

IDENTIFYING PATHWAYS TO ACCOMPLISH BRAZIL'S NDC THROUGH AN INTEGRATED ASSESSMENT MODELING APPROACH

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ABSTRACT

Background: The increasing awareness about climate change and the adverse effects of global mean temperature increasing beyond +1.5°C above pre-industrial levels resulted in a historic international climate agreement in December 2015 in Paris. Countries around the globe published their intended Nationally Determined Contributions (hereafter iNDCs)—converted into Nationally Determined Contributions (NDC), committing to take actions post-2020 to tackle global warming, mainly to mitigate greenhouse gases (GHG) emissions. The Brazilian NDC established absolute emissions targets of 1.3 GtCO₂e by 2025 and of 1.2 GtCO₂e by 2030 (GWP-100, AR5), corresponding to reductions of 37% and 43%, respectively, compared to 2005. In this work, we studied the role that each economic sector can play to meet the Brazilian NDC through an integrated assessment modeling (IAM) approach.

Results: The analysis showed that the AFOLU (Agriculture, Forestry and Land-Use) sector would contribute with mitigation amounts of 25.5 MtCO₂e in 2025 and 145.8 MtCO₂e in 2030, considering implementation of no-regret abatement measures (LC0) and LC10 scenario, which implies an economic effort to internalize a carbon price of US\$ 10/tCO₂e in the economy, respectively. Potential emissions reductions in the energy system would contribute to the mitigation of 60.4 MtCO₂e in 2025 and 211.1 MtCO₂e in 2030. Additionally, we identified critical measures with higher mitigation potential, for instance, commercially planted forests, integrated crop-livestock-forestry systems, no-tillage systems, biological nitrogen fixation application, intensification of livestock

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production through cattle confinement, deforestation reduction, expansion of native vegetation, and degraded pastures recovery in the AFOLU sector. Regarding the energy system, the integrated modeling demonstrated high mitigation potential in measures related to energy efficiency in the industry, waste management, and transport sectors; as well as a modal shift from individual to collective passenger transport and highways to railways and waterways to load transportation, and energy utilization of urban solid waste and effluent of treatment plants for the production of biomethane and electricity.

Conclusions: Projected emissions for 2025 demonstrate that the NDC target for this year could be achieved with the LC0 scenario (carbon value equal to zero) implementation, while the NDC target for 2030 could be achieved by implementing the LC10 scenario in 2030.

KEYWORDS: Brazil; Nationally Determined Contribution; integrated assessment modeling; low-carbon scenarios.

BACKGROUND

Climate change is one of the biggest global challenges, as it involves many dimensions, such as science, politics, economics, and the environment. The primary links established for this situation are that the concentration of greenhouse gases (GHG) in the Earth's atmosphere has a direct impact on the global temperature. Since the Industrial Revolution, the GHG levels have steadily increased – a higher concentration of carbon dioxide (CO₂) in the atmosphere - mainly due to the burning of fossil fuels, rising average global temperatures. In recent years, studies have gathered an overwhelming amount of evidence that has shown the effects of climate change, most comprehensively in natural systems, and the human influence on the climate system (IPCC, 2014). At the same time, the world seems to be struggling in moderate and fragmented climate action due to institutional, political, and ethical challenges stemming from the need for international coordination, transfers, and incentives.

A significant milestone in international climate policy was the COP21 in Paris in 2015 (UNFCCC, 2015). The Paris Agreement was signed under the United Nations Framework Convention on Climate Change (UNFCCC) by 195 countries, that account for about 90-

95% of global GHG emissions. These countries are committed to limit the global average temperature increase to below 2°C from pre-industrial levels, through the analysis of action plans called Intended Nationally Determined Contributions (iNDC). These INDCs were altered to Nationally Determined Contributions (NDC) after being ratified by each country. In addition, the Paris Agreement also established that the parties should indicate more ambitious long-term contributions, encouraging efforts to limit the temperature increase by up to 1.5°C (UNFCCC, 2016).

Brazil had an important role in this agreement by proposing a contribution that addresses both relative and absolute targets. Indeed, the Brazilian NDC established absolute emissions targets of 1.3 GtCO₂e by 2025 and of 1.2 GtCO₂e by 2030 (GWP-100, AR5), corresponding to reductions of 37% and 43%, respectively, compared to 2005, leading to *per capita* emissions of 6.2 GtCO₂ in 2025 and 5.4 GtCO₂e in 2030. These percentage reductions are relative to reported emissions of 2.1 GtCO₂e (GWP-100, AR5) in 2005, according to the Brazilian NDC (UNFCCC, 2015).

However, studies indicate that, in the absence of mitigation efforts, the current Brazilian energy mix will continue on a trend of increasing carbon intensity, with natural gas and coal gaining importance in the power sector, and the sugar-alcohol sector undergoing a severe crisis that has caused the closure of several ethanol distilleries. For instance, the depletion of the hydropower potential outside the Amazon region, and the vulnerability of existing hydro capacity to climate change (LUCENA et al., 2010; LUCENA et al., 2009), it means that other sources would take on increasing roles in meeting baseload demand, with results showing coal to be the least cost solution (NOGUEIRA et al., 2014; LIMA et al., 2015; HERRERAS MARTINEZ et al., 2015; PORTUGAL-PEREIRA et al., 2016).

