cars
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30 and motorcycles, 45 thousand buses and 146 thousand trucks and light commercial
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32 vehicles are electric by 2030. This amount is lower than expected by the IEA¹² in 2030
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34 (IEA, 2018). In EPS and SFE, electric and hybrid light vehicles are limited to buses and
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36 trucks in urban areas and ride-sharing services, namely from 2026 on. The lack of local
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38 suppliers and manufacturers in Brazil also contributes to this result.
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47 The penetration of electromobility is reflected in the scenarios' energy intensity,
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49 which is lowest in REF. A 19% reduction relative to 2015 levels in the energy intensity of
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51 passenger transport occurs, also due to higher active and public transportation,
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53 including passenger rail expansion (e.g., subways and urban trains). For freight
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60 ¹¹Vehicle Kilometres Travelled.

61 ¹² Considering the category "Rest of the World Scenarios".
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1 transportation, the reduction in energy intensity amounts to 31%. The energy intensity
2 of passengers reaches 862 kJ/km-pass in 2030, in the EPS and SFE scenarios (-17%
3 compared to 2015). The difference across scenarios is negligible for freight transport, as
4 mitigation measures are more attractive (lower average abatement costs) for freight
5 than for passenger transport and are implemented both in the EPS and SFE scenarios.
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13 In summary, results up to 2030 point to energy transition pathways based on
14 biofuels as crucial drivers of GHG emissions reduction in the transport sector. Still,
15 electromobility is expected to be more relevant in Brazil over the long run.
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28 **5.1.2 Industry**

29 In the Reference scenario (REF), mitigation measures for the Brazilian industry
30 are implemented and lead to significant decreases in industrial energy intensity. Unlike
31 the transportation sector, total energy demand increases between 2015 and 2030 in
32 REF, but only 4.7%
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41 Since diesel oil and gasoline consumption in the industrial sector is negligible
42 (approximately 1% of total energy use), the tax exemption for these fuels in SFE has little
43 impact. Therefore, the EPS and SFE scenarios results are virtually the same and
44 correspond to an increase in energy demand of 13% in 2030 compared to 2015. The
45 major differences between the EPS and SFE compared to the REF scenario lie in the
46 Cement, Iron and Steel, Food and Beverage and Chemicals sectors. In these four
47 industrial branches, several mitigation measures are not implemented in EPS and SFE
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1 scenarios due to high costs. This reflects in both higher energy demand and intensity
2 levels (Table 8).
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6 The share of renewables in industrial energy demand does not vary significantly
7 across scenarios and is explained essentially by the use of charcoal in the Iron and Steel
8 sector. In 2030, even though this share is lower in the EPS and SFE scenarios (19. 7%),
9 compared to REF (21. 8%), it induces a higher share of renewables in the overall energy
10 use, explained by the higher participation of the Iron and Steel branch in total energy
11 demand (21% in EPS and SFE, against 19% in REF).
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22 Food and Beverage, the industrial branch with the largest energy consumption,
23 presents a reduction of 19% in its energy intensity in REF. Iron and Steel, the second-
24 largest, presents a reduction of 8% (detailed in the SM). This smaller reduction
25 compared to other branches is due to the increase in the share of charcoal in the
26 production process (from 10% in 2015 to 13% in 2030). Albeit a low carbon route, this is
27 also a more energy-intensive one.
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39 Overall, EPS and SFE scenarios present a small reduction in energy intensity
40 compared to REF due to lower penetration of costly mitigation measures. In Iron and
41 Steel, there is even a slight increase in energy intensity. This is due to the combination
42 of increased use of charcoal and not implementing higher cost energy efficiency and
43 heat recovery measures in EPS and SFE scenarios.
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56 **Table 8**
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1 Industrial GHG emissions in the REF scenario increase 21% in 2030 compared to
2 2015 levels, from 168 MtCO₂e to 204 MtCO₂e. In the REF scenario, emissions decrease
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4 by 3.6% compared to 2015 levels, reaching 162 MtCO₂e in 2030. The major industrial
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6 branches leading to this decrease are Cement and Chemicals (-6 MtCO₂e and -2 Mt CO₂e,
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8 respectively).
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16 **5.1.3 Power generation and oil products supply**
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19 Table 9 shows the main energy supply and demand indicators for each scenario.
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21 For the country as a whole, energy demand is the lowest in the REF scenario. A slightly
22
23 higher level of electrification of the economy is also observed, mainly due to the shift
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25 from internal combustion engine vehicles (ICE) to hybrid and electric ones in the
26
27 transport sector. However, in EPS and SFE scenarios, part of the abatement yielded by
28
29 ambitious yet costly mitigation measures used in REF in the industrial, transport and
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31 power supply sectors is replaced by enhanced climate action in land use and agriculture,
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33 as explained in section 4.1 Smaller efforts to pursue energy efficiency in the EPS and SFE
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35 scenarios lead to higher overall energy demand (approximately 312 Mtoe in 2030).
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47 **Table 9**
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53 The renewables share in the SFE scenario shows that the lack of carbon pricing
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55 for sensitive fuels can delay a higher penetration of renewables in the energy mix.
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58 Emissions from energy supply are higher in the SFE scenario than in the EPS scenario
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3 due to higher demand for fossil fuels, increasing refineries' energy intensity and GHG
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6 emissions (both fugitive and due to energy self-consumption).

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Regarding power generation, results are very similar across the scenarios, mainly because the existing system is already highly based on renewables, with a large share of hydropower and increasing shares of wind and solar energy. Besides, the power sector expansion is already defined up to 2023 (derived from the outcomes of past electricity auctions), so there is little margin for significant variations in the short-to-medium terms. Table 10 shows that there is no increase in natural gas power plants in REF because no new capacity of power generation from fossil fuels is allowed, replaced by an increase of solar power. In the absence of this constraint, the natural gas power plants capacity increases in the EPS and SFE scenarios. However, this increase in the use of natural gas for power generation remains to play a complementary role to ensure the dispatching of intermittent (wind and solar) and seasonal (hydro) renewable power sources, matching the needs of the grid operator to proper adjustments to peak demands. It leads, however, to a higher grid emissions factor in these scenarios.

