DEEP DECARBONIZATION PATHWAYS

POLICY LESSONS ON DEEP DECARBONIZATION

in large emerging economies

BRAZIL

Emilio L. La Rovere, Carolina B.S. Dubeux, William Wills, Michele K. C. Walter, Giovanna Naspolini, Otto Hebeda, Daniel N. S. Gonçalvez, George V. Goes, Márcio D'Agosto, Erika C. Nogueira, Sérgio H. F. da Cunha, Cláudio Gesteira, Gaëlle Le Treut, Giovanna Cavalcanti, Mark Bermanzon

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Disclaimer

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HOW IS THIS DOCUMENT RELEVANT TO THE GLOBAL STOCKTAKE?

This document is part of a collective report that assesses the evolution of climate ambition in 26 countries and 3 hard-to-abate sectors through a granular and context-specific analysis of trends and progress of national and sectoral transformations.[1] This approach allows identifying what hinders and spurs action in countries and sectors, and understanding the conditions that can support enhanced ambition, which could be political, social, economic, governance.

These insights are directly relevant to four overarching functions of the Global Stocktake in support of its desired outcome, i.e. "to inform Parties in updating and enhancing, in a nationally determined manner, their actions and support in accordance with the provisions of the Paris Agreement, as well as enhancing international cooperation for climate action" (Article 14.3 of the Paris Agreement):

- Create the conditions for an open and constructive conversation on global cooperation (on e.g., technology, trade, finance, etc.), based on an in-depth understanding of the international enablers of enhanced country ambition.
- Organize a process for knowledge sharing and collective learning, based on concrete examples of actions already in place or being discussed, including best practices.
- Create space for open dialogues across different stakeholders to support better coordination of actions, based on a detailed understanding of the levers to be activated to enhance ambition in national and sectoral transitions
- Facilitate ownership by decision-makers of the climate challenge and the risks and opportunities of the low-emission and resilient transition, based on context-specific and granular analysis of barriers and enablers.

More specifically, the collective report in general – and this document in particular – can contribute to address some of the key guiding questions for the Global Stocktake[2], notably:

- What actions have been taken to increase the ability to adapt to the adverse impacts of climate change and foster the climate resilience of people, livelihoods, and ecosystem? To what extent have national adaptation plans and related efforts contributed to these actions (Decision 19/CMA.1, paragraph 36(c))?
- How adequate and effective are current adaptation efforts and support provided for adaptation (Article 7.14 (c) Paris Agreement)?
- What are the barriers and challenges, including finance, technology development and transfer and capacity-building gaps, faced by developing countries?
- What is the collective progress made towards achieving the long-term vision on the importance of fully realizing technology development and transfer in order to improve resilience to climate change and to reduce greenhouse gas emissions referred in Article 10.1 of the Paris Agreement? What is the state of cooperative action on technology development and transfer?
- What progress been made on enhancing the capacity of developing country Parties to implement the Paris Agreement (Article 11.3 Paris Agreement)?
- To achieve the purpose and long-term goals of the Paris Agreement (mitigation, adaptation, and finance flows and means of implementation, as well as loss and damage, response measures), in the light of equity and the best available science, taking into account the contextual matters in the preambular paragraphs of the Paris Agreement:
  - What are the good practices, barriers and challenges for enhanced action?
  - What is needed to make finance flows consistent with a pathway towards low GHG emissions and climate-resilient development?
  - What are the needs of developing countries related to the ambitious implementation of the Paris Agreement?
- What is needed to enhance national level action and support, as well as to enhance international cooperation for climate action, including in the short term?
- What is the collective progress made by non-Party stakeholders, including indigenous peoples and local communities, to achieve the purpose and long-term goals of the Paris Agreement, and what are the impacts, good practices, potential opportunities, barriers and challenges (Decision 19/CMA.1, paras 36(g) and 37(i))?

1 The full report « Climate ambition beyond emission numbers - Taking stock of progress by looking inside countries and sectors" can be found at: https://www.iddri.org/en/publications-and-events/report/climate-ambition-beyond-emission-numbers-taking-stock-progress

2 Draft Guiding Questions for the Technical Assessment of GST1 (version 20th October 2021), available at: https://unfccc.int/sites/default/files/resource/Draft%20GST1_TA%20Guiding%20Questions.pdf

FOREWORD

Henri Waisman, Marta Torres Gunfaus, Anna Perez Catala, IDDRI.

The world has agreed to prevent the irreversible damages to human and natural ecosystems caused by anthropogenic global warming by limiting the rise of global temperature to well below 2°C and to pursue efforts to limit it to 1.5°C. To this, the Paris Agreement grounds this goal in terms of global emission trajectories and the need to embed them in the in the context of sustainable development and efforts to eradicate poverty. Subsequently science (IPCC SR1.5) further specifies that global neutrality concerning carbon dioxide specifically should happen between 2050 (for 1.5°C) and 2075 (for 2°C). It also points out the necessity of minding non-CO_2 forcers to maintain the global objective. To reach this scale of emission reductions, the scientific assessment concludes that rapid and far-reaching transformations, far beyond what has been observed in the past, are required in all components of the economic system, ie in energy, urban and infrastructure, industry and land and ecosystems. Such drastic transitions in turn require profound changes in technologies but also in social, economic, institutional and policy conditions. Science finally shows that the changes required by climate objectives can be compatible with broader sustainable development objectives if action is implemented without delay, is guided by strategic visions of transformations informing the design of well-designed policy packages and the cooperation among actors and is enabled by effective international cooperation. With these framework conditions at hand, countries are set to explore national pathways to explain how the rapid and far-reaching transitions required globally can happen in each country context.

National deep decarbonisation of large emerging economies has been largely explored from a techno-economic perspective, resulting in viable sets of long-term pathways under a number of conditions. Existing analysis shows that the national transition can mostly been initiated using existing technologies and market instruments at low and often net negative financial cost and that, usually, these transformations can have associated large overall net economic benefits when external economic costs and benefits are factored in. However, similar to most parts of the world, most major necessary decarbonisation transformations are either not happening or happening at a slower pace. This gap between existing evidence and concrete action highlights that the carbon neutral transition is not only a matter of techno-economic feasibility but essentially a question of political economy. Actual implementation requires clarity about the choices to be made in the transition, about the concrete policies and actions that can be envisaged, about those who can winners and those who may loose and the measures adopted to manage the socio-economic costs of the transition. Scientific assessments should therefore be seen less as an instrument to decide transition pathways in a normative manner than as a way to inform the inclusive whole-of-society conversation that would be required to make the transition effective and acceptable.

The DDP community behind this report has committed to this vision of the role of scenario analysis in the public debate. The body of knowledge emerging from this community aims at ensuring that the features of the techno-economic deep decarbonisation transformations are contextualized in the diversity of country circumstances and described with sufficient details and granularity to inform decisions required to drive these transformations. Key challenges to date, which are critical to increase ambition and accelerate action, include: connecting the scenarios analysis and the diversity of policies and actions to implement in the real world; revealing the critical conditions that are outside the control of national authorities, where international cooperation must play a role; ensuring ownership of the insights emerging from the scenarios by a diversity of actors to empower them in the public debates.

The DDP approach underlying this report's research is established with these key challenges in mind.

It is fundamentally a country-driven exploration, back casting from the mid-century emission and socio-economic objectives to inform the short-term decisions across systems. Sectoral deep dives allow for an in-depth investigation of all levers, opportunities and challenges suited to inform domestic stakeholder debate in highly complicated sectors, such as transport, industry, or agriculture/land-use, which are traditionally represented poorly in existing long-term roadmaps. The stakeholder engagement approach to the development of the scenarios and emanating policy insights is an essential mean for these scientific assessments to serve an action agenda.

This report presents a synthesis of the results of the assessment conducted in India. Part I describes the main features of the economy-wide Deep Decarbonization Scenario(s) (DDS), including a description of key national-scale socio-economic aspects and an explicit characterisation of the emission objective and trajectory. To realise the necessary changes to get on track to this path, a description of the Current Policy Scenario (CPS) is also presented, including a description of the main policies and actions considered. Scenario results include an in-depth description at sector level for the deep dives selected by each country. Part II focuses on key policy lessons, which can serve as direct inputs into policy conversation at the country level. It includes a description of the main synergies and trade-offs with country non-climate objectives, priority short-term policies and actions, with a focus on where shifts from current paths are critically required, investments patterns and key international enablers and accelerators of domestic transitions.

BRAZIL

INTRODUCTION

The Brazilian NDC has an economy-wide goal of 37% GHG emission reduction, by 2025 and 43% reduction by 2030, compared with 2005 as the base year. Brazil also made voluntary commitments of emission reductions in 2009 during COP15 (Copenhagen) linked to its NAMAs, corresponding to keep emissions below a cap of roughly 2 Gt CO_2eq in 2020. More recently, the Brazilian President announced at the Climate Leader Summit organized by US President on 22 April 2021 the country's commitment to reach climate neutrality by 2050.

This study simulates two GHG emissions scenarios in Brazil until 2050. It provides a framework for an analysis of economy-wide and sectoral indicators of a decarbonization pathway aligned with the general objective of the Paris Agreement (net-zero GHG emissions in 2050). The Current Policies Scenario (CPS) follows the trend of ongoing mitigation actions. Its emissions are of 1.65 Gt CO_2eq in 2030, with no increase in ambition between 2030 and 2050. The CPS nearly meets the country's target for 2030 under the "new first NDC" but is above the figure (1.4 Gt CO_2eq) of a revised target when the 2005 base year emissions are updated according to the new 4th national emissions inventory. The Deep Decarbonization Scenario (DDS) reaches 1.0 Gt CO_2eq in 2030, going beyond the NDC target and following a GHG emissions trajectory compatible with the global objective of 1.5ºC, achieving net-zero emissions in 2050.