In the case of agriculture, forestry and other land use (AFOLU) sector, a long stream of studies has affirmed that reducing emissions from deforestation is a cost-effective way to mitigate climate change in Brazil (NEPSTAD, et al, 2009; KINDERMANN, et al, 2008; FEARNSIDE, 2005; KRUG, 2018). Indeed, since 2005 the emissions from deforestation have reduced substantially due to the scaling up of law enforcement, the development of new monitoring systems (RAJÃO; GEORGIADOU, 2014; RAJÃO; VURDUBAKIS, 2013), the expansion of protected areas (SOARES-FILHO et al., 2010) and the creation of deforestation-free supply chains schemes for soy and beef (GIBBS et al, 2015). At the

same time, it has become increasingly clear the importance of intensifying cattle ranching and promoting low carbon agricultural techniques in order to keep emissions from growing a scenario of intense expansion of the sector (STRASSBURG et al., 2014).

Integrated assessment models (IAMs) map the interactions between socio-economic systems and energy and environmental processes and are used to develop emission scenarios, estimating the costs and benefits of mitigation policies and the economic impacts of climate change. IAMs experiences combine models from different areas of knowledge (CLARKE et al., 2016; PRADHAN et al., 2019). A detailed representation of the energy system is necessary – considering conventional and alternative energy uses. The same applies to land use – considering agriculture, livestock, and forests - and the economic system, considering sectoral elasticities and productivities, as well as for ecosystems, even if in a simplified approach.

In this context, this study aimed at highlighting the role that each economic sector can play to meet the Brazilian NDC targets for 2025 and 2030, using the IAM approach to identify the most cost-effective mitigation options that should be given priority in order to fulfill Brazil's NDC commitment.

RESULTS

As detailed in the methods section, the three modeling tools were integrated to ensure that the energy system results were consistent with the macroeconomic outputs while also agrees with land-use evolution in Brazil (cost and productivity, and final energy demand from the agricultural sector). In other words, an iterative procedure was performed integrating the analysis until the technical coefficient of the Computable General Equilibrium (CGE) model agreed with the MESSAGE, while the output in terms of bioenergy agreed with the OTIMIZAGRO model. For this reason, our findings are entirely consistent and very detailed, allowing us to indicate where different mitigation options could be implemented to help comply with Brazil's NDC.

The integrated modeling of GHG emission scenarios was performed until 2050 (Figure 1). However, the results related to the accomplishment of Brazilian NDC emission targets (2025 – 2030 period) are emphasized (Figure 1A).

Figure 1 demonstrates GHG scenarios considering the AFOLU and energy system emissions; the reference (REF) scenario shows an emission increase of approximately 45% in 2020-2050 and 16% in 2020-2030 (Figure 1A). Projected emissions for 2025 demonstrate that the NDC target for this year (1,300 MtCO₂e) involves a 4% emission reduction effort regarding the REF scenario; thus, the commitment could be achieved with the LC0 scenario (carbon value equal to zero) implementation (Figure 2B). It is worth noting that although technically and economically feasible, the LC0 scenario is not cost-free and comprises non-economic barriers to its implementation.

The NDC target for 2030 (1,200 MtCO₂e) requires a reduction effort of approximately 16%, compared to the REF scenario. This emission reduction could be achieved by implementing the LC10 scenario (carbon value equal to 10 USD/tCO₂) in 2030 (1,079 MtCO₂e), representing a reduction of 25% compared to the REF scenario (Figure 1B).

Figure 1: Total emission scenarios for AFOLU and energy sectors

(A) Emission scenarios from 2020 to 2050, reference (REF), and low-carbon (LC) scenarios with carbon values ranging from USD 0 to USD 100/tCO₂e.

(B) Emission scenarios for 2025 and 2030, reference (REF) and low-carbon (LC) scenarios with carbon values ranging from USD 0 to USD 10/tCO₂e

When analyzing the AFOLU sector, it is possible to see that it contributes with mitigation amounts of 25.5 MtCO₂e in 2025 and 145.8 MtCO₂e in 2030, considering LC0 and LC10 scenarios, respectively (Table 1). However, it is noteworthy that emissions related to waste burning and agricultural soils are higher in LC0 and LC10 scenarios compared to the REF scenario. It happens due to an increase in biofuels production (required as a mitigation measure implemented on the transport sector), as well as mitigation actions related to degraded pastures restoration and planted forests expansion.