Table 9 also shows the different performances across scenarios for the energy sector indicators included in Brazilian NDC as indicative goals illustrating how Brazil would meet its GHG emissions economy-wide targets. It can be seen that Brazil is on a good track to meet its NDC commitments in the energy supply sector, as the 2030 goals are achieved in all scenarios. Accordingly, GHG emissions from energy supply are very low compared to the world average, as shown in Table 16. Even if oil and gas production increases substantially up to 2030, venting and flaring fugitive emissions from platforms are kept under control since regulations imposed in 2000 by the Oil and Biofuels

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Regulatory Agency (ANP) established that all new oil and gas fields production platforms should limit flaring or venting to no more than 3% of the associated natural gas.

Table 10

5.2 Economic and environmental results

This section focuses on the aggregate, country-wide results. Figure 2 presents total GHG emissions, split between energy and non-energy related.

Figure 2

Non-energy GHG emissions are dominant, mainly from deforestation in the Amazon and savannahs (“Cerrado”) and agriculture (due to methane emissions from around 210 million heads of cattle). Nonetheless, the share of emissions from fossil fuels consumption in total emissions steadily grows across scenarios, from 29% in 2015 to a range between 31% (REF) and 36% (SFE) in 2030. This is primarily driven by energy demand growth in transport and industry induced by economic activity increase (while GHG emissions from AFOLU can decrease sharply even with high GDP growth, as experienced in the past).

The adoption of carbon pricing schemes, combining a cap-and-trade system in the industry with a carbon tax imposed on fossil fuels used in other sectors, enables the use of a considerable potential of offsets (from the restoration of native vegetation) at

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an inexpensive cost (up to 6.3 US\$/tCO_{2e} in 2025 and 8.4 US\$/tCO_{2e} in 2030). This allows meeting NDC targets with limited use of costly mitigation actions implemented through command-and-control tools in the REF scenario (e.g., electromobility in transport, energy efficiency in industry, solar power generation).

The undergoing policy of mandating increasing quotas of renewable fuels to the sales by liquid fuels distribution companies creates an implicit carbon pricing scheme, as quotas can be traded (calculated according to its product carbon footprint). The *RenovaBio* program provides the framework for gradually increasing the share of renewable energy (ethanol from sugarcane and biodiesel) in the consumption of liquid fuels. In EPS, the use of biofuels increases compared to the base year, while being lower than in REF, and helps to meet NDC targets, together with other mitigation actions such as energy efficiency improvement and modal shifts. In the SFE scenario, the scope of GHG emissions covered by a carbon pricing scheme is narrower (down to 303 MtCO_{2e} in 2030) than in EPS (519 MtCO_{2e} in 2030). This leads to increased consumption of “politically sensitive fuels” (diesel oil, gasoline and LPG) and of GHG emissions from energy, compared to EPS. Therefore, energy-related GHG emissions are 4% higher in 2030 than in EPS (432 against 416 MtCO_{2e}). The demand for forest offsets is consequently higher in the SFE scenario.

Total investment requirements in EPS and SFE scenarios are, therefore, significantly lower - less than half - than in REF, as shown in Figure 3. This result confirms the effectiveness of carbon pricing and market mechanisms to provide increased flexibility and reduce the cost to meet the same mitigation target, compared to

1 command-and-control policy tools only, when lower-cost mitigation options are
2 available in other sectors (as offsets from AFOLU in the Brazilian case).
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9 **Figure 3**

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15 From a macroeconomic perspective, the greater flexibility and economic
16 effectiveness made possible by carbon pricing schemes induce higher GDP growth in the
17 EPS and SFE scenarios, compared to REF, up to 2030, as illustrated in Figure 4. This gain
18 more than compensates for the increased energy demand, and therefore the energy
19 intensity of GDP is lower in EPS and SFE scenarios than in REF. In 2030, decarbonisation
20 of energy supply is also lower in EPS and SFE scenarios than in REF. Carbon pricing and
21 the availability of low-cost offsets from AFOLU can thus make possible a smooth energy
22 transition in Brazil.
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36 As much as other elements play an important role in explaining the
37 macroeconomic and environmental results described in this section, we highlight that
38 the main focus of this study was to assess the variations in key features of the energy
39 demand and supply sectors across different pathways. Wills et al. (2021) performed a
40 similar scenario exercise applying a macroeconomic lens. The authors display results for
41 employment, price indices, trade balance, household consumption and income
42 inequality, among others, which are beyond the scope of our paper.
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55 **Figure 4**

6 Conclusion and policy implications

Carbon pricing mechanisms play an indispensable role in any cost-effective emission reduction strategy (Stiglitz et al., 2017). As an instrument internalising carbon costs into the decisions made by different agents, such a mechanism sheds light on the existing opportunities and strategies to pursue climate objectives. This paper sought to explore the extent to which carbon pricing may improve the effectiveness of achieving the Brazilian Nationally Determined Contribution (NDC). In line with existing literature (Gurgel et al., 2019; Rochedo et al., 2018), our analysis demonstrated the enormous potential of complying with official short-term climate commitments at an affordable cost, namely when seizing opportunities in the land-use and agricultural sectors. This is contrasted with fewer opportunities to decarbonise the Brazilian energy mix compared to countries with similar income levels and development goals, since hydroelectricity and biofuels already play an important role in Brazil.