The sectoral mitigation measures considered in CPS are based on national plans and policies. DDS incorporates more ambitious actions and other available technologies. DDS's main features are a radical reduction in deforestation rates and an increase of carbon sinks. Carbon pricing from 2021 is assumed for a significant share of the emissions (Energy and IPPU), with sectors introducing mitigation actions with costs under the carbon price in each period, starting with the most cost-effective. Carbon prices are introduced through a cap-and trade system in Industry, and a carbon tax on GHG emissions from the combustion of fossil fuels in other sectors. They will grow linearly, reaching 25 USD/tCO_2eq in 2030 and 65 USD/tCO_2eq in 2050. Carbon pricing will be neutral from a fiscal perspective, with 100% of its revenues recycled back into the economy through labour charges reduction aiming to foster employment, and to compensate low-income households for the average price level increase.

Population size increases from 210 million inhabitants in 2019 to about 233 million inhabitants in 2050. In this period, the urban population share grows from 86% to 89%. Following the sharp downturn in the economy from 2015 to 2020 due to a political-economic crisis and the COVID-19 pandemic, Brazilian economy economic recovery is assumed to start on 2021: annual average GDP growth rates would be of 3,5% in 2021; 2,5% from 2021 to 2030; 2,25% from 2031 to 2040; and 2% from 2041 to 2050 (with linear growth assumed within each decade). After the drawback in the 2015-2020 period, Gini index starts to decrease again, but slower than the 2000-2015 record. Household size is projected to decrease slowly while household disposable income as a % of GDP is projected to increase. Trade will become more important to Brazil during the scenario timeframe, and import taxes and protectionism will be reduced, following the global trend.

We use an integrated modelling approach, where a set of six sectoral models is linked to a CGE model (IMACLIM-BR). The sectoral models consist of four energy demand models (transport, industry, buildings, and agriculture energy demand), an agriculture, forestry and other land use (AFOLU) model and an energy supply model (MATRIZ). GHG emission estimates from Waste complete the picture.

PART 1: SCENARIO RESULTS

EMISSION PROFILES

GHG emissions reach 17 Mt CO_2eq in DDS and 1889 in CPS by 2050. Comparing 2050 in both scenarios with 2020 values, DDS is 99% lower, while CPS is 27% higher. **Table 1** presents the figures by sector.

Most GHG emission reductions come from land use change and forestry. Compared to CPS, in 2050 DDS emissions from deforestation are 93% lower, a reduction of 953 Mt CO_2eq. On the top of that, carbon removals increase 76%, equivalent to 451 Mt CO_2eq, thanks to increased forested and protected areas (indigenous lands and conservation units). Transport is the second most relevant sector, with an emission reduction of 126 Mt CO_2eq (53%), followed by the waste sector with a reduction of 120 MtCO_2eq (65%), and livestock activities with 116 Mt CO_2eq (22%). Finally, in industry the reduction is of 84 Mt CO_2eq (31%), and in energy supply added to other energy consumption sectors of 27 Mt CO_2eq (23%). The only activity with a small increase in emissions is cropping, with 4 Mt CO_2eq (4%) more emissions in DDS due to higher biofuels production.

In DDS, only two sectors have higher GHG emissions in 2050 than in the base year 2019: cropping activities increase emissions by 29%; and industry by 14%. In these cases, under the assumption of no major breakthroughs or disruptive technologies, the improvement of technologies currently in use was not sufficient to compensate for the higher production levels.

MITIGATION ACTIONS AND COSTS

In DDS, besides the huge effort to curb down deforestation and increase removals, the carbon pricing policy supplies the complementary mitigation actions in other sectors required to reach net-zero emissions in 2050. **Table 2** presents the cumulative avoided GHG emissions per decade (Mt CO_2eq).

Table 1 – Total GHG Emissions per Sector, 2005-2050, under CPS and DDS (Mt CO_2eq)

MtCO_2eq		2005	2010	2019	2020	2030	2005-2030	2040	2050	CPS-DDS (2050)
Land Use Change (LUC) – gross emissions	CPS	2,171	668	948	1,018	1,024	-53%	1,024	1,024	-93%
	DDS					614	-72%	201	71	
Removals (LUC, Forest, Protected Areas and Other)	CPS	-249	-313	-574	-591	-556	123%	-576	-593	76%
	DDS					-695	179%	-794	-1042	
Agriculture (crops + energy)	CPS	146	161	92	92	97	-34%	101	115	4%
	DDS					99	-32%	106	119	
Livestock	CPS	329	329	433	432	466	42%	485	529	-22%
	DDS					453	38%	444	413	
Transport	CPS	139	173	196	175	209	50%	220	240	-53%
	DDS					167	20%	139	114	
Industry (energy + IPPU)	CPS	139	162	162	166	194	40%	232	268	-31%
	DDS					172	23%	180	184	
Energy (supply + demand from households and services)	CPS	100	111	121	95	127	27%	115	120	-23%
	DDS					120	21%	100	93	
Waste	CPS	61	69	100	102	105	71%	145	186	-65%
	DDS					76	25%	78	65	
Total	CPS	2,837	1,361	1,479	1,488	1,665	-41%	1,745	1,889	-99%
	DDS					1,005	-65%	454	17	

Command and control policies combined with constraining the access of farmers and ranchers to public credits (subject to conformity with environmental laws and regulations) achieve 59% of total cumulative GHG emission reductions up to 2050, through the sharp reduction of annual deforestation rate. The 2004-2012 record has already shown the potential of these measures that can be successfully adopted again. Command-and-control measures also allow to avoid deforestation through the increase of the number and the surface of conservation areas (e.g., permanent preservation areas, indigenous land demarcation, and other legal reserves).

The carbon pricing policy can supply 30% of total cumulative avoided emissions up to 2050 in different sectors: AFOLU (18%), Transport (6.5%), Industry (4%), and Energy supply (1%).

Native vegetation restoration in public and private areas have a significant abatement potential and lower costs than the other sectors. It allows to remove 2,647 Mt CO_2eq up to 2050, when native vegetation restoration will reach 30.18 million ha. Private areas present more attractive costs in comparison with public areas (7 versus 17 USD/t CO_2eq in 2021, 8 versus 28 in 2031, and 9 versus 31 in 2041). Considering the enforcement of Forest Code compliance, private areas provide higher cumulative avoided emissions in 2021-2030 (121 versus 38 Mt CO_2eq) and in 2031-2040 (322 versus 302 Mt CO_2eq) than public areas. However, in the last decade, the bulk of removals will come from public areas thanks to a better cost-effectiveness, and thus its contribution to cumulative avoided GHG emissions throughout the whole 2020-2050 period will be of 1,6311 against 1,015 Mt CO_2eq from private areas.

The abatement cost assessment indicates the pathway of carbon prices. Costs for a given mitigation option may vary throughout the three decades

Table 2. Cumulative avoided emissions (CPS-DDS) per mitigation actions, per decade (Mt CO_2eq)

Cumulative avoided emissions per decade (Mt CO_2eq)			Decades
	2021 – 2030	2031 – 2040	2041 – 2050
Total Mitigation Actions	3,629	10,069	16,103
Carbon Pricing Policy	1,013	2,618	5,254
AFOLU	619	1,483	3,281
Native forest restoration in public areas (through government concession)	38	302	1,291
Native forest restoration in private areas (offsets)	121	322	572
Planted forests (homogeneous and integrated crop-livestock- forest systems)	196	244	275
Agriculture	39	76	38
Livestock (restoration of degraded pastures, intensification, other)	225	538	1,105
Transport (freight and passenger)	233	639	1,064
Modal shift	132	169	271
Electromobility	-	346	520
Biofuels	98	124	273
Industry	126	387	694
Energy intensive industries	86	257	451
Light industry (rest of industry)	40	129	243
Energy Supply	35	110	216
Power generation	8	42	107
Self-consumption and fugitive emissions	28	68	109
Other Mitigation Policies	2,616	7,451	10,849
AFOLU	2,461	6,957	9,887
Reducing annual deforestation rate	2,252	6,367	8,940
Increasing conservation units, indigenous lands and other protected areas	209	590	947
Waste	155	494	963

Source: the authors.

due to increasing economies of scale and variations in cost assumptions (e.g., decreasing costs for electric vehicles and renewable electricity). **Table 3** presents the cumulative avoided emissions per mitigation cost range (US$/t CO_2eq) in each decade.

A significant share of avoided emissions can be obtained at negative costs. Modal shifts in the freight transport sector (e.g., from roads to railways and waterways), a wide range of energy efficiency measures in industry and sustainable agricultural practices (e.g., no-till systems, biological fixation of nitrogen) can be implemented at negative costs up to 2050. In the last decade, this share is reduced to 13%.