Table 1: Emission scenarios and mitigation potential for AFOLU sector in 2025 and 2030

	GHG Emissions (MtCO ₂ e)						Mitigation of GHG Emissions ¹ (MtCO ₂ e)			
	2025			2030			2025		2030	
	REF	LC0	LC10	REF	LC0	LC10	LC0	LC10	LC0	LC10
1. Land use change	321.1	292.5	215.3	298.0	269.8	189.0	-28.6	-105.8	-28.2	-109.0
2. Agriculture and Livestock (2a+2b+2c+2d+2e)	506.4	509.6	478	536.2	539.5	499.5	3.2*	-28.4	3.3*	-36.7
2a. Enteric fermentation	305.4	305.4	276.3	319.4	319.4	283.3	0	-29.1	0	-36.1

2b. Animal waste management	23.1	23.1	22.2	24.5	24.5	22.8	0	-0.9	0	-1.7
2c. Rice	11.9	11.9	11.9	11.2	11.2	11.2	0	0.0	0	0.0
2d. Waste burning	4.2	5.0	5.0	3.3	3.9	4.0	0.8*	0.8*	0.6*	0.7*
2e. Agricultural soils (2e1+2e2+2e3+2e4+2e5)	161.7	164.2	162.4	177.7	180.5	178.1	2.5*	0.7*	2.8*	0.4*
2e1. Synthetic fertilizers	41.2	42.9	48	48.7	50.6	57.6	1.7*	6.8*	1.9*	8.9*
2e2. Agricultural waste	15.8	16.5	16.5	17.4	18.1	18.1	0.7*	0.7*	0.7*	0.7*
2e3. Vinasse	1.3	1.5	1.5	1.4	1.6	1.7	0.2*	0.2*	0.2*	0.3*
2e4. Animal grazing and manure	99.2	99.2	92.2	105.8	105.8	96.2	0	-7.0	0	-9.6
2e5. Animal waste management (N ₂ O)	4.2	4.1	4.1	4.5	4.4	4.4	-0.1	-0.1	-0.1	-0.1
Total emissions (1+2)	827.6	802.1	693.3	834.1	809.3	688.3	-25.5	-134.3	-24.8	-145.8
Removals (CA and IL)	-268.0	-268.0	-268.0	-268.0	-268.0	-268.0	NA	NA	NA	NA
Net Emissions	559.6	534.1	425.3	566.1	541.3	420.3	-25.5	-134.3	-24.8	-145.8

¹Emission reductions of LC0 and LC10 were obtained by subtracting the reference scenario emissions in their respective years (2025 and 2030).

*Activity presenting GHG emission increase in the scenario.

REF = Reference scenario; LCx = Low-carbon scenario, “x” indicates the carbon value in the scenario (USD 0 e USD 10/tCO₂e); CA = Conservation areas; IL = Indigenous lands; NA = Not applicable.

In Table 2 are demonstrated the AFOLU sectoral mitigation options to be implemented in 2025 and 2030 that allow achieving the sector mitigation potential described above. In 2025, under LC0 scenario implementation, the main measures would be increasing commercial planted forests, integrated crop-livestock-forestry systems, no-tillage systems, and biological nitrogen fixation (BNF) application.

Aiming to reach the LC10 scenario in 2030, mitigation actions related to cattle ranching intensifying through confinement, as well as increasing deforestation reduction, expansion of native vegetation, and degraded pastures recovery, would be implemented together with the measures related to the LC0 scenario.

Deforestation reduction involves reduction rates in Amazon, Caatinga, Pampas, and Pantanal biomes. In addition, it also considers the recovery of 9.3 million hectares of native vegetation by 2030.

In summary, it involves promoting actions for the reduction of deforestation in conjunction with the expansion of native vegetation areas and planted forests, as well as increasing the stock of carbon in the soil with the expansion of integrated systems and the recovery of degraded pastures.

Table 2: Main mitigation options to the AFOLU sector

Activity	Mitigation options	Mitigation potential (MtCO ₂ e) ¹	
		LC0 (2025)	LC10 (2030)
Agriculture	Expansion of no-tillage systems, 90% of crop areas for soybean, corn, rice, cotton, beans, and wheat until 2050, corresponding to 33 and 34 million hectares in 2025 and 2030, respectively.	2.0	2.1
Agriculture	Expansion of 200 thousand hectares/year for integrated cropland-livestock-forestry systems, from 2021 to 2050, corresponding to an expansion of 83% and 84% in 2025 and 2030, respectively.	0.4	0.5
Agriculture	Increase biological nitrogen fixation (BNF) using inoculants, reaching 39 and 40 million hectares in 2025 and 2030, respectively. (47 million hectares in 2050)	0.3	0.4
Livestock	Intensification of livestock production through cattle confinement, reaching a production of 8.2 and 10.5 million animals in 2025 and 2030, respectively. (19 million animals in 2050)	NA ²	47.6
Livestock	Recovery of 24 and 33.2 million hectares of degraded pastures in 2025 and 2030, respectively. (74 million hectares until 2050)	NA ²	7.4
Land use change	Deforestation reduction in Amazon (90% compared to historical average) and implementation of 40% deforestation reduction on Caatinga and Pantanal biomes and 58% to Pampas biome.	NA ²	47.7
Land use change	Nine and ten million hectares of commercially planted forests in 2025 and 2030, respectively. (14 million hectares in 2050)	25.3	23.6
Land use change	Native vegetation recovery of 6.2 e 9.3 million hectares in 2025 and 2030, respectively. (21 million hectares in 2050)	NA ²	9.5
Indirect emission/removals caused by low-carbon activities in other sectors. ³		-2.5	7.0
Total		25.5	145.8

¹ The mitigation potential refers to LC0 and LC10 scenarios in 2025 and 2030, respectively. It was obtained by integrated modeling of GHG emissions scenarios, described in the Methodological Procedures section.