Brazil is well placed to meet its NDC targets up to 2030 even under stringent commitments, thanks to its clean energy mix and the considerable potential of offsets provided by the AFOLU sector. This mitigation capacity can be better tapped by adopting a carbon pricing scheme that allows flexibility to meet domestic abatement targets with low-cost options. **On the one hand**, a pricing mechanism unravels the enormous offset supply, which would not be available in the absence of such an explicit (or at least indirect) instrument. The pricing can also help dynamise the NDC implementation, considering the implicit costs of command-and-control policies (e.g., institutional capacities and transaction costs). **On the other hand, a pricing mechanism may raise**

1 concerns regarding macroeconomic and distributional issues, which would entail
2 alternative arrangements such as the transport fuel exemption in the SFE scenario.
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6 Nonetheless, limiting the scope of the carbon pricing scheme adds pressure
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8 on other economic sectors to maintain the same economy-wide emission levels. A
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10 higher carbon price would be expected to compensate for a stricter scope,
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12 but forest offsets are abundant at low prices and served as a buffer. This allowed for an
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14 unchanged carbon price to reach the same abatement. However, the use of offsets in
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16 this scenario exceeded 20% of emissions reduction, which imposes additional pressure
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18 on the land-use sector and fails to ensure that decarbonisation would be pursued in all
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20 economic sectors, and mainly to encourage low-carbon investments in industry and
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22 transportation.
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30 Moreover, in the long run, the offset potential from AFOLU will only be available at
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32 progressively higher costs. In 2020, Brazil submitted its updated NDC to the UNFCCC, as
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34 preconised by the Paris Agreement guidelines¹³. During this process, the country issued
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36 an indicative commitment to achieving carbon neutrality in 2060 (Brazil, 2020). Previous
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38 scenario studies up to 2050 (La Rovere et al., 2018) and 2060 (FBMC, 2018) have shown
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40 the feasibility of the neutrality goal by using a substantial amount of offsets from AFOLU
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42 to compensate for the GHG emissions from the other sectors. However, in the longer
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44 run towards the end of the century, given the higher costs of the remaining offsets
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46 available, Brazil will need to implement new low-carbon options in other sectors (such
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54 ¹³Just before the conclusion of this study, the Brazilian government sent to the UNFCCC Secretariat an updated version
55 of its first NDC (Brazil, 2020). As GHG emissions in 2005 (the reference year) were officially revised upwards to 2.8
56 GtCO₂e (according to Brazil, 2016), and Brazil has confirmed the percentage reductions of its commitments (37% in
57 2025 and 43% in 2030), the new absolute caps for Brazilian economy-wide GHG emissions are now of 1.8 GtCO₂e in
58 2025 and 1.6 GtCO₂e in 2030, instead of the previous targets of 1.3 GtCO₂e in 2025 and 1.2 GtCO₂e in 2030. However,
59 we consider the first indicative targets (as in the version ratified by the Brazilian Congress in 2016). We also highlight
60 that reductions in climate ambitions are not allowed under the scope of the Paris Agreement.
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as electric vehicles, new batteries and electric storage technologies, new industrial processes for manufacturing intermediate goods and materials, among others) to ensure the sustainability of its development strategy under the climate neutrality constraint, as in the rest of the world.

The current transition in the Brazilian energy system is the shift from an oil-importing economy to a net oil exporter, thanks to the steady production increase from the pre-salt layer of offshore fields that is bound to continue and accelerate, which would seem inconsistent with the Paris Agreement goals. However, the Brazilian Congress has decided that oil production would be primarily channelled to exports, and the oil rent would fund the much needed public investments in education and health. Current trends of fossil fuel consumption and governmental scenarios up to 2050 (EPE e MME, 2020) confirm the intention to pursue this policy. In recent years, the country also experienced conflicts between energy and economic policies. The government opted for subsidising domestic prices of transport fuels (diesel and gasoline), an attempt to curb inflation rates (with disastrous economic impacts) from 2010 to 2015. This was subsequently reversed, allowing for reducing the total amount of subsidies recorded, which, however, remain high (INESC, 2020).

The Brazilian government also recently approved a new regulatory framework aiming to develop natural gas markets in Brazil. Private-public partnerships will be encouraged to build the infrastructure required to avoid wasting the energy potential of associated natural gas from offshore oil fields. This policy is not necessarily conflicting with the achievement of NDC targets in 2025 and 2030. The crucial condition would be to avoid massive use of natural gas for thermopower generation to meet baseload

1 demand (as this would displace power generation from renewable sources). Instead, if
2 priority is given to channelling natural gas to replace oil and coal products in other
3 markets (in industrial processes such as chemicals and fertiliser production, direct
4 reduction of iron ore for the steel industry, replacement of fuel oil and LPG in the
5 residential, commercial, and services sectors), then it may contribute to a smooth
6 energy transition in Brazil.
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16 Conflicts between energy, climate and economic policies can arise, especially when
17 a myopic perspective prevails. As much as pursuing the lowest-cost mitigation in the
18 short-term can help ensure development and equity objectives, this may also come in
19 the form of deleterious effects in the longer term, with consequences for the energy mix
20 and a higher cost of achieving net-zero emissions in the second half of the century. Only
21 the integration of short and long-term planning efforts will allow maximising synergies
22 and delivering both development and climate goals.
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Table 1 - Sectoral measures and targets in the Brazilian NDC

Energy-related measures and targets
<ul style="list-style-type: none"> ● Increasing the share of sustainable biofuels in the Brazilian energy mix to approximately 18% by 2030 (including advanced biofuels) ● In the energy sector, achieving 45% of renewables in the energy mix by 2030, including: <ul style="list-style-type: none"> - expanding the use of renewable energy sources other than hydropower in the total energy mix to between 28% and 33% by 2030 - expanding the use of non-fossil fuel energy sources, increasing the share of renewables (other than hydropower) in the power supply to at least 23% by 2030 (including by raising the share of wind, biomass and solar) - achieving 10% efficiency gains in the electricity sector by 2030 ● In the industry sector, promoting new standards of clean technology, enhancing energy efficiency and expanding low carbon infrastructure ● In the transportation sector, promoting efficiency and improving infrastructure for transport and public transportation in urban areas
Land use and agriculture measures and targets
<ul style="list-style-type: none"> ● In the land use and forestry sector, strengthening and enforcing the implementation of the Forest Code, achieving zero illegal deforestation in the Brazilian Amazonia and restoring 12 million hectares of forests by 2030, among other actions ● In the agriculture sector, strengthening the Low Carbon Emission Agriculture Program (Plano ABC), restoring degraded 15 million hectares of degraded pasturelands and expanding 5 million hectares of integrated cropland-livestock-forestry systems by 2030