A pathway towards net-zero GHG emissions in 2050 can be reached with a carbon price of 25, 45 and 65 USD/t CO_2eq, respectively, in each decade. AFOLU remains the key sector to this end, since it presents the largest mitigation potential with a low cost per avoided GHG emission. Energy efficiency measures in industry, and electromobility in passenger transport also provide relevant contributions. The identified portfolio of mitigation actions presents a significant decline of marginal returns after 35 USD/t CO_2eq. Therefore, a much more cost-effective trajectory of carbon prices (such as 25, 30 and 35 USD/t CO_2eq in each decade, for example) can deliver an ambitious mitigation target in 2050, not ensuring but getting close to climate neutrality, as it would provide 100%, 87% and 94% of the DDS cumulative avoided emissions in each decade. This is mainly due to the underlying assumption of counting upon available technologies only. It illustrates the huge mitigation potential ready to be tapped at low costs in Brazil even before the deployment of new disruptive technologies expected to come on stream up to 2050.

MACROECONOMIC AND SOCIAL IMPLICATIONS

DDS allows to reach carbon neutrality while keeping slightly better economic and social development results than in CPS. Throughout the period up to 2050, GDP and GDP per capita are slightly higher, unemployment rate is slightly lower and the average disposable income for the poorest household income class is slightly higher, compared to CPS. Tables 4 and 5 compare the macroeconomic and social results of the two scenarios.

The carbon pricing scheme leads to higher domestic price levels, contributing to deteriorating terms of trade and affecting trade balance results. The ratio trade balance deficit / GDP is higher in DDS than in CPS, throughout the period up to 2050, although lower than in 2020 (but higher than in 2015).

Table 3–Cumulative avoided GHG emissions (CPS-DDS) per cost range of mitigation actions, per decade

Mitigation action cost ranges (USD / t CO_2eq)	2021 – 2030		2031 – 2040		2041 - 2050	
	Mt CO_2eq	% Mt CO_2eq / period	Mt CO_2eq	% Mt CO_2eq / period	Mt CO_2eq	% Mt CO_2eq / period
up to 0	167	16%	478	18%	661	13%
up to 5	198	20%	582	22%	986	19%
up to 10	659	65%	1,613	62%	2,236	43%
up to 15	659	65%	1,613	62%	3,299	63%
up to 20	963	95%	1,619	62%	3,299	63%
up to 25	1,013	100%	1,619	62%	3,299	63%
up to 30			2,282	87%	3,308	63%
up to 35			2,309	88%	4,916	94%
up to 40			2,319	89%	4,916	94%
up to 45			2,618	100%	4,916	94%
up to 65					5,254	100%

Note: costs in present value of the first year of each decade (at 8% discount rate).

Source: the authors.

A smart recycling of carbon pricing revenues can be socially friendly. Carbon revenues are distributed back to the economy, keeping the government net lending evolution identical in DDS and CPS, under the following rules: i) part of the carbon revenues are transferred back from the government to households to neutralize the effect of the carbon price on purchasing power; ii) the rest of the carbon revenues is used to reduce labor charges. The latter decreases distortions on the economy and is key to creating additional 150 thousand jobs in DDS compared to CPS. These jobs are created mainly in the services, transport, forest, and biofuels sectors. The carbon price penalizes in a higher proportion carbon-intensive sectors, and recycling carbon revenues favors more labor-intensive sectors and poorer household classes.[1]

1 see the complementary report of Grottera et al, 2021; "Estimating net job creation in long-term decarbonization for Brazil through employment factors". Additional research work is in progress to further detailing employment generation of skilled and non-skilled manpower.

The higher employment and wage levels in DDS improve income distribution. The positive impact on households' income levels is particularly relevant in HH1 and HH_2 groups (bottom 60%), which depend more on labor income. HH1 (the 20% poorest households, most of which were under the extreme poverty line in the base year) benefit even more from the DDS scenario due to the direct transfers of collected carbon revenues from the government.

DDS allows neutralizing GHG emissions in 2050 while mitigates the adverse effects of carbon taxation on poor households. Disposable income gains in DDS are significant compared to CPS, thanks to higher activity levels, lower labor charges, and increased transfers from the government, which are reflected in more jobs and higher income. DDS is also progressive in terms of income distribution throughout the period up to 2050, as lower income household classes show higher disposable income growth than richer ones, and faster increase than in CPS.

Table 4 - Main macroeconomic results

Scenario	2015	2020	CPS (2030)	CPS (2050)	DDS (2030)	DDS (2050)
Population	203	212	225	233	225	233
GDP (Billion 2015 USD)	1,896	1,852	2,385	3,547	2,391	3,552
GDP variation in relation to CPS	-	-	-	-	0.3%	0.1%
GDP per capita (Thousand 2015 USD)	9.32	8.75	10.60	15.23	10.63	15.25
Trade Balance (% of GDP)	-0.4%	-1.0%	-0.4%	-0.2%	-0.5%	-0.9%
Unemployment rate (%)	9.5%	7.6%	6.9%	7.4%	6.8%	7.2%
Price index in relation to CPS (CPS=1)	-	-	-	-	1.01	1.04
Total net emissions (Gt CO_2eq)	1,518	1,488	1,665	1,889	1,005	17
Per capita emissions (t CO_2eq)	7.48	7.03	7.40	8.11	4.47	0.07
Carbon price (2015 USD/t CO_2eq)	-	-	-	-	25	65
Carbon pricing revenues (Billion 2015 USD)	-	-	-	-	12.9	34.6

Source: the authors.

Table 5 – Disposable income of households by scenario and per household income class, 2015-2050

Scenario	2015	2020	CPS (2030)	CPS (2050)	DDS (2030)	DDS (2050)
Disposable income_HH1 (2015=1) (poorest 20% of households)	1.00	1.05	1.44	2.40	1.45	2.45
Disposable income_HH_2 (2015=1) (40% of households)	1.00	1.04	1.37	2.15	1.38	2.17
Disposable income_HH3 (2015=1) (30% of households)	1.00	1.01	1.29	1.92	1.30	1.93
Disposable income_HH4 (2015=1) (richest 10% of households)	1.00	0.98	1.23	1.80	1.23	1.80
Disposable income_HH1 (in relation to CPS)	-	-	-	-	0.7%	1.8%
Disposable income_HH_2 (in relation to CPS)	-	-	-	-	0.4%	0.9%
Disposable income_HH3 (in relation to CPS)	-	-	-	-	0.3%	0.4%
Disposable income_HH4 (in relation to CPS)	-	-	-	-	0.1%	0.1%

Source: the authors.

SECTORAL DEEP DIVES

Agriculture, Forestry and Land Use (AFOLU)

Agriculture is an essential driver of Brazilian economic growth. Production has grown rapidly over the past decades, driven by rising global demand and technological advances. Changes in crop management practices and expansion in the harvested area have enabled Brazil to become a leading exporter of soybeans, beef, and cellulose.

Both the CPS and the DDS assume a continuation of historical trends in food preferences. Environmental concerns in developed countries lead to less consumption of animal food, giving rise to food rich in micronutrients and vitamins, such as fruits and vegetables. On the other hand, staple food (such as carbohydrates) continues to play an essential role in food preferences in low and middle-income countries. Global meat consumption per capita would increase due to a combination of income and population growth, especially in Asian and Latin American countries. Consumption levels in developed regions are already high. The demand for meat increases as it becomes more accessible in developing countries.

Agriculture, Forestry and Land Use Change (AFOLU) is the primary source of greenhouse gas (GHG) emissions. Therefore, mitigation actions in this sector are critical for Brazil to achieve climate neutrality in 2050.

In the DDS, agriculture production increases significantly, but is GHG emissions are kept in 2050 slightly (1%) under 2019 level. There is an expressive growth in crop production, while the agricultural area increases moderately due to high productivity gains. In 2019-2030, total output rises 23%, and 47% between 2030-2050. The area occupied by crops increases 8% by 2030 and 6% in 2030-2050, reaching 75 Mha in 2050. Beef production grows 75%, reaching 18.3 million CWE in 2050, with a total herd of 200 million heads. Livestock size decreases 6% over time due to productivity gains, and it is raised on 105 Mha of pasture land (a 35% reduction).

Cattle ranching intensification is the action with the most significant mitigation potential. Additional recovery of 60 Mha from degraded pastures associated with increased productivity of the cattle herd reduces emissions from enteric fermentation by 6% in 2019-2050. In this scenario, the stocking rate goes from 1.31 head of cattle/ha to 1.96 by 2050. Adopting low-carbon agriculture technologies (for example, the no-till system and biological nitrogen fixation), recommended by the Low-Carbon Agriculture Plan (ABC Plan), increases along with soybean and other crops.

The reduction of deforestation is key for Brazil to reach climate neutrality. The annual area deforested in 2019 in the Amazon biome doubled compared to 2012 and was 34% larger than in 2018 (INPE, 2020). The area deforested in the country in 2023 is projected to be 15% greater than in 2019. Efforts to curb deforestation will resume in 2023, given the possibility of change in governmental policies and increasing international pressure over agricultural chains associated with deforestation. After 2023, deforestation control policies are resumed, reaching a reduction of 10% in 2023-2025. Zero illegal deforestation in the Amazon biome will be achieved in 2050. twenty years later than the NDC target. Emissions from deforestation will amount to 71 $MtCO_2eq$ in 2050, which corresponds to a 92% reduction compared to 2019. Protected Areas (Conservation Units and Indigenous Lands) will remove 487 $MtCO_2eq$ in 2050 (24% more than in 2019), thanks to the addition of 53 Mha of public non-destinated forests, registered in the Brazilian Forest Service, to the 276 Mha protected today.