² Measures not applicable to the LC0 scenario, in 2025, due to emission abatement costs.

³ It refers to energy recovery in agricultural waste, which reduces waste burning, and land use changes from pasture to sugar cane crop due to an increase in ethanol production on the energy sector.

The emission projections for the energy system are the result of the calculation of the supply and demand for energy, modeled in MESSAGE. To do this, we first obtained primary energy consumption projections for the different scenarios (Figure 2). The predominant role of crude oil remains the main primary energy source consumed in the Brazilian energy matrix, with emphasis on expansions of refining plants between 2020 and 2030. Generally speaking, there are no significant changes in the REF scenario concerning the ratio of primary energy sources in the consumption matrix, except for coal, whose share increases from 2040 onwards, to the detriment of the share of hydroelectricity and natural gas. This trend is a result of the depletion of the remaining

hydroelectric potential from 2030 on. Finally, the use of wood fuel biomass for energy is also significant.

The results obtained to the REF scenario indicate that Brazil will follow a conservative path related to the energy mix, with fossil sources ranging between 50% and 60%, reaching its maximum value in 2040, when the oil and gas supply would also reach its production plateau. Regarding the LC0 and LC10 scenarios, primary energy consumption is reduced, mainly from 2040 to 2050, with particular emphasis on lower consumption of oil in refineries instead of sugarcane processing for ethanol production. Coal consumption is also reduced due to the lower expansion of coal-fired power generation, especially in the LC10 scenario (2030-2050).

Figure 2: Primary energy consumption by the energy system in the REF, LC0 e LC10 scenarios – 2020 to 2050.

REF = Reference scenario.

LCx = Low-carbon scenario, “x” indicates the carbon value range in the scenario (0 and 10 USD/tCO₂e).

Due to the electric sector’s significance for understanding the increase of GHG emissions on energy system, results by energy sources are presented in Figure 3.

On the REF scenario, it is possible to observe an increase in the share of thermoelectric generation based on sugarcane bagasse and fossil fuels (natural gas at first, 2020-2030, and imported coal after, 2040-2050). The expansion of distributed photovoltaic systems occurred, but still modestly in absolute terms. Wind generation also increased; however, it is still small compared to other sources. Similarly, on LC0 and LC10 scenarios, this trend is maintained, except coal-fired thermoelectric generation reduction at the same time of sugarcane bagasse increasing, mainly in 2050.

Figure 3: Electric power generation by energy source on REF, LC0, and LC10 scenarios – 2020 to 2050.

REF = Reference scenario.

LCx = Low-carbon scenario, “x” indicates the carbon value range in the scenario (0 and 10 US\$/tCO₂e).

Table 3 shows potential emissions reductions in the energy system, which contribute to the mitigation of 60.4 MtCO₂e in 2025 (LC0 scenario) and 211.1 MtCO₂e in 2030 (LC10 scenario). The LC0 scenario demonstrates the highest mitigation potentials in the industry, waste management, and transport sectors, where energy efficiency plays a

significant role in mitigating emissions in these sectors. In the LC10 scenario, the electric and energy sectors also presented key mitigation potentials due to the adoption of energy efficiency measures and the repowering of hydroelectric plants.

Table 3: Emission scenarios and mitigation potential for the energy system, by subsectors and non- CO₂¹ in 2025 and 2030.

	GHG Emissions (MtCO ₂ e)						Mitigation of GHG Emissions ² (MtCO ₂ e)			
	2025			2030			2025		2030	
	REF	LC0	LC10	REF	LC0	LC10	LC0	LC10	LC0	LC10
Industry	120.4	105.4	87.4	131.5	110.9	91.9	-15.0	-33.0	-20.6	-39.6
Agriculture	22.0	21.9	22.1	23.9	23.8	24.2	-0.1	-0.1	-0.1	0.3
Transport	214.6	200.7	198.4	228.6	208.6	203.3	-13.9	-16.2	-20.0	-25.3
Household and services	22.5	22.5	22.4	21.0	21.4	21.4	0.0	-0.1	0.4*	0.4*
Electric	49.4	47.6	25.3	53.2	52.3	27.2	-1.8	-24.1	-0.9	-26.0
Energy	118.0	108.1	85.5	140.6	131.0	106.3	-9.9	-32.5	-9.6	-34.3
Industrial processes	98.3	97.7	88.7	106.6	105.3	94.1	-0.6	-9.6	-1.3	-12.5
Non-CO₂¹	35.6	28.4	10.4	42.2	33.0	13.2	-7.2	-25.2	-9.2	-29.0
Waste management	108.5	96.6	68.5	122.2	83.1	77.1	-11.9	-40.0	-39.1	-45.1
Total	789.3	728.9	608.7	869.8	769.4	658.7	-60.4	-108.6	-100.4	-211.1

¹ CH₄ emissions related to operation on oil platforms, as well as transportation and distribution of natural gas and coal.

² Emission reductions of LC0 and LC10 were obtained by subtracting the reference scenario emissions in their respective years (2025 and 2030).

* In this scenario, the subsector presents emission increasing.