Source: Brazil (2015)

Table 2 - Exogenous assumptions of scenarios, NDC targets and emissions pricing schemes

	REF	EPS	SFE
World population in 2030		8.3 billion	
Global average annual economic growth rate		2015-2020: 3.8% 2021-2030: 3.2%	
Brazilian population in 2030		225 million	
Domestic average annual economic growth rate¹		2015: -3.8% 2016: -3.6% 2017: -1.0% 2018-2020*: 2.5% 2021-2030*: 3.2%	
International oil price in 2030²		83 US\$/bbl (constant prices of 2013).	
Deforestation rates (km² per year)			
2025		13,700	
2030		12,600	
NDC targets	✓	✓	✓
Carbon pricing mechanism		✓	✓
Offsets from native forest restoration		✓	✓
Exemption to gasoline, diesel and LPG			✓

Source: IBGE (2020), EPE (2014), IEA (2019) and expert elicitation

¹ These are the estimated growth rates for the business-as-usual scenario. The implementation of mitigation measures and emissions pricing schemes are simulated over this baseline to derive the REF, EPs and SFE scenarios, as explained in the scenarios' description. These shocks may affect the final GDP levels.

² Consistent with IEA low-oil price scenario (IEA, 2019).

Table 3 - Abatement potential (MtCO₂e) and average abatement cost (USD/tCO₂e) for periods 2021-25 (a) and 2026-30 (b)

	2021-2025 (a)		2026-2030 (b)		
	Abatement potential (MtCO ₂ e)	Average cost (US\$/tCO ₂ e)	Abatement potential (MtCO ₂ e)	Average cost (US\$/tCO ₂ e)	
Hybrid and electric buses	4.5	-309.0	Hybrid and electric buses	14.1	-310.0
Active transportation	1.6	-271.7	Active transportation	3.1	-274.8
Railways	3.2	-242.2	Railways	9.8	-260.3
Ethanol	1.6	-185.1	Ethanol	14.2	-154.2
Food and Beverages (energy efficiency)	0.6	-130.3	Food and Beverages (energy efficiency)	1.0	-111.6
Non-ferrous (energy efficiency)	0.7	-69.5	Non-ferrous (energy efficiency)	1.7	-73.4
Chemicals (energy efficiency)	0.6	-61.3	Non-ferrous (heat recovery)	0.3	-60.9
Non-ferrous (heat recovery)	0.1	-53.3	Logistics optimization	4.4	-56.2
Logistics optimization	2.3	-50.8	Chemicals (energy efficiency)	1.2	-48.4
Iron and Steel (charcoal)	0.7	-37.9	Iron and Steel (charcoal)	1.6	-39.3
Waterways	5.3	-4.4	Rest of industry (heat recovery and process improvements)	4.8	-12.0
Cement (additives)	0.6	0.4	Waterways	5.2	-9.3
Rest of industry (heat recovery and process improvements)	2.2	1.3	Hybrid and electric trucks	0.5	-3.3
Biodiesel	6.9	4.2	Cement (additives)	1.3	-0.4
*Offsets from native vegetation (EPS and SFE only)	61.0	6.3	Biodiesel	15.8	3.6
Chemicals (heat recovery)	0.3	23.4	*Offsets from native vegetation (only EPs and SFE)	122.0	8.4
Cement (energy efficiency)	1.2	35.4	Chemicals (heat recovery)	0.7	24.2
Hybrid and electric trucks	0.1	53.3	Cement (energy efficiency)	2.6	30.4
Iron and Steel (energy efficiency)	2.0	72.0	Renewables in power generation	12.6	33.1
Food and Beverages (heat recovery)	0.1	131.9	Iron and Steel (energy efficiency)	4.3	74.0
Renewables in power generation	0.4	132.5	Food and Beverages (heat recovery)	0.3	138.4
Iron and Steel (heat recovery)	1.5	336.5	Subways	0.6	149.3
Hybrid and electric cars	0.3	1,164.1	Iron and Steel (heat recovery)	3.1	347.6
Subways	n/a	n/a	Hybrid and electric cars	2.5	363.2
Biokerosene	n/a	n/a	Biokerosene	0.2	671.4

Source: the authors

Observations: Cost values for the 2021-25 period in present value of 2021 and for the 2026-30 period in present value of 2026, both using a 8% p. y. discount rate.

Table 4 – Main scenario assumptions for the transport sector

<u>Mitigation measures</u>	<u>REF</u>	<u>EPS</u>	<u>SFE</u>
Logistics optimization	Programs to encourage good practices and labelling in the sector 4. 6% improvement in energy efficiency of road and rail modes		
Railroad expansion	Increased share of rail transport in the modal split, considering investments in progress with no delay		
Waterway expansion	Increased share of water transport in the modal split, considering investments in progress with no delay		
Passenger rail expansion	Additional 18% in the extension of the rail network	Additional 5% in the extension of the rail network	Additional 5% in the extension of the rail network
Increased use of active transportation	Incentive to active transportation behaviour. Additional 608 km of cycle paths		
Plug-in electric and hybrid cars	Share of electric and hybrid cars reaching 4. 3% of the fleet. Electric motorcycles reach 1% of the fleet	Share of electric and hybrid cars reaching 1. 3% of the fleet. Electric motorcycles reach 1% of the fleet	Share of electric and hybrid cars reaching 1. 3% of the fleet. Electric motorcycles reach 1% of the fleet
Plug-in electric and hybrid buses	Widespread in urban areas. Share of electric and hybrid buses reaching 11. 2% of national fleet	Widespread in urban areas. Share of electric and hybrid buses reaching 11. 2% of national fleet	Widespread in urban areas. Share of electric and hybrid buses reaching 11. 2% of national fleet
Plug-in electric and hybrid trucks	Share of electric and hybrid trucks reaching 2. 4% of national fleet	Share of electric and hybrid trucks reaching 2. 4% of national fleet	Share of electric and hybrid trucks reaching 2. 2% of national fleet
Increased use of biodiesel (B20)	Blend of 20 vol. % of biodiesel (B20) in diesel	Blend of 20 vol. % of biodiesel (B20) in diesel	Blend of 10 vol. % of biodiesel (B10) in diesel
Increased use of biokerosene	Blend of 2 vol. % of biokerosene in kerosene	-	-
Increased use of ethanol	Blend of 27 vol. % of anhydrous ethanol (E27) in gasoline. Annual supply of ethanol in 23. 6 million toe	Blend of 27 vol. % of anhydrous ethanol (E27) in gasoline. Annual supply of ethanol in 18. 7 million toe	Blend of 27 vol. % of anhydrous ethanol (E27) in gasoline. Annual supply of ethanol in 18 million toe