Fostering reforestation and restoration of 30 Mha with native species in public and private areas is also relevant. It removes 417 $MtCO_2eq$ by 2050 and it is a measure in line with the NDC (2015), the Bonn Challenge (Bonn Challenge, 2011), and the national Native Vegetation Recovery Plan (Planaveg, 2017). This mitigation action is challenging and goes beyond the area considered in the NDC target (12 Mha by 2030). It can be made possible with government support, international funds, payment for environmental services programs, and forest offsets allowed through the cap-and-trade system imposed on Industry.

Fast-growing planted forests (eucalyptus and pine) are critical carbon removals. They include homogeneous forests and crop-livestock-forest integration systems. The surface of planted forests will reache 13 Mha in 2030 and 19.5 Mha in 2050.

This area meets the demand from all sectors: energy (charcoal and firewood), industry (pulp and paper, sawn wood, plywood, panels, and others), and pellets production for exports.

In the DDS, net emissions of the AFOLU sector reach negative values (-439 Mt CO_2eq), allowing the country to achieve carbon neutrality in 2050.

In the CPS, agricultural production grows more than in DDS (25% in 2019-2030 and 50% between 2030 and 2050). This results from a higher demand for biofuels in CPS due to more ICE and less electric vehicles than in DDS. Crop area increases 7% by 2030 and 7% in 2030-2050, reaching 76 Mha. Beef production grows 77%, reaching 18.5 million CWE in 2050, with a 23% larger herd reaching 263 million heads, and raised on 171 Mha of pasture land (5% increase).

Pasture land recovery in CPS is half of the DDS. 30 Mha are recovered up to 2050, increasing the stocking rate to 1.54 head of cattle/ha by 2050. Emissions from enteric fermentation grow 23% between 2019 and 2050. The penetration rate of low-carbon technologies, such as the no-till system and biological nitrogen fixation, is limited to the increase of the planted soy area. Emissions from the agricultural sector increase by 23% in 2050 compared to 2019.

As in the DDS, the annual deforested area increases until 2023 and decreases by 10% between 2023-2025. However, the annual area deforested in 2025 (1.97 Mha) is maintained in 2026-2050. Deforestation of this area emits approximately 1,024 Mt CO_2eq per year. Considering the current government's lack of interest in expanding the areas of environmental protection, as well as allocating human and financial resources for their management, CPS does not foresee the creation or expansion of protected areas in 2020-2050, with the 2019 level remaining constant until 2050 (279 Mha). This area will remove 391 Mt CO_2eq in 2050.

Although more modestly than in DDS, the reforestation and restoration of 3 Mha with native species in public and private areas remove 55 Mt CO_2eq by 2050. It is equivalent to 25% of the area considered in the NDC target for 2030 (12 Mha). The area of forests planted with pine and eucalyptus species grows 53% in 2019-2050, totaling 13.5 Mha.

In the CPS, net emissions from AFOLU total 1,080 Mt CO_2eq in 2050, a 21 % increase compared to 2019. Of this total, 60% comes from agriculture and 40% from land use change and forestry.

The Brazilian agricultural sector can become even more competitive globally if it increases productivity efficiently and sustainably. International pressures on the control of farming chains associated with degradation and deforestation contribute to making DDS viable. Countries that do not commit to reducing GHG emissions and controlling deforestation will face market barriers that will hamper exports. The soybean, beef, and forestry chains are examples of this context that apply to Brazil.

International and national financing programs focusing on climate change, sustainable agriculture, and the environment would help to make the DDS pathway feasible. Among them: Green Climate Fund, Global Environment Facility (GEF), Least Developed Countries Fund (LDCF - GEF), Special Climate Change Fund (SCCF - GEF), Adaptation Fund (AF), and the Amazon Fund.

Transport

The scenarios embody different visions of the future of Brazilian passenger and freight mobility. The CPS represents the continuation of current incentives for biofuels and energy efficiency, but with no increase in ambition after 2030. The DDS expands and diversifies the biofuels market, besides requiring other measures such as accelerating the electrification of the vehicle fleet and expanding the transport infrastructure in key areas.

Globally, the DDS demands a continuous reduction in the relationship between price and energy density of batteries. Fully autonomous vehicles remain a niche market, restricted to developed economies or pilot tests in emerging countries. Hydro Vegetable Oil (HVO) becomes an important energy source in oil refineries, taking advantage of the liquid fossil fuels distribution chain. International funding programs focused on sustainable policies and infrastructure become commonplace among the main financial agents.

In both scenarios, society experiences new mobility configurations linked to population aging, teleactivities, new technologies,

and structural changes. Cities are planned to increase integration and decentralize activities to reduce commuting times and congestion. The major metropolitan areas focus on high-efficiency modes and active transport, creating pedestrian-friendly environments. Teleactivities lead to changes in the pattern of passenger and freight transport. In non-metropolitan areas, transport systems maintain the historical pattern of growth and design.

In the DDS, consumers choose more efficient and eco-friendly technologies, stimulating the penetration of electromobility and biofuels. Brazil increasingly invests in charging infrastructure and basic conditions for electric vehicles, such as standards and regulations, financing, and new business models. Unlike the CPS, new local manufacturers of electric trucks and buses, and automobile components change the industry pattern, reducing the impact of the devaluation of the local currency on imports. The electrification of the bus fleet and prioritization measures induce the population to increase public transport use, reducing the need to own a private car. Financial incentives to develop a national advanced bioenergy industry expand the offer and variety of biofuels, for example, biokerosene, bio-oil, and HVO.

No new passenger cars with internal combustion engines (ICE) will be registered from 2045. At the same time, the market penetration of electric vehicles is further accelerated compared to the CPS. In 2050, almost half of the vehicle stock is composed of hybrids (HEV), plug-in hybrids (PHEV), and fully electric vehicles (BEV). Total car stock reaches 76 million, with a much lower motorization rate than in the CPS (326 against 456 cars per 1,000 inhabitants). Private mobility (pkm/cap) accounts for a 41% share in this scenario. Electricity reaches 11% of the total energy consumed in passenger transport, while liquid biofuels account for 52%. As a result, GHG emissions fall by 52%, reaching 49 MtCO_2eq. Carbon (g CO_2/MJ) and energy (MJ/pkm) intensities fall by 41% and 54%.

Freight diesel railways are gradually modernized and electrified via contractual additives in their respective concessions. Regulatory frameworks increase productivity in rail and water transport. Sustainable logistics and certification programs increase efficiency in road transport. The redesign of transport networks focusing on high-capacity modes balances the modal split of Brazilian freight transport reasonably. In 2050, road transport accounts for 42% of the transport activity (tkm), and rail and water account for 35% and 22%.

BEV, HEV, and PHEV constitute 33% of the stock of freight vehicles, concentrated on urban transport. Despite the advances made, electricity is responsible for only 2% of the energy consumed in freight transport. In turn, biofuels account for 37%. These shares stem from the strategic prioritization of electrification of passenger transport, leaving freight transport to absorb the liquid fuel supply surplus. GHG emissions fall by 32%, reaching 62 Mt CO_2eq. Carbon (g CO_2/MJ) and energy (MJ/pkm) intensities fall by 32% and 46%.

In the CPS, the biofuels industry is restricted to biodiesel and ethanol. Electromobility incentives are limited to experiments in metropolitan areas. The end of sales of ICE cars is expected to occur only in 2050 when the total stock of cars reaches 106 million. Private mobility (pkm/cap) accounts for a 50% share, much higher than in the DDS. This participation is due to a lower proportion of public and non-motorized transport, as fewer investments are expected.

Electricity is not representative in this scenario, accounting for only 4% of the total energy consumed in passenger transport by 2050. However, biofuels account for 38% in the same year. GHG emissions from passenger transport increase by 25%, reaching 126 Mt CO_2eq. Even so, carbon (g CO_2/MJ) and energy (MJ/pkm) intensities decrease by 8% and 21%, mainly due to the increased participation of biofuels and energy efficiency programs.

Freight railways continue to have only diesel-electric locomotives. Rail and water transport activities grow at levels below their potential. In 2050, road transport accounts for 48% of the transport activity (tkm). BEV, HEV, and PHEV reach 20% of the stock of freight vehicles. Electricity is less consumed than in DDS, accounting for only 0.2% of the total energy consumed in freight transport by 2050. Liquid biofuels account for 18%. Freight transport emissions increase 18%, reaching 112 Mt CO_2eq. Carbon (g CO_2/MJ) and energy (MJ/pkm) intensities fall by 10% and 23%.

Industry

The Brazilian industry accounted for 26% of the national GDP, in 2019. This participation has decreased over the last 30 years due to successive crises. Industrial growth is assumed to restart in 2021. From 2020 until 2050, the value-added annual average growth rate of the cement, iron and steel, and chemical industries reaches 2.6%, 1.9%, and 1.7%, respectively.

The industry's sector emissions correspond to about 16% (162 Mt CO_2eq) of the country total, with half of them coming from the three above-mentioned sectors. **In CPS, assuming the same performance of current mitigation policies and measures, GHG emissions will reach 290 Mt CO_2eq in 2050**, 75% from energy consumption and 25% from IPPU.

In DDS, implementing well-known mitigation measures in the industry sector reduces 35% of its GHG emissions in 2050. No new industrial processes nor mitigation technologies are assumed. Mitigation actions include: substantial acceleration of energy efficiency improvement, allowing energy intensities to decrease from 21 to 25% in 2050, according to the industrial branch; fuel shift to renewables, including an increased use of charcoal for pig iron production and of wood and residues in cement kilns; and an increased use of ashes and slag to replace clinker in cement blending. The full replacement of HFCs by low GWP gases would be nearly completion (98% reduction of its emissions) by 2050. As a result, DDS emissions will reach 190 MtCO_2eq in 2050, 35% less than in the CPS, with energy-intensive industries accounting for 87% of these emissions.