REF = Reference scenario; LCx = Low-carbon scenario, “x” indicates the carbon value in the scenario (US\$ 0 and US\$ 10/tCO₂e).

The mitigation options related to GHG emissions reductions described in the energy system are demonstrated in Table 4. Regarding the industry and energy sectors, the mitigation options identified by integrated modeling are efficiency on heat and steam recovery, flare reduction, and installation of steam recovery units in oil and gas E&P platforms, as well as substitution of coal by sugarcane bagasse on thermal plants. In contrast, the mitigation options identified to transport were a modal shift from individual to collective passenger transportation as well as from highways to railways and waterways to load transportation. In the waste management sector, the options identified were mainly the energy utilization of urban solid waste and effluent of treatment plants for production of biomethane and electricity.

Table 4: Main mitigation options to the Energy system.

Sector (segment)	Mitigation options	Mitigation potential (MtCO ₂ e) ¹	
		LC0 (2025)	LC10 (2030)
Industry (other)	Improved efficiency in recovery of heat and steam in processes	7.0	7.1
Industry (cement)	Improved efficiency in heat recovery in processes	3.2	2.8
Industry (other)	Improved efficiency of furnaces and process optimization	2.4	2.2
Industry (chemical)	Improved efficiency in heat recovery in processes	1.2	1.4
Industry (chemical)	Improved efficiency in steam recovery in processes	0.9	1.1
Industry (cement)	Fuel substitution	0.7	1.0
Industry (Iron and steel smelting)	Improved efficiency in heat recovery in processes	0.2	14.7
Industry (Iron and steel smelting)	Fuel substitution	NA ³	4.1
Industry (other)	Fuel substitution	NA ³	2.2
Energy (oil and gas E&P)	Flare ² reduction and installation of steam recovery units	7.2	22.3
Energy (refining)	Improved efficiency in recovery of heat and steam in processes	2.9	6.9
Energy (refining)	Improved efficiency in hydrogen consumption	NA ³	3.9
Energy (refining)	Improved efficiency in electrical motors	NA ³	1.2
Energy (electric)	Replacement of coal-fired thermoelectric plants with biomass and bagasse cogeneration plants	NA ³	23.1
Energy (electric)	Repowering of hydroelectric plants	1.8	2.9
Transport (road)	Improved efficiency of diesel-powered buses and trucks	NA ³	5.3
Transport (cargo)	Modal change (road freight to rail and waterway)	8.3	3.8
Transport (passenger)	Modal change (cars to buses and subways)	5.6	15.0
Buildings (residential)	Improved efficiency of liquefied petroleum gas and natural gas stoves	0.1	0.4
Waste management (MSW)	Use of landfill biogas for energy generation by flare	5.4	20.8
Waste management (MSW)	Use of biogas for the production of biomethane	2.2	8.2
Waste management (MSW)	Use of biogas for generating electricity	1.8	6.7
Waste management (effluents)	Use of biogas from effluents for generating electricity	1.3	5.0
Waste management (MSW)	Increased use of biodigestion for the production of biomethane	0.6	2.1
Waste management (MSW)	Waste incineration	0.3	1.0
Waste management (MSW)	Increased use of biodigestion for the generation of electricity	0.2	0.9
Waste management (MSW)	Expansion of MSW recycling ⁴	NA ³	0.4
	Other less significant low carbon activities for the reduction of sectoral emissions ⁵	7.1 ⁶	44.6 ⁷
	Total	60.4	211.1

¹ Potentials and mitigation options refer to LC0 and LC10 scenarios for the years 2025 and 2030, respectively.

² Flare reduction via the installation of pilot ignition.

³ Measures not applicable to the LC0 scenario in 2025 due to the cost of emission abatement.

⁴ Increase in MSW recycling from 5% to 7% in the REF and LC scenarios.

⁵ It covers mitigation measures with a potential of less than 0.1 MtCO₂e.

⁶ It considers the reduction of CO₂ and CH₄ emissions related to the decrease in the activity effect on oil platforms and the transport and distribution of natural gas and coal in the LC0 scenario.

⁷ It considers CO₂ and CH₄ emission reductions related to (i) coal extraction decrease - mitigation potential of 38.6 MtCO₂e in the LC10 scenario in 2030, (ii) effects on cement, transport, and steel sectors activities – mitigation potential of 4.1 MtCO₂e in the LC10 scenario in 2030. Also, it considers measures with a mitigation potential of less than 0.1 MtCO₂e.

MSW – Municipal solid waste.

E&P – Exploration and production.

DISCUSSION

This study investigated the role that each economic sector can play to meet the GHG emission targets for 2025 and 2030, and thus comply with Brazil's NDC commitments.

An integrated analysis was performed using soft-links between three leading Brazilian developed tools: a CGE model, named EFES, which provides and guarantees the macroeconomic consistency of the analysis; an energy system optimization model, named MESSAGE, which provides different trajectories for the Brazil' 's energy system, in a highly detailed techno-economical fashion (including GHG emissions from fuel combustion, industrial processes, fugitive emissions, and waste treatment); and a land-use optimization model, named OTIMIZAGRO, which can optimize at micro spatial resolution the AFOLU sector in Brazil.