Source: the authors

Table 5 - Energy intensity in 2015 (PJ/Mt or PJ/million USD) and main assumptions for the industrial sector in simulated scenarios (annual average growth rate (%) in BAU and efficiency improvements (% or GJ/ t product) in NDC scenarios)

	<u>Energy intensity - 2015</u>	<u>REF</u>	<u>EPS and SFE</u>
Iron and Steel	21 PJ/Mt	- Energy efficiency: Frequency inverters in COG compressors - 0.12 GJ/t Use of residual fuels - 0.18 GJ/t Variable speed drivers - 0.001 GJ/t Variable speed drivers - 0.03 GJ/t Oxygen control in the ventilation system - 0.33 GJ/t Injection of Natural Gas - 0.9 GJ/t Coke Dry Quenching - 0.37 GJ/t Injection of pulverized coal - 0.57 GJ/t Foaming Slag - 0.07 GJ/t Automatic monitoring systems - 0.21 GJ/t Regenerative burning - 0.7 GJ/t Oxi-GN burning - 0.14 GJ/t Automation process - 0.11 GJ/t Scrap preheating - 0.13 GJ/t - Heat/steam recovery: Heat recovery in sintering process - 0.55 GJ/t Recovery of blast-furnace gas - 0.07 GJ/t Recovery of BOF gas - 0.55 GJ/t LDG Recovery - 0.55 GJ/t Heat recovery from water - 0.03 GJ/t Heat recovery from furnace - 0.3 GJ/t - Charcoal replacing coal*	- Energy efficiency: Frequency inverters in COG compressors - 0.12 GJ/t Use of residual fuels - 0.18 GJ/t Variable speed drivers - 0.001 GJ/t Variable speed drivers - 0.03 GJ/t Oxygen control in the ventilation system - 0.33 GJ/t - Charcoal replacing coal*
Food and Beverage	2.4 PJ/M\$	Energy efficiency: Optimization of condensate return - 5% Periodic maintenance in the boiler - 10% Improvements in gas boiler insulation - 8% Heat recovery - 10%	Energy efficiency: Optimization of condensate return - 5% Periodic maintenance in the boiler - 10%
Ceramics	593 (PJ/M\$)	Energy efficiency: Combustion optimization - 7% Equipments replacement and maintenance - 8% Process automatization - 0.4%	Energy efficiency: Combustion optimization - 7% Equipments replacement and maintenance - 8% Process automatization - 0.4%
Cement	0.43 (PJ/mt)	Energy efficiency: Multiple stages (energy efficiency) - 10% Optimization of clinker production - 3.5% Oven combustion improvements - 8% Oven refractory - 6.8% Other process improvements: Additions in clinker - 15%	Energy efficiency: Multiple stages (energy efficiency) - 10% Optimization of clinker production - 3.5% Oven combustion improvements - 8% Oven refractory - 6.8% Other process improvements: Additions in clinker - 15%
Iron alloys	73 PJ/mt	Energy efficiency: Equipment improvements - 20% Process control improvements - 10% Heat recovery - 15%	Energy efficiency: Equipment improvements - 20% Process control improvements - 10% Heat recovery - 15%
Non-ferrous metals	160 PJ/mt	Energy efficiency: Airflow improvements in combustion - 5% Pressure control - 5% Insulating materials - 3.5% Engine optimization - 5% Heat recovery - 10%	Energy efficiency: Airflow improvements in combustion - 5% Pressure control - 5% Insulating materials - 3.5% Engine optimization - 5% Heat recovery - 10%
Mining and pelleting	0.28 PJ/mt	Energy efficiency: Combustion optimization - 3%	Energy efficiency: Combustion optimization - 3%

		Process control improvements - 2. 8% Heat recovery – 3% Condensate recovery - 13%	Process control improvements - 2. 8% Heat recovery – 3% Condensate recovery - 13%
Pulp and Paper	18 PJ/mt	Energy efficiency: Combustion optimization - 3% Process control improvements - 2. 8% Heat recovery – 3% Condensate recovery - 13%	Energy efficiency: Combustion optimization - 3% Process control improvements - 2. 8% Heat recovery – 3% Condensate recovery - 13%
Chemicals	0. 0097 PJ/mt	Energy efficiency: Furnace improvements - 2% Engine and furnace monitoring and maintenance - 10% Process integration – 20% Heat recovery - 2% Condensate recovery - 10%	Energy efficiency: Furnace improvements - 2% Engine and furnace monitoring and maintenance - 10% Heat recovery - 2% Condensate recovery - 10%
Textiles	0. 0009 PJ/M\$	Energy efficiency: Combustion optimization - 6% Process control improvements - 5% Heat recovery – 5% Condensate recovery - 4%	Energy efficiency: Combustion optimization - 6% Process control improvements - 5% Heat recovery – 5% Condensate recovery - 4%

*The process of producing steel using charcoal decreases the emissions of GHG. However, it can increase the energy intensity of the sector. An increase from 10% in 2019 to 13. 7% in 2030 was assumed.

Source: the authors based on (DNPM, 2016; EPE, 2019; Guedes, 2017; IABr, 2012; IBGE, 2014; MME, 2019) for energy intensity andand (Couto, 2017; de Oliveira, 2017; EPE, 2018; Guedes, 2017) for mitigation measures.