Energy Supply

Offshore oil and gas production from the pre-salt layer increase steadily in both scenarios. After the sharp oil price reduction due to the COVID-19 crisis (from 66 USD/barrel in 2019 to 23 USD/barrel in 2020), it is assumed that oil price will grow linearly to 45 USD/barrel in 2025 and remain constant at this level until 2050. Under these assumptions, increasing shares of Brazilian oil production are directed towards exports, as production costs are kept low and remain competitive in the world market. In DDS, this share is higher as oil and gas domestic consumption are 30% lower than in CPS, which also allows to keep GHG emissions from refineries and fugitive emissions under control.

Total energy supply emissions in 2050 are 95 Mt CO_2eq in CPS and 68 Mt CO_2eq in DDS. Brazil`s energy supply-related emissions are expected to grow in the immediate future (mainly those from energy self-consumption and fugitive emissions, while emissions from power generation present little growth), peak around 2035, and then decline through 2050. Power generation expansion trend in Brazil is already based on renewable sources, and thus presents low GHG emissions than most other countries. In both scenarios, GHG emissions from power generation decrease further, from 24 Mt CO_2eq in 2019 to 16 Mt CO_2eq in CPS and only 1.7 Mt CO_2eq in DDS, in 2050.

Electricity consumption grows faster than overall energy consumption, but end-use efficiency gains allow for a lower growth in DDS. In CPS, electricity consumption grows by almost 78% from 2019 to 2050, reaching 972 TWh (terawatt-hours), but in DDS, its growth is limited to 928 TWh (70% increase), despite an increase of 25 TWh of its use in transport, thanks to a consumption reduction of 63 TWh in the industrial sector, compared to CPS.

In DDS, the Brazilian power generation reaches nearly net zero emissions by 2050. In both scenarios, hydro, wind energy and photovoltaics are the main sources to expand their power generation. After 2040 when the Brazilian hydropower potential will be almost fully explored, biomass will replace its role and complement wind and solar contributions. In 2050, the required installed capacity of hydropower is 146 GW on both scenarios. Onshore wind capacity reaches 50 GW in CPS and 46 GW in DDS, while photovoltaic systems account for 51 GW in CPS and 53 GW in DDS. Biomass reaches 31 GW in CPS and 28 GW in DDS. Natural gas is restricted to CPS with 11 GW and offshore wind to the DDS with 3 GW. Moreover, old thermopower plants are decommissioned and replaced by renewable power plants (wind, solar photovoltaic, and biomass) due to their lower costs in both scenarios. However, in CPS, natural gas still plays an important role in dispatchable power generation. On the other hand, in DDS, the development of large intermittent renewable capacities is made possible by increasingly using hydropower generation and batteries to ensure grid operation flexibility.

Global carbon pricing and fast technological development in renewable energy technologies (mainly batteries, solar and wind), are the key international enablers of DDS. A domestic carbon tax can reduce the competitiveness of power generation from natural gas, while technology improvements and growing international experience of developers can enable the competitiveness of renewables.

Waste

Both scenarios consider that national solid waste policy (PNRS) and national sanitation plan (PNSB) goals are met regarding the extension of service coverage.

Regarding solid waste, the percentage of collected waste increases from 90% today to 100% in 2030. Adequate final disposal goes from 40% to 95% in 2050. In DDS, landfilling is limited to around 70%, with biogas capture and methane destruction rate reaching 65%. As in developed countries, thermal and biological plants would be introduced, reaching 8% and 10% of total waste disposal, respectively. Recycling rate goes up to 10%. In CPS, only landfilling is the technical option considered, with biogas capture and methane destruction remaining at a constant rate of 15% throughout the period. The recycling rate remains at 3%.

Sewage collection rates go from 53% today to 84% in 2050, with anaerobic treatment plants treating 21% of the collected volume. Of the methane generated in these plants, in DDS the destruction rate goes from 40% to 80% in 2050, while in CPS it reaches only 55%.

GHG emissions in DDS are cut by 36% in 2050, while in CPS they grow by 82%. The substantial extension of sanitation services to bridge the current infrastructure deficit can lead to a huge increase of emissions unless biogas capture and burning technologies are massively introduced. The amount of cumulative avoided GHG emissions in this sector is high. These technologies will be cost-effective thanks to global pricing schemes leading to international trade of mitigation outcomes and the financial flows required to meet the funding requirements of these investments.

PART 2: KEY POLICY LESSONS

SYNERGIES AND TRADE-OFFS WITH COUNTRY NON-CLIMATE OBJECTIVES

Living standards in Brazil will improve slowly, and the distance to developed countries will be reduced by 2050, following the global trend. Under DDS, a **smart recycling of carbon pricing revenues delivers reductions of both GHG emissions and social inequalities.** Compensating poor households for increased price levels through green checks and fostering employment through reduction of labor taxes are the key enablers to maximize the synergy between climate and fiscal policies. Several complex iterations exist with SDGs, but overall synergies with DDS are summarized in **Table 6**.

Next synergies and trade-offs with non-climate objectives are discussed in detail at sector-level.

Table 6. Synergies with SDGs

Very high synergy with SDGs	
#13	Climate action (radical mitigation),
#7	Affordable and clean energy (power generation reaches nearly net zero emissions),
#11	Sustainable cities (cleaner cities due to higher use of biofuels, electric vehicles, and increased use of mass public transport systems),
#15	Life on land (radical reduction of deforestation and increase of protected forests).
High synergy with SDGs	
#9	Industry, innovation and infrastructure (more innovation and competitiveness in industry and higher investment in low-carbon infrastructure),
#17	Partnerships for the goals (higher levels of international cooperation),
#6	Clean water and sanitation (faster growth of public sanitation infrastructure thanks to higher investment targeted at GHG emissions reduction).
Moderate synergy with SDGs	
#1	No poverty,
#2	No hunger,
#3	Good health,
#4	Quality education,
#8	Decent work and economic growth,
#10	Reduced inequalities,
#12	Responsible consumption and production (slightly higher GDP/capita and disposable income to poorer households; lower unemployment rate and new jobs in the services, transport, forest, and biofuels sectors).
Neutral for SDGs	
#5	Gender equality,
#14	Life below water,
#16	Peace, justice and strong institutions.

AFOLU

Global food security and maintenance of high biodiversity can be complementary and synergistic goals by using sustainable agricultural practices that protect, restore, and promote rational use of ecosystems and at the same time reduce GHG emissions.

Increased use of sustainable agricultural practices such as mixed, rotational, and succession crops, with zero tillage and crop-livestock-forestry integration, deliver co-benefits such as optimization and intensification of soil nutrient cycling, greater soil water retention, conservation of biodiversity, and increased agricultural productivity.

Protecting, restoring, and promoting the sustainable use of forests, including forest diversification and management, prevents desertification, halts / reverses land degradation, and reduces biodiversity losses. In addition, the forest carbon stock also contributes to reducing emissions through the use of forest-based products to replace non-renewable resources.

Transport

Electric mobility provides considerable co-benefits for the urban population's health, energy security, and social security spending, besides reducing GHG emissions. There is a direct relationship between the health budget and air pollution in cities, mainly caused by vehicles equipped with internal combustion engines. The more urban planners perceive a reduction in hospital admissions for respiratory problems, the more they encourage the use of electric vehicles in metropolitan areas, especially buses and light trucks. The dissemination of electric mobility goes together with expanding the supply of electricity and telecommunications to remote areas. It allows the installation of larger commercial and industrial buildings such as hospitals and schools, which demand higher voltages. Finally, electric mobility in road and rail transport reduces dependence on diesel oil, which is currently a major problem in Brazil, especially in freight transport. In addition to being a more expensive and polluting source of energy, the high volatility of crude oil and diesel prices has caused social instability, including strikes and protests, as well as inflation.

Industry

Decarbonization through higher energy efficiency fosters industrial productivity and employment generation for skilled human resources in the industry and across its entire supply chain. The adoption of low-carbon industrial processes and other innovations increases competitiveness and resilience. Additionally, since these measures require investments in retrofit or construction of new facilities, they create direct and indirect jobs in the supply chain and induce new jobs due to workers' spending on goods and services. Furthermore, improving energy efficiency and increasing alternative fuels reduce external dependence and the risks associated with fluctuations in currency and energy commodity prices, as the steel and cement industries import a significant share of their fuels.

Energy Supply

Expanding affordable and renewable energy production (with power generation reaching nearly net zero emissions by 2050) fosters employment generation, reduces air and water pollution, and improves overall societal well-being and resilience. Decentralized wind and solar energy deployment allows for regional development, and it is an excellent opportunity for stimulating economic growth in distant communities. Bioenergy deployment in various forms, and for different purposes, has many synergies with industrial development and environmental protection in rural areas.

Waste

Cheap GHG emissions reduction available through capture and flaring of biogas encourage investment in sanitation and help to accelerate the building up of the infrastructure required to bridge the historical gap in the level of service coverage. Low-income households are the main beneficiaries of this service expansion that brings considerable social benefits. Power generation through controlled incineration of waste in big cities, the use of refuse-derived fuel (RDF), and biogas as a fuel in the industry increase energy supply.