As a result of the iterative procedure, this study can add different mitigation options into a greenhouse gas emission strategy to reach the Brazilian NDC. This strategy is compatible with the same trajectory of the economy, the energy system (supply and demand), and the land-use sector; this approach avoids incompatibility of measures between the sectors. For instance, it is expected to measure the mitigation potential and the marginal cost of GHG emission reduction by mapping technical-economic parameters of low carbon activities. However, the sectoral analysis does not allow the detection of non-additive mitigation potentials that may derive, for example, from the competition for energy inputs and technologies aimed at the reduction of GHG emissions. It is the case of natural gas, which is a contested energy input to mitigate emissions in thermoelectric generation and production of heat and steam for industrial processes, replacing more energy-intensive fuels (coal and fuel oil). Sectoral models are not able to measure the effects of the dispute on the availability and prices of natural gas and, as a consequence, tend to over and underestimate, respectively, the potential and cost of mitigation associated with the substitution of coal and fuel oil by natural gas.

The results showed that the LC0 scenario is compatible with meeting the NDC target for 2025. In 2030, compliance with the commitment would require the adoption of the LC10 scenario, which implies an economic effort to internalize a carbon price of US\$ 10/tCO_{2e}, which is a reasonable level of carbon pricing, compatible with the values employed in the second phase of the EU-ETS emissions trading scheme (THE CLIMATE GROUP, 2013).

However, two critical uncertainties, related to assumptions considered make meeting additional GHG emission reduction targets challenging: (i) full implementation of PNMC (National Policy on Climate Change) by 2020, in light of the economic and COVID-19 crisis; and (ii) carbon removal in conservation units (CUs) and ILs.

With the deepening of the economic crisis in the country, the federal government adopted the imposition of budgetary restrictions through Constitutional Amendment N° 95, which limits public spending for 20 years (PEC 55/2016). This crisis was recently aggravated by the effects of the COVID-19 pandemic in the country, as well as by the weakening of environmental governance at the federal level (SCHAEFFER et al., 2018; RAJÃO et al., 2020).

These aspects could lead to only a partial implementation of the PNMC since the restriction of the federal budget would affect fundamental actions of the policy, in addition to investments in the states and municipalities, among which we can cite: (i) financing for integrated crop-livestock-forest farming (CLF), no-till farming and recovery of degraded pastures; (ii) research and development for BNF; (iii) monitoring and control of deforestation; and (iv) technical assistance and rural extension (ATER); among others. Within the energy system, we can cite factors that potentialize the increase of emissions in the REF scenario, such as (i) delays in the completion of infrastructure works, especially roads, railroads, and ports; (ii) deterioration of the asphalt of federal roads not administrated under concession; and (iii) non-compliance with the National Policy on Solid Waste (PNRS) targets, especially the deadline for banning landfills; among others.

In the case of carbon removals in CUs and ILs, in the context of climate change and an increase in the occurrence of droughts in the Amazon biome, there is a real possibility that forests will become net emitters of GHG (DAVIDSON et al., 2012). Moreover, even without significant effects caused by climate change, there is the possibility that the forest will reach a threshold and become carbon neutral.

These factors give rise to the possibility that the REF scenario emissions could be higher than projected in 2025 and 2030. Given the above, in future revisions of the NDC targets, it may be necessary to consider broadening the sectoral mitigation options. If there is the possibility of not fully complying with the policies considered in the assumptions, it may

be necessary to implement the complete set of measures described in the LC0 and LC10 scenarios, representing a higher national effort for compliance with the NDC.

CONCLUSIONS

Through the IAM approach, we demonstrate that the NDC target for 2025 could be achieved with the LC0 scenario (carbon value equal to zero) implementation, while the NDC target for 2030 could be achieved by implementing the LC10 scenario in 2030, which implies an economic effort to internalize a carbon price of US\$ 10/tCO_{2e}. In addition, it was identified the low carbon activities with higher mitigation potential in all sectors of the economy, which need to be implemented to comply with the NDC targets. The results obtained indicated a rationale that takes into consideration sector cost-carbon effectiveness and key technologies for compliance with the NDC. However, it is necessary to establish a national consensus where technology action plans can build from, aiming to support the policy-making process. Therefore, this study contributed to the development of a comprehensive Technology Needs Assessment, which is a methodology defined as a group of activities conducted by a country leading to the identification, prioritization, and diffusion of environmentally friendly; the initiative is funded by the Green Climate Funding (www.greenclimate.fund/document/strategic-frameworks-support-brazil-through-unep), and it is expected to be concluded at 2021.

METHODS

The integrated modeling of GHG emissions scenarios started with boundary conditions from a macroeconomic consistency model (dynamic stochastic general equilibrium – DSGE) that generated data for the EFES Model (KANCZUK, 2001 and 2004; HADDAD, DOMINGUES, 2016). The key variables used for the construction of sectoral scenarios of energy supply and demand, as well as land use and land use changes, were projected at EFES, including Gross Domestic Product (GDP), the gross value of production, value-added, staff employed, work income.

Due to the correlation between the level of economic activity and GHG emissions, it was considered projections of macroeconomic aggregates that reflect, especially in the short

term, the current conditions of the Brazilian and world economy. The GDP projections considered are shown in Table 5.