Table 6 - Main scenario assumptions for the energy supply sector

Scope	REF	EPS and SFE
E&P levels		
Oil (Mboe/day)	3. 2 in 2020; 4. 3 in 2025; 5. 9 in 2030	
Natural gas (Mm³/day)	130 in 2020; model results in 2025 and 2030	
Refineries expansion¹	RNEST second train implementation in 2024 and operation of a new natural gas processing plant in COMPERJ in 2021	
Fugitive emissions control (Flaring e Venting)²	2020: 3. 2%	2020: 3. 2%
	2025: 2. 6%	2025: 3. 0%
	2030: 2. 0%	2030: 3. 0%
Fugitive emissions (Refining and transport)³	Annual mitigation of 0. 5 MtCO ₂ eq	-
Electricity sector (Contracted plants up to 2023)	Nuclear plant Angra III: 2026	
	Hydropower plant São Roque: 2023	
	Diesel and fuel oil plants: decommissioning after 25 years	
Electricity Sector (Expansion restrictions - from 2023)	Wind: 4, 000 MW/year maximum	
	Centralized photovoltaic: 1, 000 MW/year to 3, 000 MW/year	
	Distributed photovoltaic: 1, 880 MW until 2020; 5, 290 MW until 2025; 10, 800 until 2030	
	Hydroelectric: projects considered in EPE (EPE, 2020a)	
	Small hydroelectric: 350 MW/year until 2024; 450 MW/year until 2027; 600 MW/year until 2030	
	Sugarcane bagasse: 700 MW/year maximum	
	Firewood: 200 MW/year	
Electricity Sector (Thermoelectric plants expansion restrictions)	Fossil fuels: no free expansion, only power plants already contracted at the New Energy Auctions	No restrictions

1- RNEST: *Abreu e Lima* refinery in Pernambuco state; COMPERJ: Petrochemical Complex of Rio de Janeiro; Source: Petrobras (2019)

2- Based on flaring levels in Stewart (2014)

3- Source: Petrobras (2017)

Source (other assumptions) : EPE(2020b)

Table 7- Main results for the transport sector

	2015	2020	2025			2030		
			REF	EPS	SFE	REF	EPS	SFE
Road mode share in the modal split								
Passenger transport	92%	90%	90%	90%	90%	90%	90%	90%
Freight transport	56%	52%	47%	47%	47%	43%	43%	43%
Energy intensity								
Passenger intensity (kJ/pass-km)	1, 038	1, 058	941	947	947	838	862	862
Freight intensity (kJ/t-km)	1, 023	934	801	802	802	708	709	709
Renewable energy share								
Renewable energy use	21%	23%	31%	29%	26%	40%	32%	27%
Market share of hydrous ethanol	33%	33%	50%	40%	36%	75%	60%	47%
Biodiesel blend	7%	10%	15%	15%	10%	20%	20%	10%
Total energy use (million toe)	84. 5	85. 4	79. 6	81. 0	81. 2	77. 4	81. 6	81. 4
Plug-in electric vehicle stock (thousands)								
Light passenger vehicles	1	3	421	51	51	2, 502	243	243
Buses	-	0	9	9	9	45	45	45
Light commercial vehicles and trucks	0	0	23	9	9	146	66	66
Emissions (Mt CO₂e)	204	203	170	178	186	144	171	184

Source: the authors

Table 8- Energy demand per industrial branches across scenarios (million toe)

Energy demand	2015	2020	2025			2030		
			REF	EPS	SFE	REF	EPS	SFE
Cement	4.7	4.1	4.0	4.2	4.2	4.0	4.4	4.4
Iron and steel	16.7	16.7	16.7	18.3	18.3	16.8	20.1	20.1
Iron alloy	1.2	1.5	1.8	1.8	1.8	2.2	2.2	2.2
Mining and pelleting	3.3	2.9	2.7	2.7	2.7	2.5	2.6	2.5
Non-ferrous metals	5.6	6.1	7.0	7.0	7.0	8.2	8.1	8.1
Chemical industry	6.9	7.0	6.6	6.9	6.9	6.1	6.6	6.6
Food and beverage	21.5	24.0	22.3	23.6	23.6	20.7	23.2	23.2
Textiles	0.90	0.91	0.91	0.91	0.91	0.91	0.92	0.92
Pulp and paper	11.7	13.5	14.3	14.3	14.3	15.0	15.1	15.1
Ceramic	4.6	4.4	4.4	4.5	4.5	4.4	4.5	4.5
Other industries	7.9	8.2	8.3	8.4	8.4	8.4	8.5	8.5
() Total	85.1	89.4	89.1	92.7	92.7	89.1	96.2	96.2
Share renewables (total industry)	39.0%	40.6%	40.1%	40.1%	40.1%	39.6%	39.7%	39.7%
Share biomass (Iron and Steel)	17.9%	14.7%	17.9%	17.1%	17.1%	21.8%	19.7%	19.7%
Variation in energy intensity compared to 2015	-	7.9%	-9.3%	-6.5%	-6.5%	-22.5%	-18.1%	-18.1%

Source: the authors

Table 9- Main results and indicators for the energy supply sector in simulated scenarios

	2015	2020	2025			2030			NDC goals - 2030
			REF	EPS	SFE	REF	EPS	SFE	
Final demand (Mtoe)	261.4	276.3	284.6	289.9	290.2	300.4	312.5	312.2	n/a
Primary energy transformed into electricity (Mtoe)	77.6	68.6	77.7	78.9	78.9	90.9	93.8	94.2	n/a
Other primary energy supply (Mtoe)	222.0	233.0	228.9	234.0	234.1	236.2	247.6	247.5	n/a
Total primary energy supply – TPES (Mtoe)	299.6	301.6	306.6	312.9	313.0	327.1	341.4	341.7	n/a
Sectoral indicators									
Grid emission factor (kgCO ₂ /MWh)	130.0	50.5	50.5	51.7	51.8	41.9	51.0	54.8	n/a
Share of bioenergy ¹ () in energy supply (%)	17.9%	21.1%	22.3%	21.8%	20.9%	23.7%	21.8%	20.2%	18.0%
Share of renewables in energy supply (%)	41.3%	48.6%	52.7%	51.8%	50.2%	56.0%	52.9%	49.7%	45.0%
Share of renewables in energy supply, except hydropower (%)	30.0%	35.4%	38.2%	37.6%	36.0%	42.1%	39.5%	36.3%	28.0%
Share of electricity from renewables, except hydro (in total electricity supply) (%)	11.5%	19.4%	21.0%	21.1%	21.0%	29.3%	27.7%	26.8%	23.0%