PRIORITY SHORT-TERM POLICIES AND ACTIONS

The main priorities for the short-term derived from the scenario analysis are:

- Resuming policies successfully adopted in the recent past (2004-2012) to sharply reduce annual deforestation rates: both command-and-control and economic instruments.
- Developing smart financial mechanisms to foster the funding of investments in mitigation actions, and mainly in forest cover restoration and low-carbon infrastructure.
- Carbon Pricing: provide a long-term, stable signal to induce economic agents to choose low-carbon technologies through a well-structured cap-and-trade scheme for industry and a carbon tax on other sectors.
- Relying on the AFOLU sector to reduce and capture the largest share of emissions in the first half of the century to get close to the net-zero target by 2050 helps to reduce overall costs for Brazil and provides sufficient time for disruptive technologies to be economically viable.

For AFOLU, policies and actions focused on reducing deforestation and increasing carbon sinks are key in Brazil. The current government has discontinued several successful environmental policies, and therefore annual deforestation rates have increased in recent years. The resumption of command and control strategies - monitoring, inspection, collection of fines, and application of embargoes - that are already known and effective in reducing deforestation is considered a short-term priority. Other effective policies and actions are: promoting articulation and integration between the various government agencies; environmental and land tenure regularization; forest concession on public lands not assigned for any specific use; expansion of areas conservation units category, and demarcation of indigenous lands.

In the agricultural sector, effective policies and actions are associated with the conditioning of

soft public loans to farmers and ranchers upon compliance with the forest code and environmental regulations (Environmental Rural Registry - CAR); monitoring the origin of agricultural products (traceability) and restriction of the market for products associated with deforestation; and enabling financial mechanisms to foster low-carbon agriculture practices, including technical assistance and rural extension.

In transport, the fastest GHG emission reductions in the short-term can be achieved by an acceleration of the RenovaBio program with higher targets for biofuel sales and regularly updating energy efficiency targets for internal combustion engines. This includes greater public encouragement of second-generation biofuels, particularly HVO, increasingly added to biodiesel-diesel blends. The introduction of carbon taxes on gasoline and diesel oil is also necessary. Furthermore, a complementary set of policy instruments regarding the prioritization of public transport needs to be deployed. This means increasing subsidies and tax exemptions to mass public transport systems to improve the sector's capacity to deal with post-pandemic economic uncertainty and instability. The design and implementation of new business models associated with the penetration of electric buses can help the recovery and improvement of the urban buses transport service (highly damaged by the pandemics). Besides, the development and approval of missing standards and regulations, combined with education and awareness campaigns, are required to allow for the growth of the electric vehicle market (mainly in metropolitan areas).

Financial support for investment in low-carbon technologies through credit mechanisms and fiscal exemptions are short-term priorities for industry. The transition to a less carbon intensive industry is to be supported by significant investments and a change in the current financial structure that does not favour low-carbon technologies. Providing access to financial products and fiscal exemptions for those types of investment are required to make them more profitable. **In addition, a cap-and-trade system for GHG emissions reduction in industry, allowing for offsets from AFOLU up to a limit, is key to help decarbonize the sector.** Carbon pricing improves the competitiveness and benefits of those companies that take the lead.

Regarding the energy supply, is pivotal to keep the national energy policy oriented to tapping the potential for renewable energy deployment. A carbon pricing scheme will encourage biofuels use and production and avoid additional fossil fuel-fired thermopower generation capacity. Natural gas is a transitional fuel for a sustainable energy system transformation, while incentives are to be applied to accelerate the decommissioning of coal-fired power generation. The gradual elimination of fossil fuel subsidies, which do not help the poor and hamper renewable energy and energy efficiency efforts, is also a key measure. Reform of fossil fuel subsidies should be accompanied by targeted and time-limited transitional support for vulnerable industries, communities, regions, and consumers. Incentives for distributed solar PV generation have to be kept for a while (subsidies and tax exemptions to be fully withdrawn only in 2045).

In the waste sector, is key to design and implement incentives and adequate regulations to promote the capture and flaring of biogas and its use as a fuel. It is also fundamental to promote municipalities' capacity building and encourage partnerships to develop a portfolio of investment opportunities. Increased recycling rates can be achieved through stricter regulation and correct market signals to encourage the reinsertion of scrap materials and post-consumer wastes into the economic cycle.

INVESTMENTS PATTERNS

The highlights of the study with regards to investment can be summarized as follows:

- A significant share of avoided emissions can be obtained at negative or very low costs. Costs for a given mitigation option may vary throughout the three decades due to increasing economies of scale and variations in cost assumptions (e.g., decreasing costs for electric vehicles and renewable electricity).
- Additional investment in mitigation would sum about USD 83 billion in a pathway leading to net-zero GHG emissions in 2050.
- This would represent a 0.5% increase in the investment rate (Total Investments/GDP) in DDS over CPS.
- Most of the investments would be needed in industry, agriculture and forestry, and transportation sectors.

For AFOLU: Adequate investment patterns can be made possible by sales of forest offsets through a cap-and-trade system applied to industry, and by expanding credit for a number of sustainable forest uses and agriculture practices.

Mechanisms introducing payments for environmental services can attract private investments to restore native forests and compensate forest producers for maintaining forest stocks. Law 14,119/2021 makes provision for these payments and considers modalities such as compensation for reduced emissions from deforestation and degradation (REED +), green bonds, and Quotas for Environmental Reserve (CRA). In addition, changes proposed in the Forest Concessions Law (Law 11,284 / 2006) can streamline contracts and make the concession process viable.

In the agricultural sector, the leading financial players are banks, cooperatives, capital equity, industry, suppliers, traders, and distributors. Green bonds have the potential to support agriculture towards sustainable production. Law 13,986 / 2020 that creates a solidarity guarantee fund helps the country's agricultural sector to access international markets. One of the significant innovations facilitating access to capital markets is the possibility of directly issuing Agribusiness Credit Receivables Certificates (CRAs) in the offshore market.

For Transport: Strengthened national industry to support electric mobility and smart grids, reducing the negative effects of exchange rate volatility and inflation. Government can provide financial incentives and basic infrastructure to attract electric vehicle industries and suppliers. Also, credit lines can be supplied to finance intensively used electric vehicles (mainly buses and light trucks) at lower rates compared to conventional internal combustion vehicles. Access to financial instruments for green investments such as green bonds and structured green funds can also be increased. Modern standards and regulations can enhance legal security and guarantees for public/private partnerships to invest in railways and waterways. Also related to these transport modes, public and private partnerships can be fostered to improve intermodality, increasing the number of terminals, expanding road access to ports, and interconnecting regional railways and waterways.

For Industry: Specific credit lines for decarbonization - energy efficiency, fuel shifts, and new processes - of heavy industry (mainly cement and steel) are to be supplied. Creating specific and diversified credit lines through federal bank regulation is vital to promote massive investment in less carbon-intensive technologies and processes. Uniform guidelines for credit analysis and appropriate rates for the specificities of the industrial sector can be highlighted as important features for new credit lines. Access to green bonds can also help spur investments in low-carbon technologies.

Energy Supply: Higher investments required in hydro, wind, and solar power, as well as in bioenergy, benefit from smart financial mechanisms allowing to de-risk low-carbon projects and to attract larger financial flows at lower capital costs. Expanding or reinforcing the transmission system (national grid) is a pre-requisite to accommodate a considerable growth of renewable power generation, mostly located in remote sites. Similarly, it is necessary to expand the Brazilian gas pipeline network, which might be used in the long run for the transport of "green hydrogen". In addition, financial support is needed in the form of grants, loans, and tax cuts aimed at green transport, circular economy, energy efficiency improvements, and clean energy research, development, and deployment.

For Waste: An appropriate regulatory framework is required to enable funding mechanisms of investments for biogas capture and flaring in new and existing landfills and sewage treatment plants. This would also simultaneously foster waste recycling and re-use.

At economy-wide level, additional mitigation investments in DDS (compared with CPS) amount to USD 24.12 billion in 2021-2030, USD 90.62 billion in 2031-2040, and USD 148.75 billion in 2041-2050, in Transport (41.7%), Waste (25.7%), AFOLU (21.0%), Industry (9.4%) and Energy Supply (2.2%) sectors (considering the whole 2021-2050 period). **Table 7**–Additional mitigation investment in DDS compared to CPS, per economic sector, per decade details the additional investment (CAPEX) in DDS compared to CPS.

Figure 1 presents the marginal abatement cost curve (MACC) for the first period (2021-2030). **Figure 2** and **Figure 3** present the MACC for the following decades (2031-2040 and 2041-2050, respectively). Over the whole period, DDS includes the adoption of 32 mitigation actions. However, to better illustrate the relationship between mitigation costs and abatement potential, we highlighted separately in the three figures below the main mitigation actions (including only those avoiding at least 5 $MtCO_2eq$) contributing to the total abatement in each decade.

KEY INTERNATIONAL ENABLERS AND ACCELERATORS OF DOMESTIC TRANSITIONS

The key international conditions that make DDS plausible in Brazil are:

- Strong international effort to meet the Paris Agreement, with most countries adopting carbon pricing.
- Substantial support of Annex I countries to foster financial flows targeted at mitigation actions in non-Annex I countries, including both the climate finance tools within UNFCCC (GCF, SDM) and international financial initiatives to channel private capital to low-carbon investments.
- International oil price allowing the domestic offshore pre-salt oil production to be competitive
- Preferential commercial mechanisms to require traceability and proof of origin of agricultural and forestry product exports can contribute to the control of deforestation in Brazil.