Table 5: Average growth rates of domestic GDP (%) from 2016 to 2050

2016-2020	2021-2025	2026-2030	2031-2035	2036-2040	2041-2045	2046-2050	2016-2050
0.6	2.3	2.2	2.0	1.8	1.6	1.4	1.6

Those data, together with variables of characterization and evolution of the economic sectors, such as production, technological, energy, land use, and GHG emissions profile, enabled a bottom-up disaggregated sectoral modeling. Optimization and simulation models were developed and applied for the following sectors: industrial, energy, transport, buildings (residential, commercial, and service), AFOLU, and waste management.

The sectoral modeling was applied to simulate the sectoral agents' behavior, translating it into energy demand and land use and land-use changes to project GHG emissions. Therefore, the use of sectoral models allowed a database elaboration to enable the integration of projections into the energy, AFOLU, and economic models (MESSAGE, OTIMIZAGRO, and EFES, respectively). This integration was a *soft-link* type, which demanded the transposition of results between the models. More information on these models can be found in the Supplementary Material.

MESSAGE integration was carried with the sectoral demand models, OTIMIZAGRO, and EFES. Data on energy demand was provided by sectoral models, as well as the technical-economic parameters of technologies likely to be employed, and options implying reductions of GHG emissions. Regarding the iteration of energy demand with OTIMIZAGRO, it was verified any restrictions on land use for production expansion of wood and charcoal from planted forests, as well as sugarcane and soybean.

For the iterative procedure with EFES, modeling rounds were performed in order to converge growth projections of energy inputs production. In addition, MESSAGE and OTIMIZAGRO were applied to generate direct technical intensities of energy (EI), and carbon intensities (CIS) of the different sectors analyzed, in scenarios with and without the internalization of carbon prices in the economy, aiming to measure deviations in terms of GDP, level of employment and income.

In this regard, the mathematical basis of the MESSAGE required the incorporation of an implicit carbon value for the construction of GHG emissions scenarios (0, 10, 25, 50, and 100 USD/tCO₂e), aiming to generate a model perturbation or shock to induce optimization decision according to marginal abatement curves.

The integration modeling steps mentioned above are demonstrated in Figure 4.

Figure 4: Flowchart of modeling integration between EFES, OTIMIZAGRO and MESSAGE models

GHG emissions scenarios for the period 2011-2050 were projected: i) a reference, or baseline, scenario (REF), and ii) low carbon scenarios (LCx – where “x” indicates the carbon value considered in the scenario).

The REF scenario includes future pledges of current governmental public policies, as well as official sectoral expansion plans; for example, the expansion of the energy system from the Brazilian Ten-Year Energy Plan 2027 (PDE 2027), the goals described in the National Policy on Climate Change (PNMC), and the Sectoral Plan for the Mitigation and Adaptation to Climate Change for a Low-Carbon Emission Agriculture (ABC Plan) (MMA, 2008, 2017a and 2017b; MAPA, 2012; EPE, 2018). Other plans have also been considered, including, but not limited to: the Action Plan for the Prevention and Control of Deforestation and Burning in the Cerrado (PPCerrado), the Action Plan for the Prevention and Control of Deforestation in the Legal Amazon (PPCDAm), the National Plan for Logistics and Transport (PNLT), the National Water Resources Plan (PNRH), the National Sanitation Plan (Plansab), National Policy on Solid Waste (PNRS), and the Growth Acceleration Program (PAC) (MMA, 2006; 2008; MT, 2012; MCIDADES, 2013; MP, 2017).

The LC scenarios consider the implementation of the best available technologies (BAT) that produce emission mitigation effects. Its construction, together with the integrated models (MESSAGE and OTIMIZAGRO), takes into account different levels of carbon value: 0, 10, 25, 50, and 100 dollars per tonne of carbon dioxide equivalent (USD/tCO₂e). The LC0 scenario (considering USD 0/tCO₂e) contains *no-regret* abatement measures that are economically feasible over their useful life but are not implemented due to other barriers, such as information asymmetry, different opportunity costs of capital,

transaction costs, access to credit, technological lock-in, and others. The USD 10/tCO₂e carbon value range also considers measures that require the internalization of the carbon value for its incorporation into the economic sectors. It covers null carbon value measures and additional mitigation opportunities that demand an implicit carbon value for their viability. The other carbon value ranges have the same logic, requiring higher levels of internalization of carbon value for their adoption.

Regarding general scenarios assumptions, it was considered the CO₂, CH₄, and N₂O (nitrous oxide) emissions related to combustion, waste management, energy, and industrial processes, fugitive emissions, and emissions from land use and land-use changes. The account of emissions using a unit of carbon dioxide equivalent was performed applying the methodology of the GWP 100 years, contained in the Fifth Assessment Report of the Intergovernmental Panel on Climate Change (IPCC, 2014). The reference year (2010) calibration and equalization of emission factors and land-use transitions were performed by the data of the Third National Communication (TNC) of Brazil (MCTIC, 2016). Finally, population growth projections of the Brazilian Institute for Geography and Statistics (Projection of the Population of Brazil by sex and age: 2000-2060) were used (IBGE, 2013).