¹ Ethanol and biodiesel

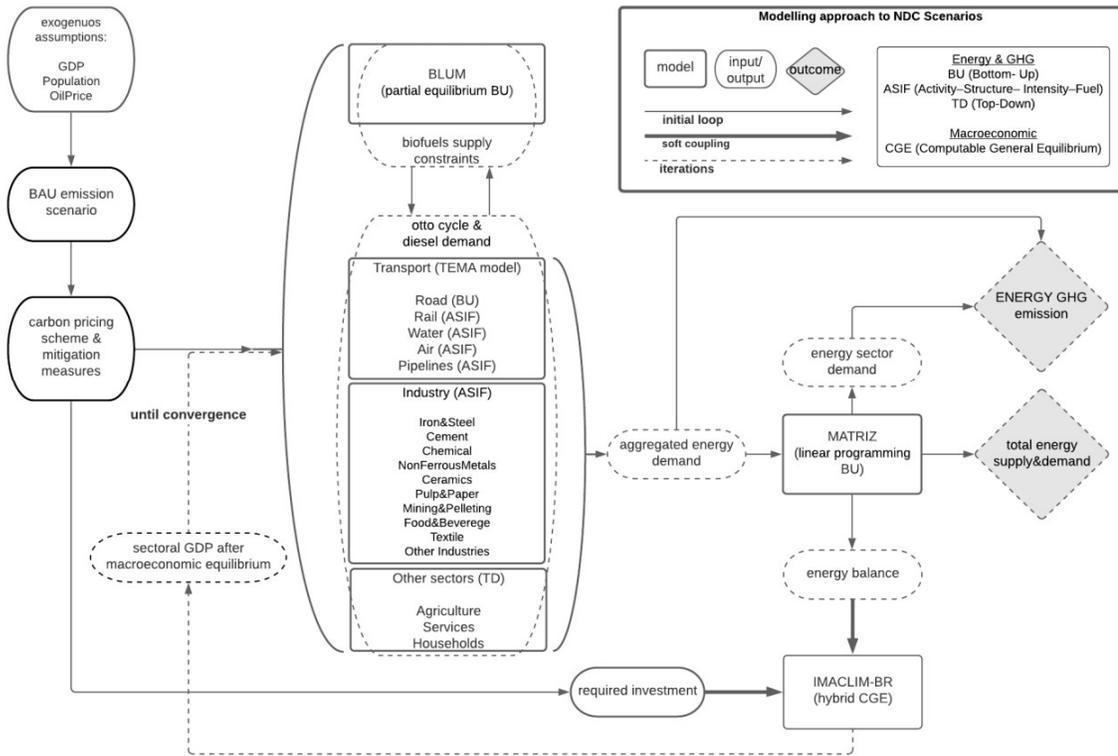
Source: the authors

Table 10 - Installed capacity of power generation across scenarios (MW)

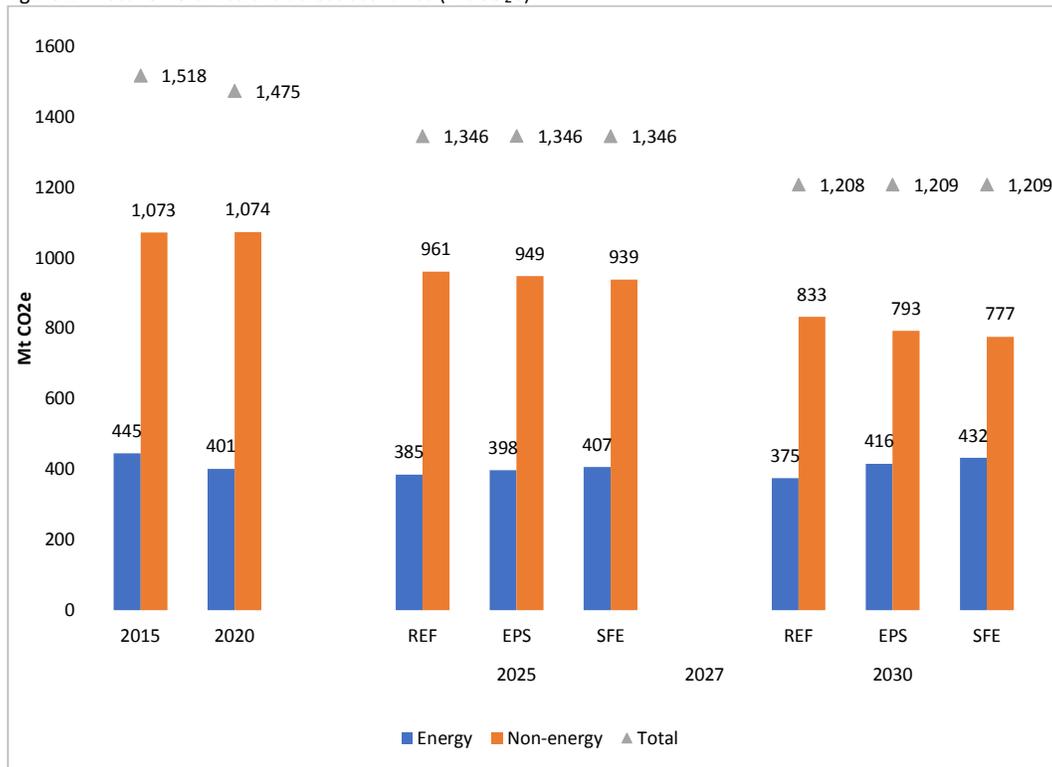
	2015	2020	2025			2030		
			REF	EPS	SFE	REF	EPS	SFE
Nuclear	1,990	1,990	1,990	1,990	1,990	3,395	3,395	3,395
Coal	3,389	3,515	3,515	3,515	3,515	3,515	3,515	3,515
Natural Gas	12,743	14,537	18,344	18,344	18,344	18,344	22,828	23,418
Other non-renewables	10,174	5,171	4,139	4,139	4,139	1,836	1,836	1,836
Hydropower	91,650	108,437	110,850	110,850	110,850	115,591	115,291	115,291
Biomass	13,257	13,853	14,189	14,319	14,253	18,687	17,819	17,753
Wind	7,633	15,537	18,630	18,630	18,630	30,600	31,363	29,341
Solar	21	4,529	12,273	12,273	12,273	28,868	22,781	22,781
Total	140,857	167,569	183,929	184,058	183,992	220,835	218,827	217,329