AFOLU: Border taxes adjustments according to carbon footprints and market incentives for agricultural and forestry products with traceability and proof of origin can help control deforestation in Brazil. A growing international demand for wood pellets can help Brazil to massively plant forests for export. Global per capita meat consumption will increase, and Brazil will continue to be a major global player in beef supply. Demand will keep increasing as meat becomes more affordable in developing and least developed countries. Global economic growth, especially in Asian and Latin American countries with large middle classes, will support the growth in demand for meat, even with a decline in demand from developed countries.

Transport: Global awareness and local interests (policymakers and potential investors) will converge, making electric mobility the main technological change in the transport sector (to the detriment, for example, of hydrogen fuel cell vehicles, non-plugin hybrid vehicles, and internal combustion engine vehicles). The end of large-scale production of internal combustion engine passenger vehicles will take place first in the main manufacturing countries. At the same time, the relationship between price and energy density of batteries will continue to decline, reaching purchase price parity in Brazil between 2035 and 2040. The slow pace compared to major global players is due to the absence of local electric vehicle manufacturers and suppliers and an unstable local currency. The main routes connecting regional and national metropolitan areas between countries will provide charging stations for trucks, buses, and cars. Problems related to interoperability between stations managed by different operators, as well as the second life of electric vehicle batteries, will not be representative. Drop-in biofuels will be a key element when considering non-electric solutions across countries, mainly applied to long-distance freight transport.

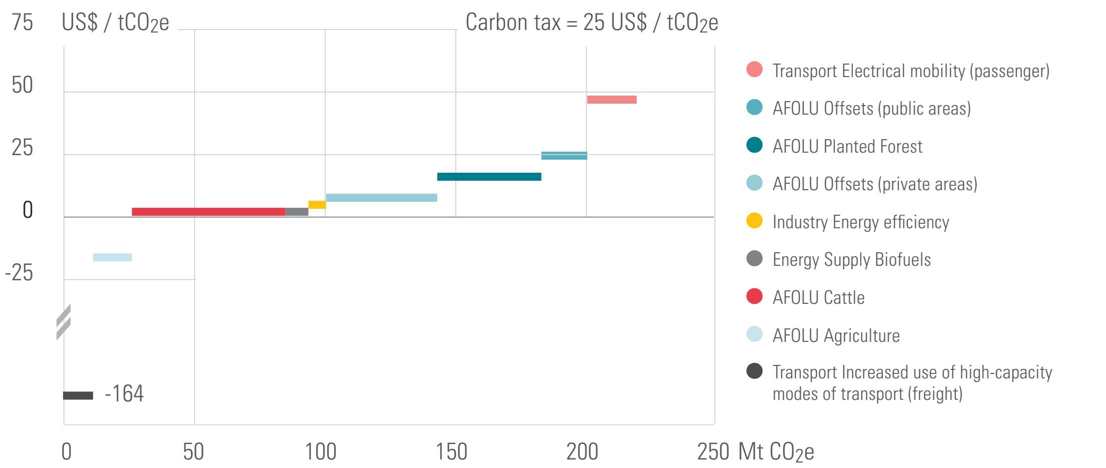
Industry: Global carbon pricing and deployment of low-carbon technologies help the national indus-

Table 7–Additional mitigation investment in DDS compared to CPS, per economic sector, per decade

Sectoral investment (USD billion)	2021-2030	2031-2040	2041-2050
AFOLU	4.26	14.59	36.38
Transport	17.02	38.32	54.55
Industry	2.39	7.88	14.63
Energy Supply	0.45	1.74	3.49
Waste	-	28.09	39.70
TOTAL	24.12	90.62	148.75

Notes: 1. Additional investment in energy supply considers power and biofuels. 2. Exchange rate 3.15 R$/USD (values of 2015). 3. Values not discounted.

Figure 1. Marginal Abatement Cost Curve 2021-2030 (mitigation actions avoiding at least 5 $MtCO_2eq$)



** Increased use of high-capacity modes of transport - in this measure, the following actions are taken: (i) expansion of the railway network, restricted to projects under implementation; (ii) investments in waterway and land access, such as port areas, as well as expansion of port capacity; (iii) increasing energy efficiency and expanding the capacity of profitable railroads; (iv) recovery of underused railways in strategic locations; (v) logistical optimization; and (vi) increased activity by reducing bureaucracy in cabotage and rail transport.*

Figure 2. Marginal Abatement Cost Curve 2031-2040 (mitigation actions avoiding at least 5 $MtCO_2eq$)

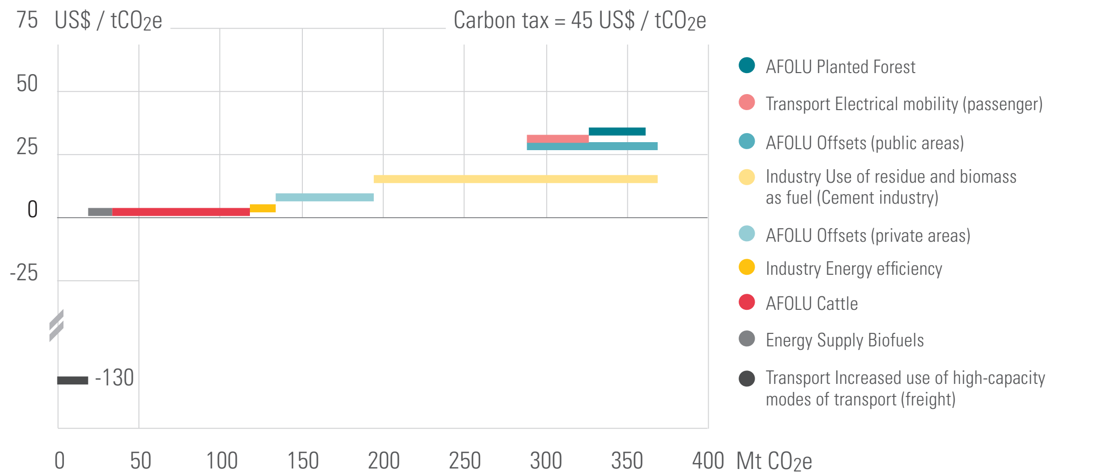
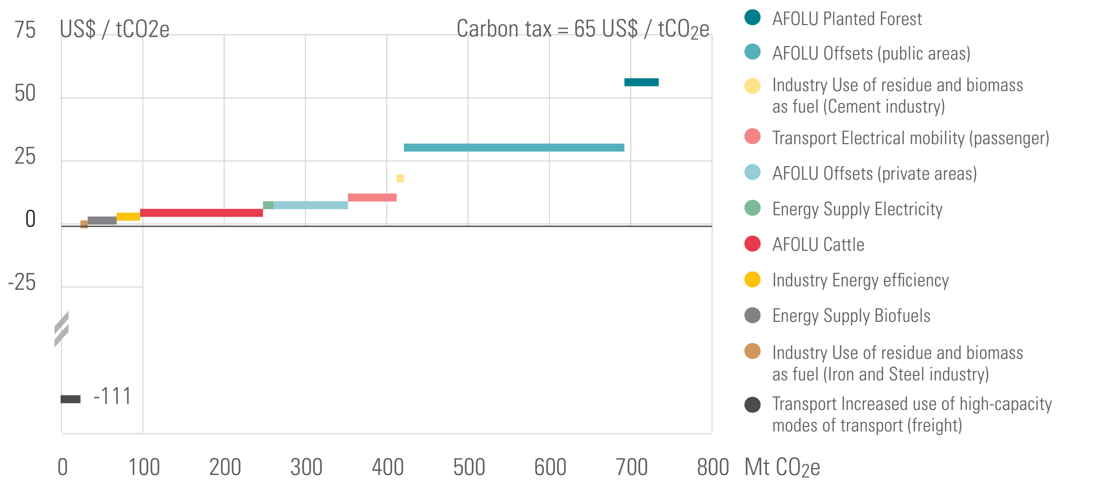


Figure 3. Marginal Abatement Cost Curve 2041-2050 (mitigation actions avoiding at least 5 $MtCO_2eq$)



try embark on a decarbonization pathway. Global carbon prices will make less carbon-intensive products more competitive, rewarding early runners investing in low-carbon technologies. New cost-effective industrial processes will reduce the carbon footprint of cement and steel. Investment costs are one of the major obstacles for the sector. Technologies like Direct Reduction Iron using hydrogen are expensive for the Brazilian industry. The consolidation of new technologies and decreasing its costs will be fundamental to help the decarbonization of the industry sector.

Energy Supply: More effective technology research, development and transfer, and international long-term investment funding are key enablers for decarbonization in the sector. Availability of natural gas cost-effective technologies to replace coal and oil products in the industry (e.g., direct reduction of iron ore for steel manufacturing), as well as for power generation at low load factor (for complementing intermittent power sources, like wind and solar generation) will help avoiding carbon lock-in (if natural gas was chanelled to baseload power generation). International oil prices will allow domestic offshore pre-salt oil production to be competitive. This will supply the opportunity of scaling up the use of oil rent for the improvement of education and health in the country. Recycling carbon pricing revenues to lower taxes on labor and reduce capital costs will encourage job creation and investment in low-carbon infrastructure, improving overall economic productivity.

Waste: International financial flows, both through Article 6 of the Paris agreement and voluntary carbon markets, can significantly increase investments in biogas capture and flaring. Promoting the use of biogas as an energy source, (e.g. as biomethane) and technology transfer of other environmentally friendly solutions can help mitigation in this sector.