Table 6 summarizes the main assumptions considered in the reference and low-carbon scenarios.

Table 6: Main assumptions of REF and LC scenarios

Subsector	Main assumptions	
	REF scenario	LC scenario
Agriculture	80% of soybean, corn, cotton, rice, bean and wheat production areas with conservation systems.	Increase to 90% of these areas with conservation systems.
	Target of the ABC Plan for the area occupied with integrated farming systems by 2020 and maintenance of the adopted ratio between 2021 and 2050.	Target of the ABC Plan to 2020 and a 50% increase in the target of the occupied area between 2021 and 2050.
	Application of BNF in 100% of areas planted with soybean and 10% of rice, bean, corn and wheat areas.	Expansion of BNF to 30% of the areas of rice, beans, corn and wheat and the inclusion of sugarcane areas.
Livestock	Projection of cattle ranching aiming to meeting the expected demand for meat, according to Agribusiness Projections: 2013/2014 to 2023/2024, with growth reduction from 2031 to 2050.	Maintenance of meat production, but with increased productivity (intensification) in cattle ranching. For this, we consider increases of 16% and 27% in livestock confinement farming and 35% and 37% in pasture recovery in 2025 and 2030, respectively, relative to the REF scenario.

Planted forests	Sectoral demand of 53% for fuel wood from native forests in the period.	Decrease in the ratio of native forest fuel wood to 10% by 2050.
Native forests	Deforestation reduction targets of 80% and 40% in the Amazon and Cerrado biomes, respectively, applied to the deforestation target for 2002 and 2010, and prohibition of cutting native vegetation in the Atlantic Forest; Recovery of environmental liabilities of 12.5 million hectares in 20 years and additional recovery of 4.5 million hectares between 2035 and 2050.	Same as the previous item, with only legal deforestation in the Amazon, and the application of a 40% deforestation reduction target in the Caatinga and Pantanal biomes, and 58% in the Pampas biome; Expansion of native vegetation restoration to 21 million hectares by 2050.
Energy System	Expansion of the energy system at minimum cost; Introduction of available technologies in the baseline; No adoption of additional mitigation policies; Predominance of the sectoral perspective on modeling; Short-term trajectory adhering to the current and planned expansion of the energy system.	Expansion of the energy system, considering different levels of carbon pricing; Introduction of the best available technologies and production practices; Internalization of different levels of carbon pricing in the economy; Freedom to select the evolution of the technological profile and the optimization of the energy system, according to a logic of GHG emission mitigation.

LIST OF ABBREVIATIONS

ABC – Sectoral Plan for the Mitigation and Adaptation to Climate Change for a Low-Carbon Emission Agriculture

AFOLU – agriculture, forestry and other land use sector

ATER – technical assistance and rural extension

BAT – best available technologies

BNF – biological nitrogen fixation

CA – conservation areas

CGE – computable general equilibrium

CH₄ – methane

CIS – carbon intensities

CLF – crop-livestock-forest farming

CO₂ – carbon dioxide

COP – Conference of the Parties

CU – conservation units

DSGE – dynamic stochastic general equilibrium

E&P – oil and gas extraction and production

EI – intensities of energy

EPE – Energy Research Company

EU-ETS – European Union emission trading scheme
GDP – gross domestic Product
GHG – greenhouse gases
GWP – global warming potential
IAM – integrated assessment models
IBGE – Brazilian Institute of Geography and Statistics
IL – indigenous lands
iNDC – Intended Nationally Determined Contributions
IPCC – Intergovernmental Panel on Climate Change
LC – low-carbon
LC0 – carbon value equal to zero
LC10 – carbon value equal to 10US\$/tCO₂
MAPA – Ministry of Agriculture, Livestock and Supply
MCIDADES – Ministry of Cities
MCTIC – Ministry of Science, Technology, Innovations and Communications
MMA – Ministry of Environment
MP – Ministry of Planning
MSW – municipal solid waste
MT – Ministry of Transportation
N₂O – nitrous oxide
NA – not applicable
NDC – Nationally Determined Contributions
PAC – Growth Acceleration Program
PDE – Brazilian Ten-Year Energy Plan
Plansab – National Sanitation Plan
PNLT – National Plan for Logistics and Transport
PNMC – National Policy on Climate Change
PNRH – National Water Resources Plan
PNRS – National Policy on Solid Waste
PNRS – National Policy on Solid Waste
PPCDAm – Action Plan for the Prevention and Control of Deforestation in the Legal Amazon

PPCerrado – Action Plan for the Prevention and Control of Deforestation and Burning in the Cerrado

REF – reference scenario

TNC – Third National Communication

UNFCCC – United Nations Framework Convention on Climate Change

USD – United States dollars

DECLARATIONS

Availability of data and materials

The data are presented in the study. Secondary input data for the models are presented in MCTIC (2017).

Competing interests

The authors declare that they have no competing interests.

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Authors contributions

Régis Rathmann and Ricardo Araujo carried out the analysis and wrote the paper. Dominique Mouette, Márcio Rojas da Cruz and Edmilson Moutinho dos Santos reviewed the paper. Both authors read and approved the final manuscript.

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