Source: the authors

Figure 1 - Integrated modelling framework

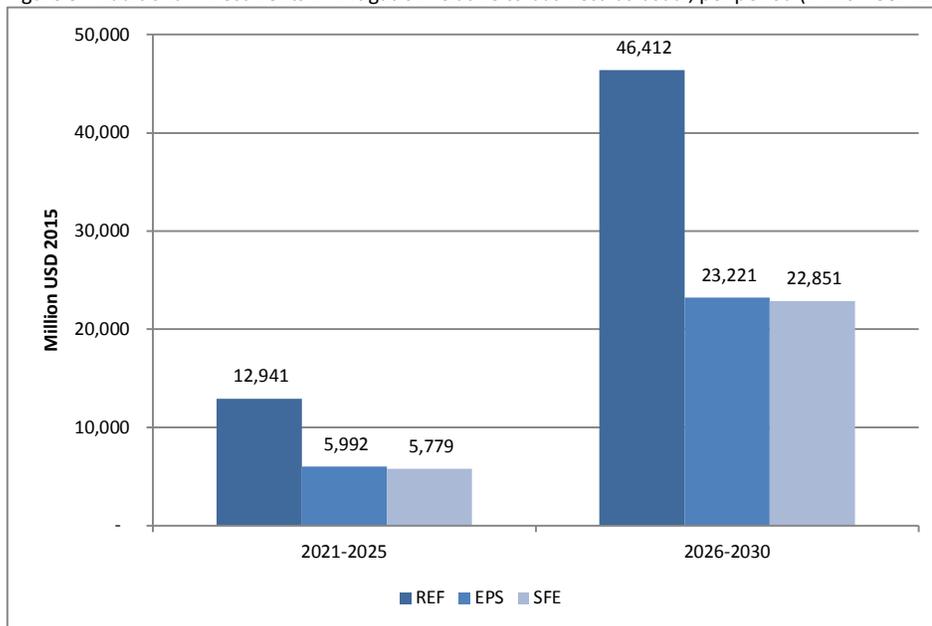


Source: the authors

Figure 2 - Total GHG emissions across scenarios (Mt CO₂e)

Source: the authors

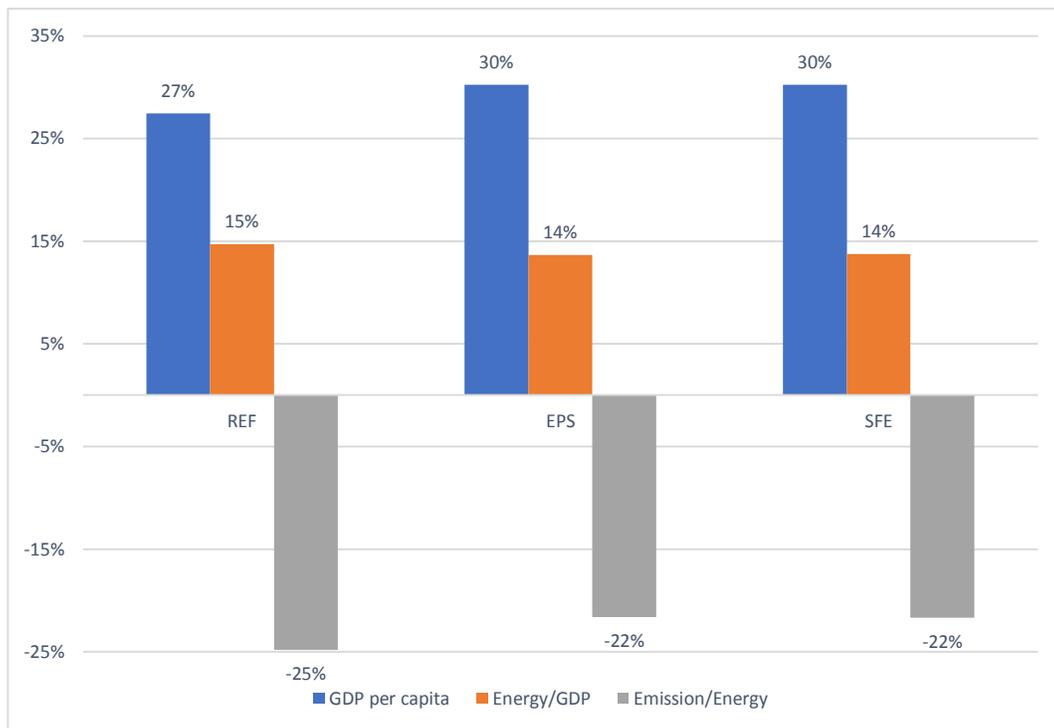
Figure 3 - Additional investments in mitigation relative to business-as-usual, per period (million USD 2015)



Note: includes investments in the energy, industry and transport sectors. Land-use change and agriculture are not included.

Source: the authors

Figure 4 - Economic, Energy and GHG Emissions Indicators in 2030 relative to 2015 (growth in %)



Source: theauthors