SUMMARY OF KEY FINDINGS

- DDS is just one among many pathways for Brazil to reach climate neutrality by 2050.
- Underlying assumption: use of available technologies only; huge mitigation potential at low costs in Brazil even before the deployment of technological “breakthroughs”.
- Sharp reduction of annual deforestation rate and native vegetation restoration in public and private areas have a significant abatement potential and lower costs than mitigation actions in other sectors.
- A pathway towards net-zero GHG emissions in 2050 can be reached with a carbon price of 25, 45 and 65 USD/t CO_2eq, respectively, in each decade.
- DDS allows to reach carbon neutrality while keeping slightly better economic and social development results than in CPS (smart recycling of carbon pricing revenues).

ANNEX

Visualization of country results

Figure 4. GHG Emissions under Current Policies & Deep Decarbonization Scenarios (Mt CO_2eq)

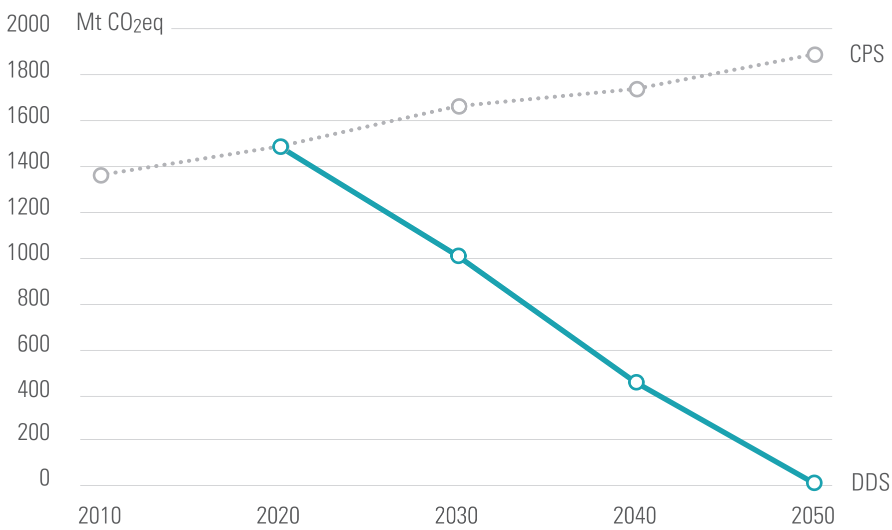


Figure 5. GHG Emissions, CO_2 and non-CO2 (Mt CO_2eq)

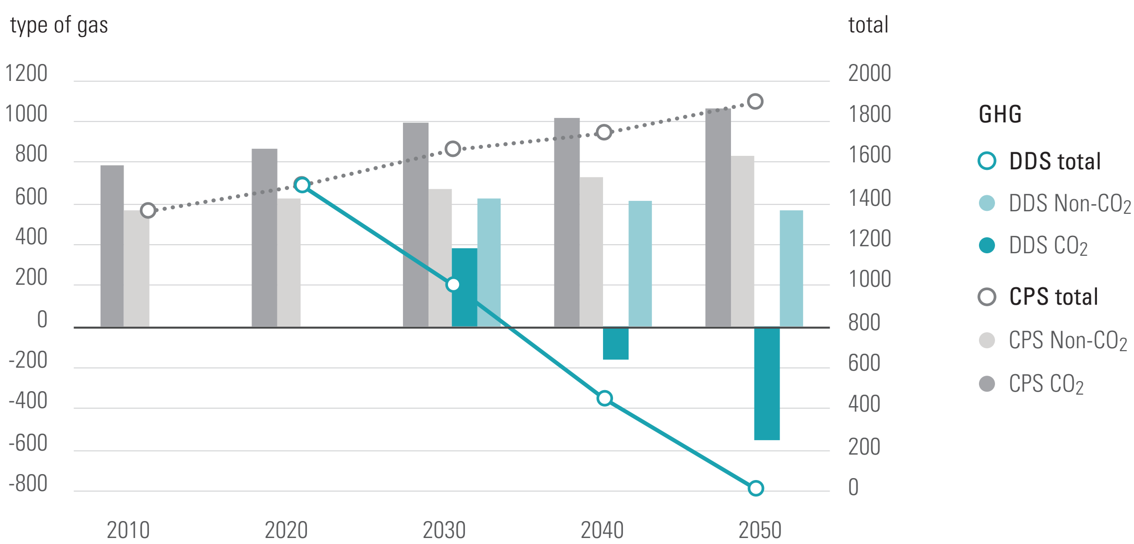


Figure 6. GHG Emissions x Population x GDP (2010 =1)

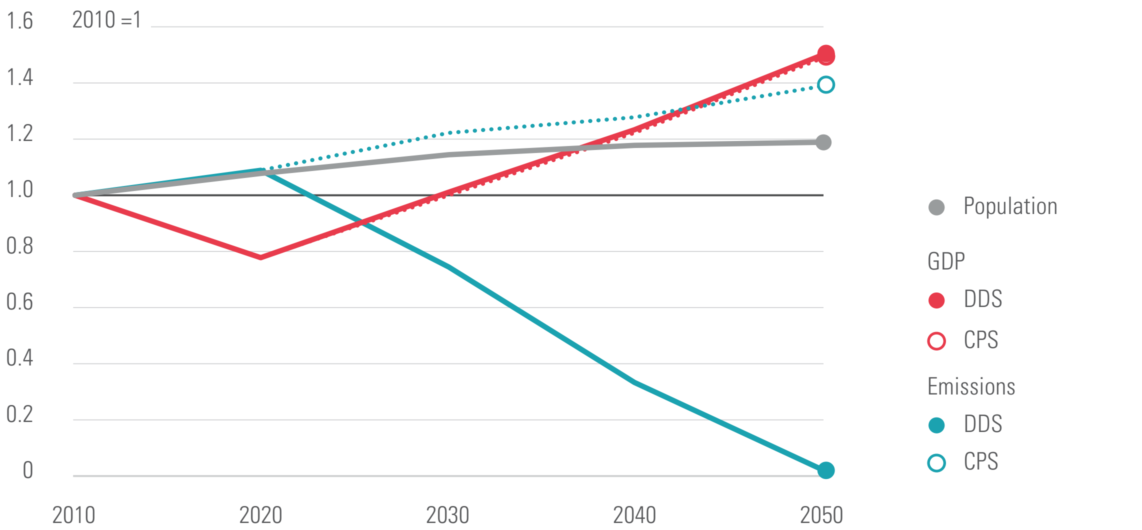
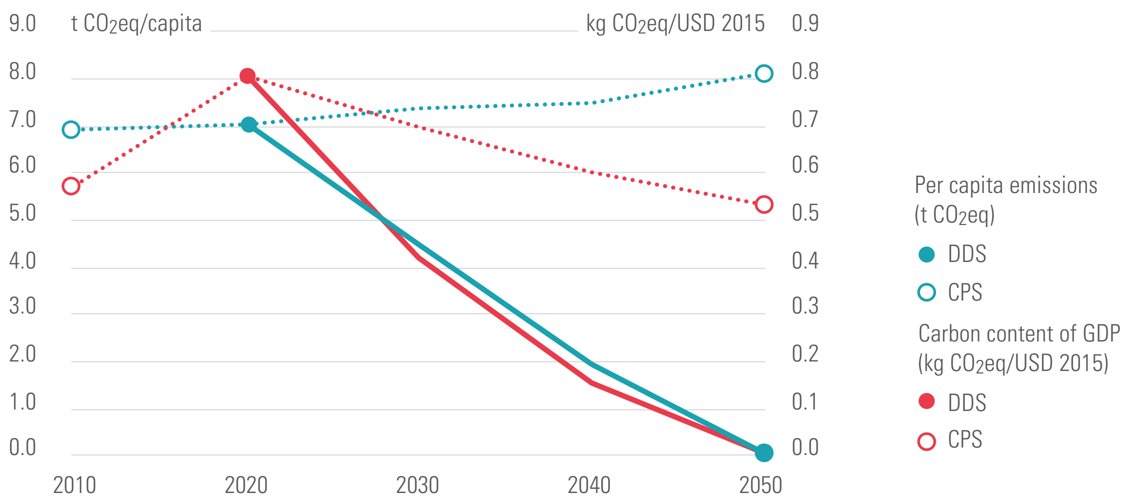


Figure 7. Emissions Intensity per capita and per GDP



The DDP is an initiative of the Institute for Sustainable Development and International Relations (IDDRI). It aims to demonstrate how countries can transform their economies by 2050 to achieve global net zero emissions and national development priorities, consistently with the Paris Agreement.. The DDP initiative is a collaboration of leading research teams currently covering 36 countries. It originated as the Deep Decarbonization Pathways Project (DDPP), which analysed the deep decarbonization of energy systems in 16 countries prior to COP21 (deepdecarbonization.org). Analyses are carried out at the national scale, by national research teams. These analyses adopt a long-term time horizon to 2050 to reveal the necessary short-term conditions and actions to reach carbon neutrality in national contexts. They help governments and non-state actors make choices and contribute to in-country expertise and international scientific knowledge. The aim is to help governments and non-state actors make choices that put economies and societies on track to reach a carbon neutral world by the second half of the century. Finally, national research teams openly share their methods, modelling tools, data and the results of their analyses to share knowledge between partners in a very collaborative manner and to facilitate engagement with sectoral experts and decision-makers.
www.ddpinitiative.org

Instituto Alberto Luiz Coimbra de Pós-Graduação e Pesquisa de Engenharia

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